University of Zagreb

Faculty of Mechanical Engineering and Naval Architecture

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VIRTUAL REALITY SUPPORTED TRANSITION PROCESSES IN TEAMS DEVELOPING PRODUCTS

DOCTORAL DISSERTATION

Zagreb, 2023.

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Supervisor:
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Sveučilište u Zagrebu

Fakultet strojarstva i brodogradnje

Nikola Horvat

TIMSKI TRANZICIJSKI PROCESI PODRŽANI TEHNOLOGIJOM VIRTUALNE STVARNOSTI U RAZVOJU PROIZVODA

DOKTORSKI RAD

Mentor:
Izv. prof. dr. sc. Stanko Škec

Zagreb, 2023.

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CONTENTS

ABOUT THE SUPERVISOR

Stanko Škec was born in Zagreb, Croatia. He holds PhD degree from the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb (UNIZAG-FSB) and is currently an Associate Professor at the Chair of Design and Product Development at UNIZAG-FSB. He was appointed as a Visiting Assistant Professor (2018-2019) at the Engineering Systems Group, DTU – Technical University of Denmark, Lyngby, Denmark. Previously, he was visiting researcher at several institutions abroad – Ecole Centrale Paris, the University of Bristol and The University of British Columbia.

As a project team member, he previously participated in various national (i.e., two Croatian Science Foundation projects and one government-founded project) and international projects (i.e., one EUREKA project, two ERASMUS+ projects, and one HORIZON2020 projects). He was also responsible for leading the international ERASMUS+ project "E-learning Platform for Innovative Product Development" (http://www.elpid.org/).

Dr Škec has published his work in international journals (e.g. TFSC, Design Studies, Research in Engineering Design, Journal of Engineering Design) and peer-reviewed conferences (e.g. ICED, DESIGN, NordDesign). He acted as a reviewer for several international journals (e.g. Sustainability, IEEE Access, IEEE TEM, AI EDAM). The primary field of research and scientific focus of Dr Škec has been a multidisciplinary field of product-service systems design and development. His research interests are primarily focused on the management and monitoring of development processes and activities, as well as on studies of distributed work and virtual collaboration.

He has actively participated in the organisation of the biennial DESIGN series event since 2012, which regularly attracts more than 300 experts from more than 30 countries around the world. In addition, he was elected to serve as an Assistant Programme Chair of ICED17 (21st International Conference on Engineering Design), which was held at The University of British Columbia, Vancouver (http://iced17.org/).

Besides the scientific and professional work summarised above, Dr Škec is involved in teaching through UNIZAG-FSB undergraduate and graduate study programs in product development and design theories. As a part-time assistant lecturer, he held tutorials at the Polytechnics of Zagreb and the Faculty of Industrial Engineering Novo Mesto (Slovenia).

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ABSTRACT

Virtual reality (VR) technologies have great potential to improve design reviews. However, their effect on these activities is still inconclusive. One of the reasons is the lack of understanding regarding design reviews. This thesis addresses this gap by introducing transitions, an overarching concept of evaluation and/or planning activities, such as design reviews and reflections on actions. Through two proposed theoretical models, transitions are introduced from multiple facets on a micro- and meso-scale. In addition, an experimental framework is developed to consolidate the considerations when studying VR-supported transitions in an engineering design context. The proposed models and framework are used to design two experiments in which 10 and 14 teams conducted transition activities using a traditional user interface (mouse, keyboard, monitor) or VR (head-mounted displays). The results show that considering cognitive, affective, and social aspects together better predicts the team's actions and provides evidence for studying transitions as multifaceted activities. The teams that used VR worked together more often, which makes this technology useful when the goal is to achieve collective decision-making. VR also supported identifying issues related to the design problem and the interaction between design and users, suggesting its suitability for the early design phases. Hence, VR and traditional user interfaces are not substitutable but rather complementary technologies.

Keywords:

Product development; design teams; virtual reality; design review; transitions; team transition processes; experimental framework; collaborative work

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PROŠIRENI SAŽETAK

Konstruiranje je ključni proces u razvoju proizvoda kojim se definira funkcija i oblik proizvoda. Taj proces se obično sastoji od aktivnosti koje se mogu podijeliti na razvojne i tranzicijske. Razvojne aktivnosti su usmjerene na postizanje ciljeva konstruiranja (npr. izrada računalnog modela), a tranzicijske na evaluaciju prethodnog i planiranje budućeg rada (npr. pregled konstrukcije). Iako oba tipa aktivnosti utječu na ishode razvoja proizvoda, tranzicijske aktivnosti su rijetko proučavane u kontekstu konstruiranja. S obzirom na to da se tijekom tranzicijskih aktivnosti donosi niz važnih konstrukcijskih odluka, proučavanje tih aktivnosti nužno je za razumijevanje i poboljšanje procesa konstruiranja.

Tranzicije se često provode kroz sastanke u kojima članovi konstrukcijskog tima raspravljaju o proizvodu s ostalim dionicima u procesu razvoja proizvoda (npr., menadžeri, voditelji proizvodnje, krajnji korisnici), tvoreći tako privremeni tranzicijski tim koji se sastoji od unutarnjih i vanjskih članova. Zajedničkim radom unutarnjih i vanjskih članova, tranzicijski tim donosi odluke za budući rad. Na taj način tranzicije pridonose unaprjeđenju konačnog proizvoda.

Kako tranzicijski tim obično donosi odluke na temelju stanja razvijanog proizvoda, promjena interakcije s prikazom proizvoda (npr. pregled 3D modela pomoću miša i tipkovnice ili pregled 3D modela pomoću tehnologija virtualne stvarnosti) može utjecati na izvršavanje tranzicija. Također, promjena načina interakcije između članova tima (npr., isključivo verbalna komunikacija ili verbalna komunikacijama s prenošenjem gestikulacija) može utjecati na tranzicije.

Iako imaju veliki potencijal za promijeniti način na koji se provode tranzicije, tehnologije virtualne stvarnosti nemaju uvijek pozitivni utjecaj na tranzicije. Dok dio istraživača zaključuje da tehnologije virtualne stvarnosti poboljšavaju razumijevanje prikaza proizvoda i razumijevanje ishoda tranzicija, drugi dio pokazuje da te tehnologije smanjuju ili ne utječu na razumijevanje prikaza proizvoda i ishoda tranzicija. Osim toga, utjecaj tehnologija virtualne stvarnosti na tranzicije ovisi o različitim faktorima, kao što su prethodno iskustvo članova tranzicijskog tima, kompleksnost proizvoda, dostupne funkcionalnosti alata itd.

Kontradiktorni rezultati vezani uz utjecaj tehnologija virtualne stvarnosti mogu biti povezani s nejasnim opisom tranzicija. Naime, razumijevanje tranzicija zahtijeva uvođenje spoznaja iz različitih područja (inženjerstvo, psihologija, menadžment, sociologija). Iz područja inženjerstva i menadžmenta, tranzicije se opisuju kroz niz akcija koje postepeno mijenjaju trenutno stanje tranzicijske aktivnosti u novo. Na primjer, pri pregledu reduktora, tranzicijski tim može u jednom trenutku procjenom ili mjerenjem pokušati razumjeti visinu ulaznog vratila reduktora (akcija razumijevanja). Zatim, tim može provesti provjeru visine ulaznog vratila (akcija evaluacije) te predložiti eventualnu promjenu visine (akcija planiranja). Nizom takvih akcija donose se odluke kojima se teži napraviti što bolji konačni proizvod. Iako je ovakav opis omogućio djelomično razumijevanje tranzicija, proširenje opisa uključivanjem psiholoških i društvenih aspekata može rezultirati boljim razumijevanjem ovih kompleksnih aktivnosti.

Psihološki aspekti koji se često uključuju u analizu konstrukcijskih aktivnosti su kognicija i afekt. Iako su prethodna istraživanja pronašla vezu između kognicije i afekta i izvršenja tranzicijskih akcija, spoznaje se uglavnom temelje na istraživanjima u kojima pojedinci provode konstrukcijske aktivnosti. Takve spoznaje imaju ograničenu primjenu u praksi gdje se često koriste timovi. Iako istraživači posljednjih godina sve više proučavaju timove, obično se pretpostavlja da tim cijelo vrijeme radi kao cjelina. Međutim, rad u timu ne znači da članovi uvijek rade kao cjelina, već da se zajednički cilj ostvaruje kombinacijom individualnog rada, rada u podtimovima i rada svih članova zajedno. Stoga je za razumijevanje tranzicija nužno uključiti i društvene aspekte koji proizlaze iz timskog rada.

Kombinacijom spoznaja iz različitih područja u koherentan opis tranzicija može rezultirati boljim razumijevanjem ovih aktivnosti. Također, utjecaj tehnologija virtualne stvarnosti na tranzicije može biti preciznije opisan. S obzirom na važnost tranzicija i nedostatak spoznaja o njima, cilj istraživanja je razvoj teorijskog modela timskih tranzicijskih procesa (akcija) u razvoju proizvoda, teorijskog modela timskih tranzicija te razvoj okvira za eksperimentalno proučavanje timskog rada podržanog tehnologijama virtualne stvarnosti. Ovim istraživanjem verificira se hipoteza da tehnologije virtualne stvarnosti u timskom radu proširuju razumijevanje tranzicijskih procesa tijekom razvoja proizvoda i unaprjeđuju izvršavanje aktivnosti evaluacije/planiranja tijekom razvojnih projekata prema definiranim metrikama.

Istraživanje je provedeno u skladu s osnovnom istraživačkom metodologijom znanosti o konstruiranju, koja se sastoji od tri ciklusa istraživačkih aktivnosti: određivanje relevantnosti, razvoj i utvrđivanje valjanosti. Određivanje relevantnosti obuhvaća pregled područja kojemu je cilj postavljanje zahtjeva vezanih uz tranzicije u razvoju proizvoda, konstrukcijske timove i tehnologije virtualne stvarnosti. Ciklus razvoja započeo je razvojem teorijskih modela tranzicija i eksperimentalnog okvira na temelju dosadašnjih spoznaja. Modeli i okvir su zatim evaluirani kroz dvije eksperimentalne studije slučaja. Konačno, u ciklusu utvrđivanja valjanosti provedene su teorijska i empirijska validacija modela i eksperimentalnog okvira.

Teorijski modeli

Na temelju pregleda istraživanja predložena su dva teorijska modela: model timskih tranzicijskih procesa i model timskih tranzicija. Model timskih tranzicijskih procesa razvijen je u kontekstu aktivnosti evaluacije/planiranja, a sastoji se od niza tranzicijskih akcija koje postupno mijenjaju stanje tranzicije prema cilju tih aktivnosti. Stanje tranzicije obuhvaća karakteristike agenata, informacijski sadržaj, prostor konstruiranja i druge karakteristike tranzicija. Agenti su adaptivni sustavi (npr. konstruktori, korisnici) koji su u interakciji s informacijskim sadržajem i ostalim agentima. Agenti su sa psihološke perspektive opisani kognitivnim (tj. stanje nesigurnosti) i afektivnim stanjem. Stanje nesigurnosti predstavlja osviještenost agenata o ograničenjima njihovog trenutnog znanja ili razumijevanja dok stanje afekta opisuje iskustvo agenta o njihovom emocionalnom intenzitetu. Informacijski sadržaj opisan je okruženjem i artefaktima koji se često koriste tijekom tranzicija (prikaz konstrukcijskog problema, prikaz konstrukcijskog rješenja, tranzicijski izvještaj, tranzicijski cilj i avatari). Nadalje, prostor konstruiranja je opisan trenutnim i budućim stanjem konstrukcije. Modelirana stanja mogu se mijenjati pomoću tranzicijskih akcija. Iako akcije mogu promijeniti bilo koje od navedenih stanja, one se najčešće odnose na razumijevanje ili evaluaciju trenutnog stanja konstrukcije te na planiranje budućeg stanja konstrukcije. Konačno, kako bi se uključila društvena perspektiva, akcije se mogu izvršiti sa svim uključenim članovima ili u podtimu, opisujući tako vrstu rada članova tima.

Model timskih tranzicija razvijen je na srednjoj razini granularnosti, uzimajući u obzir spoznaje modela timskih tranzicijskih procesa (mikro-razina). Model se sastoji od ulaza, medijatora, izlaza i ishoda. Ulazi i izlazi sastoje se od faktora prostora konstruiranja (trenutačno stanje konstrukcije, buduće stanje konstrukcije), faktora informacijskog sadržaja (okolina, artefakt), faktora tima (kompozicija i kontekst) i drugih faktora tranzicija (proces konstruiranja, kontekst zadatka tranzicija, organizacijski kontekst, kultura). Razlika između izlaza i ulaza prikazana je ishodima koji su opisani promjenama u prostoru konstruiranja (npr. promjena u kvaliteti), timovima (npr. učenje), informacijskom sadržaju (npr. kreirani artefakti) i procesu konstruiranja (npr. tranzicija u novu fazu konstruiranja). Ti se ishodi postižu kroz medijatore, podijeljene na timsko ponašanje i karakteristike koje proizlaze iz rada tima. Timsko ponašanje opisano je pomoću dva faktora: tranzicijske akcije i način rada tima. Konačno, karakteristike koja proizlaze iz rada tima predstavljaju dinamičke promjene u kognitivnim i afektivnim aspektima tima.

Eksperimentalni istraživački okvir

S obzirom da postoji veliki broj faktora koji mogu utjecati na tranzicije, te zbog specifičnosti novih tehnologija virtualne stvarnosti, istraživači pri proučavanju tranzicija moraju razmotriti brojne elemente planiranja eksperimenta. Kako bi se objedinili elementi koje je potrebno razmotriti i time dala podrška istraživačima pri planiranju studija vezanih uz tranzicije podržane tehnologijama virtualne stvarnosti, predložen je eksperimentalni okvir za osmišljavanje takvih studija.

Okvir se sastoji od četiri kategorije razmatranja: eksperimentalna, teorijska, metodološka i provedbena. Eksperimentalna razmatranja opisuju ograničenja koja istraživači trebaju uzeti u obzir, kao što su istraživačka etika, raspoloživi resursi, pouzdanost eksperimenta, ponovljivost eksperimenta te valjanost eksperimenta. Teorijska razmatranja odnose se na tranzicijsku perspektivu i uključuju definiranje cilja istraživanja (npr. istraživačka pitanja, hipoteza) i tranzicijskih faktora (npr. definiranje faktora korištenjem razvijenog teorijskog modela timskih tranzicija). Nadalje, metodološka razmatranja opisuju načela planiranja eksperimenta vezanih uz pouzdanost, ponovljivost i valjanost eksperimenta. Ova razmatranja uključuju definiranje mjerenja faktora, uzorka, tipa eksperimenta i analize podataka. Implementacijska razmatranja opisuju karakteristike eksperimenta, tranzicija i tehnologija virtualne stvarnosti koje treba uzeti u obzir pri razvoju eksperimentalnog postava i procedure za istraživanje tranzicija podržanih tehnologijama virtualne stvarnosti. Konačno, svako od ovih razmatranja može se testirati pomoću probnih studija. Ova razmatranja korištena su pri planiranju eksperimentalnih studija slučaja provedenih u sklopu ovog rada.

Eksperimentalne studije slučaja

U okviru rada, provedene su dvije eksperimentalne studije slučaja. Cilj prve eksperimentalne studije slučaja bio je prikupiti empirijske podatke koji će služiti za evaluaciju teorijskog modela timskih tranzicijskih procesa, dok je cilj druge bio prikupiti podatke za evaluaciju teorijskog modela timskih tranzicija. Osim toga, obje studije su služile i za evaluaciju eksperimentalnog istraživačkog okvira. Kako bi se provjerila značajnost zaključaka iz studija, prikupljeni podaci su obrađeni prikladnom statističkom analizom (npr. hi-kvadrat test, t-test, analize varijance, multinomna logistička regresijska analiza), uzimajući u obzir pretpostavke kao što su normalnost, homogenost varijanci i faktor inflacije varijance.

U prvoj studiji slučaja, 10 tročlanih studentskih timova konstruiralo je uređaje (uredska stolica, naprava za vježbanje, dječja kolica, dječji tricikl i invalidska kolica) u sklopu projektnog kolegija. Nakon što su timovi izradili 3D modele uređaja, proveden je eksperiment pregleda konstrukcije (jedan tip tranzicije). U eksperimentu su dva recenzenta (industrijski eksperti) i jedan konstruktor (student) pregledavali konstrukciju u 3D alatu (Onshape, Autodesk VRED) koristeći tradicionalno računalno sučelje (miš, tipkovnica, monitor) ili tehnologije virtualne stvarnosti (HTC Vive uređaji koje korisnici nose na glavi). Rezultati usporednih testova (npr. t-test) i veličine učinka (npr. Cohenov *D*) pokazali su da je uzastopna verbalna komunikacija između recenzenta bila značajno viša pri korištenju tehnologija virtualne stvarnosti u usporedbi s radom na računalu. Također, tranzicijski timovi koji su koristili tehnologije virtualne stvarnosti su značajno više radili kao cjelina (svi zajedno) od timova koji su koristili tradicionalno računalno sučelje. Međutim, tranzicijski timovi koji su koristili tehnologije virtualne stvarnosti identificirali su značajno manji broj grešaka od timova koji su koristili tradicionalno računalno sučelje. Osim toga, hijerarhijskom multinomnom logističkom regresijskom analizom pokazano je da model koji uzima u obzir nesigurnost i afekt agenata znatno bolje predviđa tranzicijske akcije nego model koji kao prediktor ima samo nesigurnost. Također je utvrđeno da nesigurnost, afekt i vrsta rada (svi zajedno, podtim) značajno bolje predviđaju tranzicijske akcije kada je okruženje kontrolirano (npr. predviđanje akcija izvršene tijekom tranzicija u kojima se koriste tehnologije virtualne stvarnosti).

U drugoj studiji slučaja, 14 tročlanih studentskih timova konstruiralo je dječja kolica, također u sklopu projektnog kolegija. Nakon što su izradili 3D model uređaja, proveden je eksperiment pregleda konstrukcije. Tijekom eksperimenta, dva recenzenta (industrijski eksperti) i dva konstruktora (studenti) su provela dva pregleda konstrukcije koristeći 3D alat (Onshape, Siemens NX) u jednom od dva okruženja: tradicionalno računalno sučelje (miš, tipkovnica, monitor) i tehnologije virtualne stvarnosti (HTC Vive uređaji koje korisnici nose na glavi). Prvi pregled je bio vezan uz tranzicijski cilj verifikacije kako bi se provjerilo zadovoljava li rješenje postavljeni konstrukcijski problem. Drugi pregled je bio vezan uz tranzicijski cilj validacije kako bi se provjerilo rješenje s obzirom na vrijednosti koje imaju korisnici kolica (npr. roditelji, djeca). Rezultati kombinirane analize varijanci (engl. *mixed analysis of variance*) nisu pokazali značajne razlike u broju identificiranih grešaka, ali jesu da kontekst identificiranih grešaka ovisi o okruženju (tradicionalno računalno sučelje ili tehnologije virtualne stvarnosti). Točnije, rad pomoću tehnologija virtualne stvarnosti rezultirao je u značajno većem broju identificiranih grešaka koje se odnose na konstrukcijski problem i na one koje se odnose na odnos konstrukcije i vanjskih elemenata (npr. korisnik, vozna podloga). Osim toga, pregled u virtualnoj stvarnosti rezultirao je značajno većom efektivnošću validacijskog dijela tranzicije. Naposljetku, timovi koji su proveli tranziciju korištenjem tehnologija virtualne stvarnosti imali su tijekom kasnijih konstrukcijskih aktivnosti veći udio akcija vezanih uz kreiranje novih elemenata na 3D modelu od timova koji su proveli tranziciju korištenjem tradicionalnog računalnog sučelja. Ovi rezultati poslužili su kao osnova za empirijsku validaciju teorijskih modela i eksperimentalnog istraživačkog okvira.

Validacija

Validacija doprinosa provedena je koristeći metodu Validacijskog kvadrata (engl. *Validation Square*) u kojoj se empirijskim rezultatima i teorijskom raspravom vrednuje unutarnja konzistentnost i učinak doprinosa. Također, s obzirom da se validacija modela u znanosti o konstruiranju izvodi postepeno od laboratorijskih do stvarnih okruženja, doprinosi su u okviru istraživanja testirani u laboratoriju pod kontroliranim uvjetima.

Teorijskom raspravom za svaki element i njihovu integraciju potvrđena je unutarnja konzistentnost modela timskih tranzicijskih procesa. Učinak modela ispitan je u okviru prve studije slučaja gdje je utvrđeno da nesigurnost i afekt agenata zadovoljavajuće predviđaju tranzicijske akcije bez obzira na okruženje, a nesigurnost, afekt i vrsta rada (svi zajedno ili u podtimu) u kontroliranom okruženju. Ovi rezultati podržavaju uključivanje različitih perspektiva u model i tako empirijski potvrđuju glavne relacije u modelu timskih tranzicijskih procesa.

Model timskih tranzicija je također validiran teorijskom raspravom za svaki element i njihovu integraciju, te empirijskim studijama za testiranje specifičnih relacija. Eksperimentalne studije slučaja ukazuju da okruženje (tradicionalno računalno sučelje ili tehnologije virtualne stvarnosti) i cilj tranzicije (validacija ili verifikacija) utječu na medijatore i ishode. Preciznije, tehnologije virtualne stvarnosti utjecale su na medijatore povećanjem broja verbalnih sekvenci između recenzenata, povećanjem razine afekta i povećanjem broja akcija koje su proveli svi članovi (suprotno od provođenja aktivnosti u podtimu). Nadalje, utjecaj tehnologija virtualne stvarnosti na ishode tranzicije bio je moderiran ciljem te aktivnosti. Dok je u verifikacijskoj tranzicijskoj sesiji rad s tehnologijama virtualne stvarnosti rezultirao manjim ili podjednakim brojem identificiranih grešaka, u validacijskoj tranzicijskoj sesiji je broj grešaka vezanih uz cilj bio veći pri korištenju tehnologije virtualne stvarnosti. Korištenje tehnologija virtualne stvarnosti je također rezultiralo identifikacijom većeg broja specifičnih vrsta grešaka. Točnije, tranzicije pomoću tehnologija virtualne stvarnosti rezultirale su većim brojem grešaka koje se odnose na interakciju između konstrukcije i vanjskih elemenata (npr. korisnik, vozna podloga) te grešaka koje se odnose na konstrukcijski problem. S obzirom da rezultati podržavaju relacije između faktora predviđene modelom te da faktori odgovaraju modelima u literaturi, model timskih tranzicija je validiran.

Eksperimentalni istraživački okvir validiran je usporedbom različitih pristupa planiranju eksperimenata. Točnije, elementi pristupa planiranju ostalih istraživača mapirani su na elemente razvijenog okvira specifičnog za tranzicije podržane tehnologijama virtualne stvarnosti. Time se zaključuje da istraživački okvir ima sve potrebne elemente. Dodatno, provedenim eksperimentalnim studijama pokazano je da razvijeni okvir može rezultirati etički ispravnim istraživanjem koje ima zadovoljavajuću pouzdanost, ponovljivost i valjanost. Zadovoljavanje etičkih principa potvrđeno je prilagodbom eksperimenta smjernicama za korištenje tehnologija virtualne stvarnosti i odobravanjem istraživanja od strane etičkog povjerenstva. Pouzdanost eksperimenta je osigurana korištenjem već provjerenih mjera i njihovom definicijom te izračunom podudaranja dva ocjenjivača za različite mjere korištene u analizi: tranzicijske akcije, nesigurnost, afekt, tip rada, kontekst grešaka, raspravljani elementi i povezanost raspravljanih elemenata s ciljem tranzicije. Kako su podudaranja znatna, pouzdanost eksperimenta je prihvaćena. Ponovljivost je osigurana detaljnim opisima eksperimentalnih studija slučaja. Konačno, valjanost eksperimenta je teorijski raspravljena i potvrđena za svaki od tri aspekta: valjanost mjera, unutarnja valjanost, i vanjska valjanost. S obzirom da elementi eksperimentalnog okvira odgovaraju ostalim pristupima planiranju eksperimenta te da okvir može rezultirati eksperimentima koji zadovoljavaju etičke uvjete i uvjete kvalitete istraživanja (pouzdanost, ponovljivost, valjanost), eksperimentalni istraživački okvir je validiran.

Verifikacija hipoteze

Provedeno istraživanje djelomično je potvrdilo istraživački hipotezu. Prvi dio hipoteze (tehnologije virtualne stvarnosti u timskom radu proširuju razumijevanje tranzicijskih procesa tijekom razvoja proizvoda) je potvrđen. Budući da timski rad ovisi o okruženju koje koriste tranzicijski timovi, istraživanje je pokazalo da tehnologije virtualne stvarnosti mogu proširiti razumijevanje društvenog aspekta tranzicijskih procesa. Nadalje, uvođenje tehnologije virtualne stvarnosti rezultiralo je rekonceptualizacijom informacijskog sadržaja. Za razliku od prethodnih studija koje promatraju informacijski sadržaj kao cjelinu neovisno o načinu interakcije, u ovom istraživanju pokazano je da različite vrste interakcije utječu na izvršenje tranzicija, sugerirajući da je potrebno razlikovati okruženja i artefakte. Treće, uvođenje tehnologija virtualne stvarnosti također je pomoglo u razumijevanju moderirajućeg utjecaja cilja tranzicija na odnos između okruženja i ishoda. Konačno, mogućnosti tehnologija virtualne stvarnosti da utječu na znakove koji služe za prostornu percepciju, na način komunikacije te na vrstu interakcije s okruženjem omogućuje istraživačima da korištenjem te tehnologije prošire razumijevanje tranzicija. Time je prvi dio hipoteze potvrđen.

Drugi dio hipoteze (tehnologije virtualne stvarnosti unaprjeđuju izvršavanje aktivnosti evaluacije/planiranja tijekom razvojnih projekata prema definiranim metrikama) je djelomično potvrđen. Naime, tehnologije virtualne stvarnosti unaprijedile su samo specifične aspekte aktivnosti evaluacije/planiranja (tranzicije). Prvo, tehnologije virtualne stvarnosti potaknule su da članovi tima izvršavaju akcije svi zajedno, a ne u podtimovima. Ova spoznaja sugerira da bi te tehnologije mogle poboljšati izvršenje tranzicija poticanjem kolektivnog donošenja odluka. Drugo, tehnologije virtualne stvarnosti su u usporedbi s tradicionalnim računalnim sučeljem unaprijedile identifikaciju grešaka povezanih s konstrukcijskim problemom, dok se identifikacija grešaka povezanih s rješenjem nije značajno razlikovala. Osim toga, tehnologije virtualne stvarnosti pospješile su identifikaciju grešaka koje razmatraju odnos između konstrukcije i okoline (npr. dijete, atmosferski uvjeti), ali i smanjile identifikaciju grešaka vezanih uz odnos unutar konstrukcije (npr. veličina provrta za vijak). Konačno, tehnologije virtualne stvarnosti unaprijedile su identifikaciju grešaka vezanih uz cilj validacijskih tranzicija, ali ne i verifikacijskih tranzicija. Stoga unaprjeđenje izvršavanja tranzicija pomoću tehnologija virtualne stvarnosti ovisi o cilju tranzicija i o korištenim metrikama. Dobiveni rezultati sugeriraju da tehnologije virtualne stvarnosti unaprjeđuju izvršenje tranzicija kada je njihov cilj usmjeren prema krajnjim korisnicima i razumijevanju konstrukcijskog problema – uobičajeni cilj u ranim fazama razvoja proizvoda. Time je drugi dio hipoteze djelomično potvrđen.

Ovo istraživanje rezultiralo je boljim razumijevanjem tranzicija iz različitih perspektiva i načina na koji nove tehnologije, poput virtualne stvarnosti, mogu podržati njihovo proučavanje i izvođenje.

Ključne riječi:

Razvoj proizvoda; konstrukcijski timovi; virtualna stvarnost; pregled konstrukcije; tranzicije; timski tranzicijski procesi; eksperimentalni okvir

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

CAD	-	Computer-aided design
FBS	-	Function-Behaviour-Structure
IC	-	Information Content
PD	-	Product development
VR	-	Virtual reality

Symbols

Δ	-	Difference between inputs and outputs
Aff.	-	Affect
CDS	-	Current design
FDS	-	Future design
I	-	Input
i	-	Number of stages in a design process
j	-	Number of activities in a design stage
n	-	Number of actions in an activity
O	-	Output
S	-	State
Unc.	-	Uncertainty
t	-	Time step
WM	-	Working Mode

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GLOSSARY

Activity	A goal-directed sequence of actions executed by one or more agents and organised by the agents' self-regulation toward achieving a conscious goal.
Affect	Agents' experience of emotional intensity.
Agent	Adaptive systems that interact with the information content and other agents in the same transition state.
Artefact	Information element in the transition state.
Current design	Current design problem and solution to that problem.
Design space	A set of all possible design solutions for the design problem.
Designer	An agent that does design.
Development activity	An activity in the design where agents orient toward goal accomplishment.
Effectiveness	The extent to which the design space outcomes are related to the transition goal.
Efficiency	The extent to which the design space changed per unit of resource.
Environment	A context that surrounds agents, thus describing the interaction with the artefacts.
Future design	Alternative solutions to the current design problem or alternative design problems.
Goal-related efficiency	The extent to which the design space changed according to the transition goal per unit of resource.
High-immersion environment	An environment that stimulates a higher number of sensory cues. Usually includes stimulating a stereoscopic vision and motion parallax.
Immersion	The extent to which technology simulates various sensory cues.

Information content	A subset of the characteristics related to the transition state (e.g., design space, agents) that is available to agents. Includes characteristics of the environment and artefacts.
Low-immersion environment	An environment that stimulates a lower number of sensory cues. Usual interaction is through mouse and keyboard while the content is rendered on a desktop monitor.
Macro-scale level	A granularity level that describes the design process as a sequence of design stages (e.g., conceptual design) linked by a common focus (e.g., to develop a product).
Meso-scale level	A granularity level that describes the design stage as a sequence of design activities.
Micro-scale level	A granularity level that describes the design activity as a sequence of actions that gradually change the current situation to the preferred one.
Other transition elements	Elements that describe the transition state at the micro-scale level but are not depicted by the design space, information content or agents
Taskwork	A team behaviour that represents what it is that agents are doing.
Team	Two or more agents who interact through specified roles as they work towards shared and valued goals.
Team behaviour	Describes what team members do – actions primarily focused on accomplishing objectives.
Teamwork	A team behaviour that describes how agents are doing taskwork with each other.
Transition	An activity in product development where agents evaluate the conducted work and plan future directions.
Transition action	Change in the value of transition state characteristics. These actions are executed by agents on a micro-scale level. See also the *Transition process.*
Transition goal	A desired result of transition activity. Although the result includes evaluation and planning, the goal also includes specific contextual aims (e.g., focus on manufacturability, user, etc.)

Transition process	Change in transition inputs to outputs on the micro-scale level. See also the *Transition action.*
Transition state	Characteristics of the transition activities (e.g., characteristics of the product being developed) that affect actions or that are affected by actions.
Uncertainty	Agents' awareness of the limitations of their current knowledge or understanding.
Virtual reality	An experience of virtual content through natural sensorimotor contingencies, thus providing an illusion of being present in another environment.
Virtual reality technology	A human-computer interface that seeks to perfect an all-inclusive sensory illusion of being present in another environment.

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1. INTRODUCTION

This chapter starts by describing the motivation for the research. Based on the motivation, research questions, aims, and a hypothesis are introduced. After that, a methodology that was followed throughout the research is explained, and expected scientific contribution is enlisted. The final section provides an overview of the thesis chapters.

Design reviews are one of the core design activities [1], where many important decisions are made [2, 3]. These activities are used to evaluate the developed designs and plan future actions [2, 4, 5], thus serving as control mechanisms in product development [2, 4, 5]. Design reviews are often executed by design team members discussing their work with other stakeholders (e.g., managers, users) in a synchronous (e.g., meeting) setting. Stakeholders provide their stance on the current design, thus helping designers broaden their perspective on the product. For example, a design review of a baby stroller might be executed by design team members and senior experts to identify and improve weak points in the proposed design. As another example, end users (e.g., new parents) might also be present during the design review, providing their opinion regarding the values they have towards a baby stroller. Hence, improving the execution of design reviews is critical for the design practice.

Design reviews are typically conducted with multiple people in one physical space and/or distributed physical spaces, using various design descriptions (e.g., documents, 3D models). Many researchers have suggested that influencing the way designers and stakeholders interact with the current design representation (e.g., 3D models) might affect these activities [6]. Similarly, influencing how review team members interact with each other might also affect design reviews [7, 8]. In this context, virtual reality (VR) technologies showed great potential to change the way design reviews are executed [9] as they seek to perfect the sensory illusion of being present in another environment [10, 11]. These technologies alter interaction [12] and navigation [13, 14] modes and affect sensory [15] and social [16] cues, thus affecting cognitive [17], affective [18], and social [19] aspects of design reviews. Given these effects, it is indisputable that VR technologies have been actively used in the industry to support design reviews [20].

Although having large potential, the effect of VR technologies on design reviews is still inconclusive. Its effect on understanding the design artefacts is unclear [21], with researchers reporting both positive [22–24] and negative [25, 26] relationships. Moreover, while subjective evaluations of team members suggest that using VR positively affects teamwork [27–29], objective measures of design review outcomes have provided contradictory evidence. In terms of design review duration, previous studies reported increased [26] and reduced [30] time. Similarly, the effect of VR on the number of identified issues was found to be positive [31, 32] and negative [33]. Furthermore, the effect of VR depends on various factors, such as VR technology functionalities [34], product complexity [23], and prior experience with the technology [21]. Hence, while VR technologies influence design reviews, their exact effect remains unclear.

The inconclusive effect of VR might be related to a limited understanding of design reviews. In the design field, these activities are mainly conceptualised on a micro-scale, describing them as a sequence of understanding, evaluation, and planning actions [2, 4, 5]. Through an intertwined sequence of these actions, a review team changes the state from the current one (before review) to the desired one (i.e., evaluated current and planned future work). This evolutionary facet thus considers actions as the main elements of design reviews at the micro-scale granularity level [4, 35–40]. However, the similar micro-scale description also represents other activities in design, such as reflection on action [41], after-action review [42], design review [2], design studio [43–45], design critique [43, 46], reflexivity [47], and feedback [3, 48]. Consolidating these activities into an overarching concept might help synthesise the literature and provide a better understanding of design reviews.

Management literature observes these kinds of activities through a concept called transition – an activity in which agents evaluate the conducted work and plan future directions [49, 50]. In contrast to the design literature that focuses on the micro-scale perspective (i.e., as a sequence of actions), the management literature is focused on a higher granularity level (i.e., the meso-scale perspective). Indeed, many researchers in management point to the lack of studies related to transition processes [49, 51] – a management term for actions. Therefore, introducing transitions as an overarching concept provides an opportunity to understand design reviews at different granularity levels, i.e., at the meso-scale level (transitions) and the micro-scale level (transition actions or transition processes).

Furthermore, while design researchers are mainly focused on the evolutionary facet (i.e., the sequence of actions), they usually neglect the team aspect of transitions. More specifically, the studies have mainly been related to individuals [52] and have limited implications for the practice that usually utilises teams [53, 54] as the core building blocks of PD organisations [55]. Although the focus has been changing in recent years [56], design researchers still view the team as a whole (i.e., assume that they all work together). However, social forces that arise from the team's working structure are another element that might play a role during transitions [57, 58]. These various facets are depicted in the management literature, as they often observe transitions from more than one facet (e.g., cognitive, affective, social) [59–61]. This multifaceted conceptualisation of transitions provides an opportunity to better understand these activities.

Transitions are constituent activities in PD that still need to be understood. This lack of understanding might be the reason for the unclear effect of VR technologies on transitions. Conceptualising transitions on various granularity levels and from multiple facets might provide a basis for studying various factors influencing this activity. This conceptualisation might shed more light on the complex relationship between VR technologies and transitions.

1.1. Research aims, questions and hypothesis

Given the relevance of transitions for PD [1, 49, 62], coupled with the lack of studies that investigate them [1, 3, 49, 51], this thesis first aims to better understand these activities. Prior studies revealed different factors that affect transitions, such as the PD field [63, 64], team composition [65–69], the current state of the product being developed [23, 33, 65], and the technology used for transitions [27, 28, 32]. However, these factors have not been captured in a coherent model of transitions. One reason might be that researchers focus primarily on explaining the activities without specifying relationships between factors relevant to their performance [70]. Another reason could be a high number of factors arising from the complexity of design problems [71], designers [72], and social interactions [73, 74]. Therefore, there is a need to develop a coherent model of transitions that would shed more light on the currently fragmented and contradictory findings related to these activities, including the effect of VR [21–33]. Consequently, the first research question (RQ) is as follows:

RQ1: *How to describe the multifaceted* context *of team transitions in PD?*

Given the many factors affecting transitions, previous studies often had many assumptions that restricted their implications to PD practice. For instance, transition studies often utilised controlled design artefacts with artificially introduced issues (e.g., an intentional collision between two parts) [28, 32, 65, 75]. As transitions usually include team members that created a design artefact, i.e., designers, and members that evaluate the artefact (e.g., reviewers, managers) [66, 68, 76], transition processes such as discussion, argumentation, and negotiation might be significantly altered with the controlled design artefacts. Another assumption relates to studying individual transitions – a common setup when analysing the effect of VR in this context [21, 22, 26]. While the findings from these studies might help control and isolate the effect of the team, they also restrict any generalisation to the context of team transitions. Hence, researchers should consider their assumptions and how they might influence the corresponding findings. In addition, the use of VR technologies introduces new concerns, such as the experimental setup of the equipment and potential problems with using the technology (e.g., cybersickness). In order to consolidate the considerations that researchers need to take into account while studying VR-supported transitions, there is a need to provide an experimental framework that can enable researchers to systematically conduct experiments related to transitions and thus collectively build knowledge about these activities. The second RQ is:

RQ2: *How to plan empirical studies related to understanding VR-supported team transition processes in PD?*

Considering the importance of team members in transitions, the means of their interaction with the product being designed and agents might affect the execution of transitions [6–8]. As VR technologies can affect how team members interact with the environment (e.g., by stimulating spatial cues and affecting interaction means) and with each other (e.g., by affecting social cues), they could help design researchers augment their understanding of transition processes. More specifically, design researchers can use VR technologies to explore the effect of various individual and team aspects on transitions. This technology might thus augment the understanding of transition processes in PD. Therefore, the third research question is as follows:

RQ3: *How do VR technologies augment understanding of team transition processes in PD?*

The new way of interacting with the environment and between team members was the rationale for many researchers to study the effect of VR on transitions. However, despite much interest in recent years, the effect of VR on transitions remains unclear [21–33]. While various reasons might be behind these contradictory findings (e.g., ecological validity, confounding variables), the possible way forward could be to understand the effect that VR technologies have on the execution of transitions. While various metrics related to transition execution have been studied (e.g., number of identified issues, time to resolve them), they are mainly oriented towards the outcomes, neglecting the evolutionary facet. Moreover, metrics also usually neglect the goals of transitions [77, 78], thus providing a limited understanding of the context in which the transition occurred. Hence, the effect of VR on transition execution remains unclear. The fourth research question that drives the study is thus formulated as follows:

RQ4: *How do VR technologies affect the execution of team transitions throughout the PD process?*

By answering the research questions, the thesis aims to verify the following hypothesis:

Virtual reality technologies within teamwork augment understanding of the transition processes during product development and improve execution of evaluation/planning activities throughout development projects according to defined metrics.

1.2. Research methodology

The methodology used in the presented research is based on the Design Science Research framework [79–81]. This framework enables the execution of research that is relevant for both research and practice while at the same time being methodologically sound. The framework consists of three research activity cycles: relevance, development, and rigour (Figure 1.1).

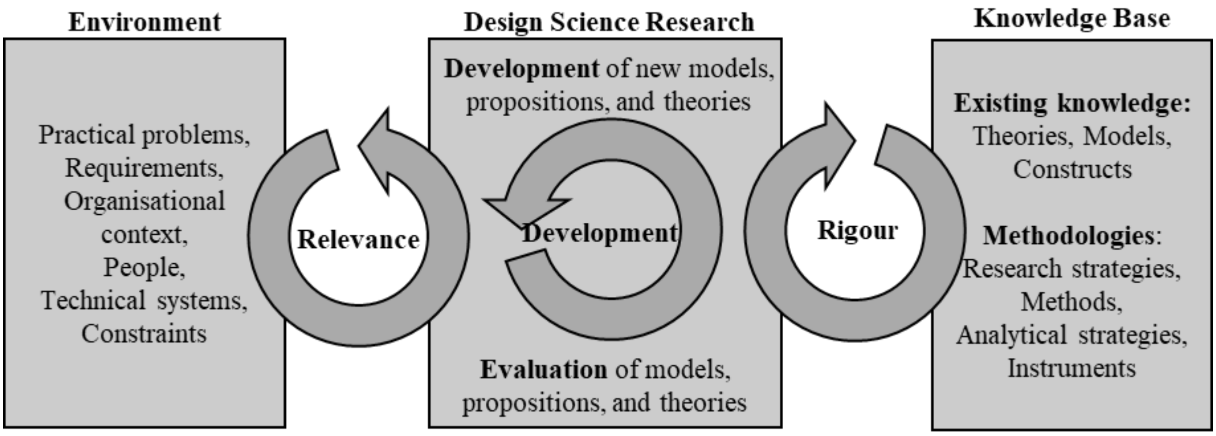

Figure 1.1 Design science research framework; based on [79–81]

In the relevance cycle, the study is positioned within the current research and practice environment. More specifically, considerations from the perspectives of organisational systems, teams and teamwork, and technical systems define the problem space. These considerations are associated with transitions across PD, design teams, and VR technologies. They are identified by reviewing scientific and expert literature within the research area and conducting preliminary experiments. The identified considerations served as input into the development cycle.

During the development cycle, theoretical models of team transitions and transition processes in PD and the experimental framework that enables the study of VR-supported teamwork for transition processes have been developed and evaluated. More precisely, the cycle started with the development of a theoretical model of team transition processes, which includes models of evaluation/planning activities, team behaviour models, and models of information content being transformed throughout the process. Based on this model and the prior findings identified within the relevance cycle, another theoretical model has been developed, i.e., the team transition model. The team transition model is at a higher granularity level and represents factors that affect and describe transitions. Furthermore, based on the preliminary experiments and literature review conducted within the relevance cycle, a new experimental framework that enables the study of VR-supported teamwork for transition processes in PD has been developed. Given the multifaceted context of transitions, the models and the framework have been evaluated through experiments within a case. These types of experiments enable in-depth analysis of the data collected from various sources [82] and usually have higher external validity than traditional ones [83]. In addition, experiments within a case often have high measurement and internal validity [84–86], which is necessary for the causative nature of the research hypothesis (see Section 1.1). Therefore, experimentation within a case study has been used as the main methodology for empirical studies.

The rigour cycle links the research and knowledge base to compare the results of the experimental studies with the existing knowledge and to ensure that validation findings are added to the knowledge base. A review of the scientific literature conducted within the relevance cycle enabled a comparison of the new findings with the existing knowledge base related to transitions across PD, design teams, and VR technologies. This cycle also included the identification of validation criteria for the proposed theoretical models and experimental framework. Systematic validation of scientific contributions has been conducted based on the identified criteria. Moreover, based on the research findings, the hypothesis was evaluated. Finally, the validation of the theoretical models and experimental framework resulted in extensions and advancements of the existing knowledge base related to transitions in PD.

Answering each research question followed the three cycles. More specifically, answering each research question started by providing an overview of the current work related to the question. Then, the development cycle for each research question was divided into the development and evaluation parts. Finally, the rigour cycle ensured valid answers to research questions. The mapping of the research questions to these cycles is shown in Table 1.1.

Table 1.1 Mapping research questions to the methodological cycles

Research questions (RQs)	Relevance cycle	Development cycle		Rigour cycle
		Develop	Evaluate	
RQ1: How to describe the multifaceted context of team transitions in PD?	§1, §2	§3	§5, §6	§7.1, §7.2
RQ2: How to plan empirical studies related to understanding VR-supported team transition processes in PD?	§1, §2.4, §2.4.3	§4	§5, §6	§7.3
RQ3: How do VR technologies augment understanding of team transition processes?	§1, §2.5.1	§3, §4	§5, §6	§7.4.1
RQ4: How do VR technologies affect the execution of team transitions throughout the PD process?	§2.5.2, §2.5.3	§3, §4	§5, §6	§7.4.2

1.3. Scientific contribution

The expected scientific contribution of this thesis is manifested through:

1) **Theoretical contribution at the micro-scale:** A theoretical model of team transition processes within product development, which includes models of evaluation/planning activities, team behaviour models, and models of information content being transformed throughout the process.

2) **Theoretical contribution at the meso-scale:** A theoretical model of team transitions within product development.

3) **Methodological contribution:** An experimental framework that enables the study of the VR-supported team transition processes in product development.

4) **Content contribution:** Evaluation of the effect of VR on team transitions through design review cases.

1.4. Thesis structure

The thesis is divided into eight chapters, organised around the methodological cycles and research questions (see Table 1.1).

Chapter 1 corresponds to the relevance cycle and describes the motivation for the research, research questions, aims, hypothesis, methodology, and expected scientific contribution.

Chapter 2 also corresponds to the relevance cycle, summarising the background work for each research question. The main design paradigms (rational problem-solving and reflective practice) are explained and compared. From the two paradigms, transitions emerge as constituent elements of the design. Transitions were then explained on a micro-scale level, from different facets, and on a meso-scale level. Finally, an overview of the effect that VR has on transitions has been provided.

Chapters 3-6 correspond to the development cycle of the utilised methodology. They represent the development and evaluation of the main scientific contributions. Chapter 3 develops two theoretical models of transitions. The first model is developed from the micro-scale and multifaceted descriptions of transitions. The second model is developed by mapping the micro-scale and multifaceted aspects to a meso-scale level.

Chapter 4 presents an experimental framework that enables the study of VR-supported teamwork for transition processes in PD. The framework is built upon experimental, theoretical, methodological, and implementational considerations. The experimental considerations include research ethics, resources, reliability and replicability, and validity. Theoretical considerations are divided into research questions and transition factors. Methodological considerations include factor measurements, sample definition, experimental setting, and data analysis. Implementational considerations consist of the experimental setup and experimental procedure for the VR-supported transitions. Finally, pilot studies are suggested to fine-tune all aspects of planning team transition experiments.

Chapters 5 and 6 present two design review (one type of transition) case studies. These studies provide empirical evidence for validating the theoretical models, the experimental framework, and the research hypothesis. As part of the case, design review experiments with transition teams (10 in the first and 14 in the second case) working in collaborative computer-aided design (CAD) or VR environments have been conducted. Design reviews were executed by industry professionals acting as reviewers and students that created the design under transition.

Chapter 7 corresponds to the rigour cycle and includes validation of the theoretical models and the experimental framework and verification of the research hypothesis. The models and the framework have been validated by following the Validation square [87] method, i.e., by evaluating their structural and performance validity. The hypothesis has been verified by discussing and comparing the empirical findings with the current knowledge identified in the background work. This chapter also discusses the theoretical and practical implications of the thesis. Finally, the limitations of the research are also acknowledged.

Chapter 8 concludes the thesis.

2. RESEARCH BACKGROUND

The second chapter summarises the background work for the research conducted. The main design paradigms (rational problem-solving and reflective practice) were first explained and compared. From the two paradigms, transitions emerge as constituent elements of the design. Transitions have first been introduced and described on the micro-scale. Next, transitions have also been explained from the three facets that augment the two design paradigms: evolutionary, agent-oriented, and social. The evolutionary facet emerges from the focus of design scholars on observing activities from the perspective of the product being designed, suggesting that designers develop problems and solutions in parallel. Agent-oriented and social facets emerge from the body of literature that examines the actors that develop problems and solutions. In this context, the agent-oriented facet is focused mainly on the individuals that conduct a design activity, while the social facet is focused on the team perspective (e.g., interaction among individuals). Thirdly, a meso-scale description of transitions has also been given. Next, as VR technology might change the way transitions are executed, an overview of its effect on transitions has been provided.

Product development comprises various processes, such as design, marketing, and operations [88]. While these processes are necessary for developing a successful product, design is the foundation around which product development exists. Design shapes a product's form and function to provide a user experience and is considered a driver for innovation in many companies [89]. Over the years, various models of design processes have been proposed [90], describing specific situations in design. These models could be on various granularity levels [90], broadly categorised into macro-, meso-, and micro-scale levels [91, 92], as shown in Figure 2.1.

While various different terms exist for constituent elements at each level (see Table 2.1), this thesis incorporates the terminology proposed by McMahon [93]. The design process at the macro-scale level is a sequence of design stages (e.g., conceptual design) linked by a common focus (e.g., to develop a product). Design stages transfer outputs from a previous stage into inputs for a subsequent one through a sequence of steps. These steps are presented at the meso-scale level and are called activities – a goal-directed sequence of actions executed by one or more agents and organised by the agents' self-regulation towards achieving a conscious goal

[94]. Therefore, actions (e.g., evaluating a design feature) gradually transform a design process from the current state to the preferred one [41] and are a constituent element while observing design at the micro-scale level. More fine-grained levels have also emerged, in which actions might be observed as a sequence of steps. These steps are at the cognitive level and are being increasingly studied in an emerging discipline called design neurocognition[1]. However, as the focus of this thesis is on the micro and meso scales, the lower granularity levels are not included in the research background.

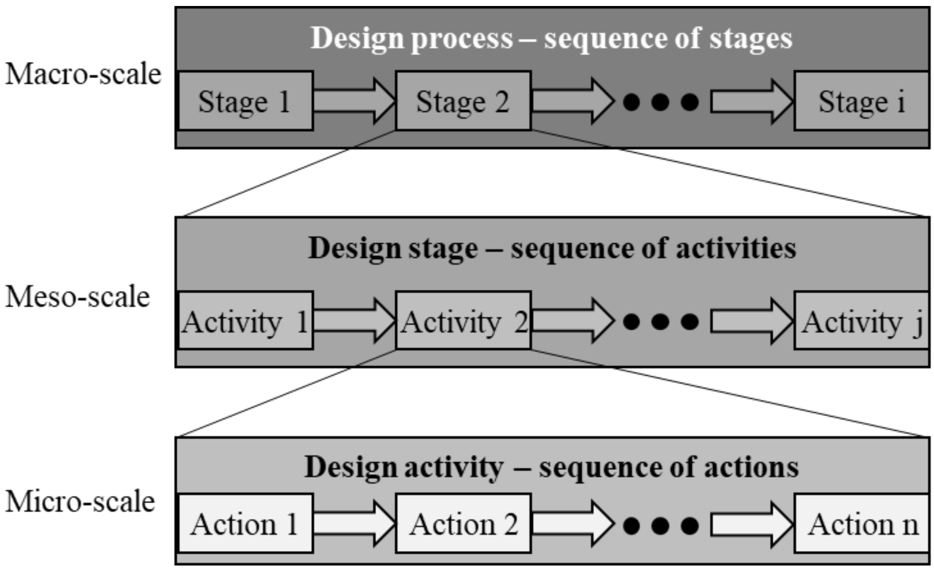

Figure 2.1 Design process at three granularity levels, based on [93] and [91]

While describing the design process, the design field is also often differentiated. Researchers distinguish fields such as engineering design, architectural design, industrial design, construction, etc. Design fields differ in various aspects, such as the type of product they create (e.g., building, consumer product), product aspects they are focused on (e.g., form, function), and working approach [63, 95–97]. Despite these differences, several researchers described the design process as independent of the field [4, 41, 98]. Therefore, the design might have common mechanisms that describe its core. Following this view, design is often described through one of the two paradigms [99–101]: rational problem-solving [102] and reflective practice [103, 104]. These paradigms are analogous to science philosophy [100], namely positivism (related to rational problem-solving) and constructivism (related to reflective practice). Both paradigms contributed significantly to the development of the design discipline [105, 106] and are used to introduce transitions in design.

[1] Interested readers can check papers by Gero and Milovanovic [507], Ohashi et al. [508], and Hay et al. [509] for an introduction to the design neurocognition.

Table 2.1 Terminology at each design granularity level

Level	Design			Management	**Thesis**	**Example**
	Cash et al. [91]	McMahon [93]	Hubka and Eder [107]	Marks et al. [50]		
Macro	Activity	Stage	Stage	*Not stated*	**Stage**	**Conceptual design**
Meso	Task	Activity	Basic operations	Phases	**Activity**	**Transition (e.g., design review)**
Micro	Action	Action	Elementary operations	Team process	**Action**	**Evaluation, Planning**

2.1. Introducing transitions in design

The most common paradigm in the engineering design field is rational problem-solving, introduced by Herbert Simon's seminal work *The Sciences of the Artificial* [102]. Simon suggested that design problems can be clear and stable, which makes them possible to decompose and hierarchically organise [108]. The approach to design is to discover ways of decomposing problems into subproblems, solving them, and combining them into a coherent solution. To define and solve problems, Simon suggested the adoption of a search process until a satisfying solution is found [102]. The search process usually goes through several stages, such as defining a problem, searching for and generating solutions, evaluating them, and selecting one as a final design [109, 110]. During the process, it is advisable to consider a set of solutions that designers can compare and reflect on [110].

This paradigm described various practice-based models of the design process that have been developed [108, 111], such as the one proposed by Hansen [112], Asimow [113], and Archer [114]. Moreover, it provided a basis for various design models that followed, such as those proposed by Hubka and Eder [107, 115], Suh [116, 117], Pahl and Beitz [118], and Ullman [119, 120] (see Wynn and Clarkson [90] for an overview of the models). These models usually propose that the design process starts by clarifying the design problem, which is then decomposed into subproblems. Based on the problem definition and decomposition, solution alternatives are proposed. Finally, alternatives are evaluated, and the best one is further developed. These models dominate the design fields in which the problems can be defined [110].

Tackling design problems in this paradigm is based on agents being rational information processing systems [99, 100], suggesting that the complexity of agents' behaviour arises from the environment in which they find themselves [102]. Moreover, this paradigm proposes that the agent's behaviour can be predicted from knowledge of design goals and the environment, with only minimal assumptions about the agent. This view enabled the development of design methods independent of the agent using them [108]. However, by ignoring the agents' judgement, intuition, experience, and social interaction [110, 121], this paradigm provided a limited understanding of the design. To address the limitations of rational problem-solving, researchers proposed a reflective practice paradigm (also called a situated design).

The reflective practice paradigm is described by Donald Schön in *The Reflective Practitioner* [103]. Schön suggested that design problems are unique and that designers determine how every problem should be tackled [99]. Later work showed that design problems have a particular structure [122] but that it is difficult to determine which approach to solving them provides better outcomes. This paradigm suggests that design problems cannot be fully defined before they are solved. Hence, they have to be developed together with the solution [123]. More specifically, although agents behave rationally, they frame the design state by taking a specific stance they think provides fruitful results regarding the design problem and solution [103]. Framing provides an opportunity to develop solutions within this state and is considered the core of *design thinking* [71]. Within this frame, agents make moves and evaluate them moment-by-moment, thus providing local control over the design process [60]. Therefore, this paradigm suggests that agents evaluate both the outputs and the actions that have resulted in these outputs [108].

The focus on agents and their actions rather than outputs emphasised that agents adapt and learn throughout the design process [110]. In contrast to the rational problem-solving paradigm, reflective practice suggests that agents' behaviour cannot be characterised without including their constructed worldview. This view is described by Gero and Kannengiesser [98] in their situated function-behaviour-structure (FBS) framework. The framework comprises three linked worlds: external, interpreted, and expected. The external world is composed of representations outside the agent. The interpreted world is created inside the agents in terms of sensory experiences and concepts. Finally, the expected world is also within the agent in terms of the effect that the imagined actions will produce. Therefore, agents' perception of the design state influences the process [108]. In contrast to rational problem-solving, this view dominates less technical disciplines [108, 124], such as industrial design and architecture. Moreover, it is also more suited for early phases, where the design problem co-evolves with the solution [108, 124].

While both paradigms can be used to describe the design process [99, 108], their accuracy depends on the design phase [108, 124], the design problem [99], and the design process granularity level [100]. The current consensus is that design is a combination of rational problem-solving and reflective practice [60, 100]. The reflective practice emphasises local control of the process that enables agents to learn [125] and develop problems and solutions in parallel [35]. In contrast, rational problem-solving emphasises global control of the process that enables the decomposition of the problem and the distribution of work.

Several scholars used both paradigms as the basis for their design descriptions. Rational problem-solving is usually utilised through the description that design includes devising a course of action to change the current state into a preferred one [102]. This description suggests the dichotomisation into activities that aim to devise courses of action and activities that aim to execute those actions. Contrarily, reflective practice is usually utilised to emphasise experimentation that enables agents to adapt and learn throughout the design process [110]. For instance, Reymen et al. [41] proposed a field-independent design model that consists of development and reflection activities. Development activities are oriented towards creating the product, while reflection ones aim at evaluating prior work and planning future ones, thus supporting Simon's dichotomisation. Furthermore, they also suggest that each activity advances through a sequence of actions [41]. Each action updates the current state of the design and the agents. Hence, in their model, agents also evolve in parallel to design, which aligns with Schön's reflective practice. Similarly, Steinert and Leifer [125] developed a Hunter-Gatherer model with *hunting* activities oriented towards finding a solution in a specific direction and *gathering* activities oriented to the discussion for the next *hunting* direction. During the hunt, agents try different ways to get to the solution by reflecting on their process, which is in line with the experimentation emphasised by the reflective practice paradigm. Marks et al. [50] also proposed two types of activities: development and transition[2]. In this framework, development activities are periods where agents are engaged directly towards goal accomplishment. In between the development activities, transitions are utilised to evaluate the work conducted and plan future directions. Moreover, they suggested that agents in development activities might engage in actions common to transitions [50], thus supporting the experimentation emphasised by the reflective practice paradigm.

[2] The actual names used by Marks et al. [50] are the action and transition phases. Their work is highly relevant in the management literature, where phases are used on the meso-scale (see Table 2.1). This terminology contrasts with the design literature, where phases are usually used to describe the process at the macro-scale. In addition, the term action in management literature is also used to describe a specific instance at the meso-scale level (i.e., action phase) rather than on the micro-scale, as is the case in the design literature. In order to avoid contradictions with the terminology described in Table 2.1, two changes to these names were made. Firstly, *phases* are renamed into *activities* to depict their meso-scale nature. Secondly, *action* is renamed into *development* as one type of activity to avoid confusion with micro-scale actions.

These models suggest that design at the meso-scale can be represented as a combination of development and transition activities (Figure 2.2). Development activities are oriented towards creating the design problem and solution, while transition ones are oriented towards evaluating prior work and planning the following development activity. Although both development and transition activities positively affect team performance [62], the latter are rarely studied in both the design [1, 3] and management [49, 51] literature. This lack of research regarding transitions needs to be addressed, given that transitions are one of the core design situations [1] where key decisions are made [2, 3]. The following sections provide an overview of transitions.

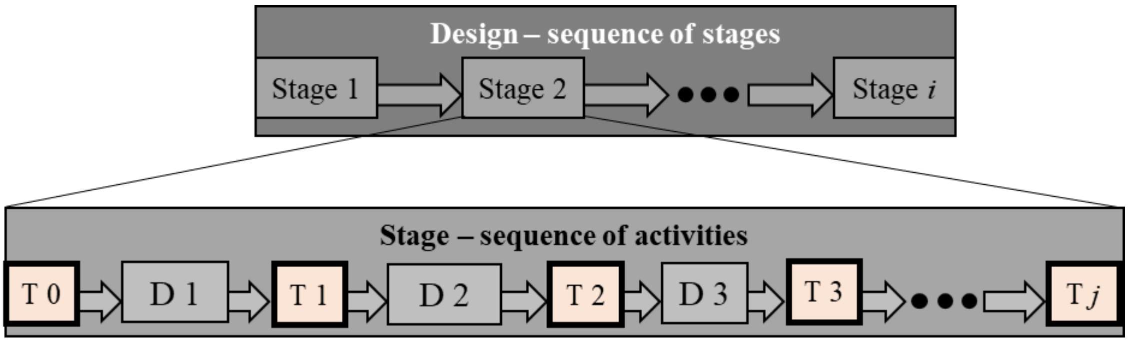

Figure 2.2 Design at meso-scale as a combination of development and transition activities; T – Transition, D – Development

2.2. Micro-scale description of transitions

Transitions in product development have been defined as activities where agents evaluate the created design and plan future actions [50]. This definition holds for many different types of transition activities, such as reflection on action [41], after-action review [42], design review [2], design studio [43–45], design critique [43, 46], reflexivity [47], and feedback [3, 48]. Transitions under these terms are studied in various design fields, such as industrial design [63, 126], engineering design [4], software design [127], aerospace design [2], architectural design [22, 128], construction [5], and design education [43–45]. Hence, transitions are an overarching concept that might help consolidate the literature and help in theory development regarding the design process – one of the design research areas lacking theory development [70, 129].

Given that transitions are activities by definition, they can be described as a sequence of actions [94]. The input to each action is the previous action's output. This input is transformed into output that is then used by the subsequent action as input (Figure 2.3 in the centre). To describe this transformation, researchers often incorporate the concept of state [4, 41]. The state comprises characteristics of the transition activities that might affect actions or that are affected by actions. In addition, the state also describes the current values for these characteristics (e.g., the current colour of the product being developed). Actions are therefore used to change these values from one state to another. Various actions have been identified as part of activities within the design process [35, 109, 130]. However, researchers often agree that the activities can be distinguished by the type of underlying actions [4, 50, 131]. Therefore, the next two subsections provide an overview of the literature related to the transition state and actions.

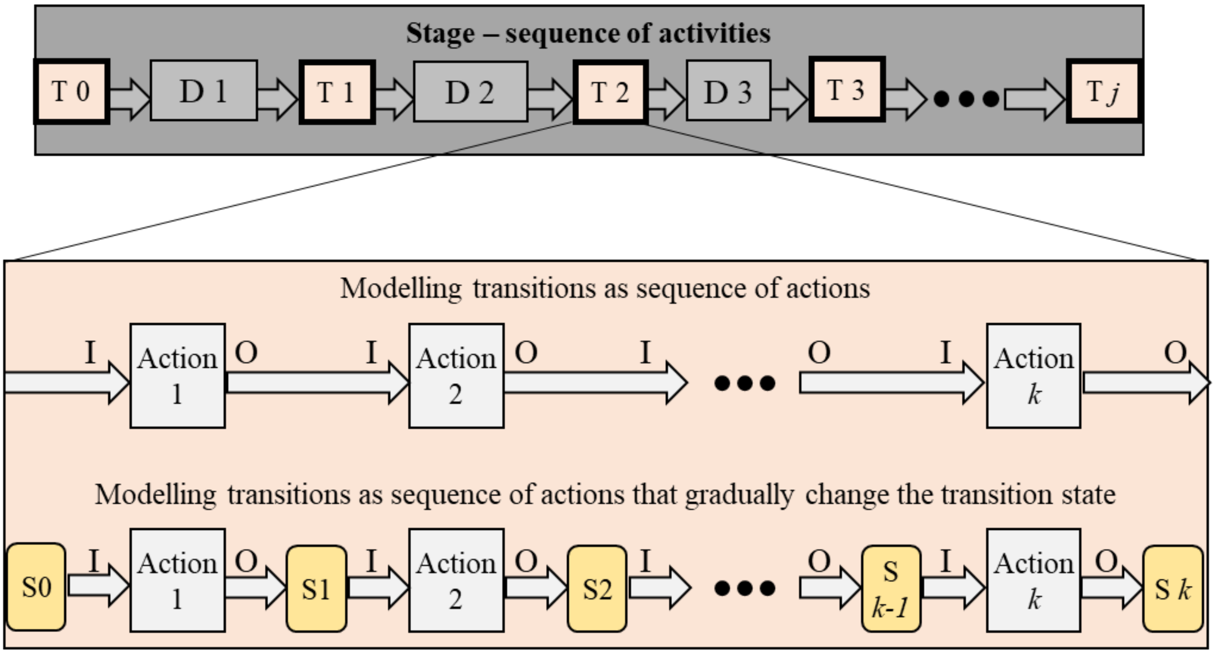

Figure 2.3 Transitions as a sequence of actions; I – input, O – Output, S – State, T – Transition, D – Development

2.2.1. Transition state[3]

Design researchers usually model a transition state by considering only the product being designed. In this context, Hubka and Eder [115] use an information state that changes throughout the design process. This information state is a set of values for all characteristics of a system at a certain time. They also suggested that, during design activities, only the state of a selected group of characteristics is reported. This selected group of characteristics is usually provided through the information content available to agents during transitions. For example, as all transitions have specific goals, agents usually have information content that describes those goals [132].

[3] Please note that transition states are different from state-transition models that are often used to describe the activity at the micro-scale [4, 41]. The term *transition* in these models is here referred to as actions or transition processes. Transition in this thesis is used exclusively to refer to activities.

Information content representing these characteristics is usually in the form of checklists based on standardised requirements [77] or requirements developed throughout product development [133]. This content might also include information about the current state of the product being designed. In this context, the team usually relies on descriptions of the problem and solution space [77, 133], such as a list of requirements, sketches, drawings, 3D models, physical prototypes, etc. Finally, given that transitions include evaluation and planning, they usually involve feedback on the identified issues and planned work [2, 5]. To ensure that the feedback is received by the design team, this aspect of transitions is supported by meeting minutes [77] or specific transition report templates [2]. In addition to describing the current state, information content also serves as a boundary object [134, 135] that aids in communication and the development of shared understanding among various product stakeholders [68].

Furthermore, Hubka and Eder's [115] description of state has been extended by introducing the concept of design space, described as a set of all possible states of the product being designed [4, 41]. Martinec et al. [4] described design space using the problem-solution framework [136], consisting of problem and solution entities that describe a product being designed. Gero and Jiang [95, 137] used elements from the function-behaviour-structure framework [138]. These elements can also be divided into problem-related (function and expected behaviour) and solution-related (structure and behaviour from structure).

The reflective practice paradigm suggests that agents are also an element in the transition state. More specifically, transition models usually differentiate between agents that worked on the design (i.e., internal agents) and agents that did not work on the design (i.e., external agents) [5, 68, 76]. Internal agents are considered to know the requirements and structure of the design before transition [126], which can help them with evaluation and planning [139]. In contrast, external agents might give alternative views on the design but might take more time to understand the current state of the product being designed [33]. Therefore, to utilise the advantages of both types, transitions are usually executed with a combination of internal and external agents [5, 127].

Several researchers described the transition state by focusing on both the product being designed and the agents. Reymen et al. [41] differentiate three elements in the transition state: the product being designed, the design process, and the design context. The first element describes a set of values for all characteristics that describe the product being designed, such as dimensions and colour. The second element describes a set of values for all characteristics that describe the design process, such as characteristics of a design team and its members (e.g., knowledge, skills, attitude, experience) and design aids (e.g., methods, computer support). They suggested that the first two elements can be described with the concept of design space – a set of all possible states of the product being designed and of the design process [41]. This definition of design space is thus different from Gero and Jiang's [95, 137] and Martinec et al.'s [4] definitions, as it also includes the design process. Another difference is that Reymen et al.'s [41] definition of design space does not include all aspects of the problem space (e.g., regulative constraints). These aspects are depicted in the third element, which describes a set of factors that influence the product being designed and its design process, such as external constraints (e.g., dimensions of production machines and environmental laws).

Furthermore, Visser [140] described the transition state with three elements: the design process, the designer, and the artefact. The design process is described by the way designers plan to organise their work (e.g., individually or in a team, design duration), the tools they use (e.g., design methods, representation tools), and how they include users (e.g., integration of user data into the design). The designers are described by their design expertise (e.g., level of expertise, contextual experience), task fit (e.g., how routine the task is for the designer), idiosyncrasy (e.g., their way of working and abilities), and personality. Finally, the artefact is described through its type (e.g., software code, physical artefact), maturity (e.g., the extent to which components of the artefact may be subject to change, similarity with the final product), and social embeddedness (i.e., the extent that the design problem requires the inclusion of the social environment).

Various descriptions of the transition state have been proposed, with the main distinction between the product being designed, the agents, and the factors that influence them. The next subsection provides an overview of how these states are used and changed by transition actions.

2.2.2. Transition actions

Transition actions were usually observed in terms of changing the state of the agents and the state of the product being designed. Changing the state of the agents is usually depicted by actions related to understanding the current design. For example, Huet et al. [2] proposed s*haring information about the design* action, described as gathering information relevant to completing the task, identifying means to achieve the design (e.g., past designs, methodologies, tools), and exploring the design space without committing to solutions. Liu et al. [5] proposed an *understanding* action that consists of understanding the design intent, asking questions by reviewers, clarifying the design, and describing the design intent. More generally, Martinec et al. [4] described an *analysis* action that aims to increase understanding of the design.

Changing the state of the product being designed includes two actions: one related to changing the state by evaluating the current product, and another related to changing the state by editing the current product. Huet et al. [2] suggested that changing the state by evaluating includes assessing the quality of the design solution (i.e., evaluating), choosing the best alternative (i.e., decision-making), and selecting the feasible alternative (i.e., selecting). More generally, Martinec et al. [4] suggested an evaluation action, described as the assessment of the appropriacy of a problem or solution within the explored design space. Furthermore, Liu et al. [5] proposed a cycle of actions that relate to the evaluation, consisting of describing requirements/concerns and describing and evaluating the existing solution.

Changing the state by editing the current product is described by Martinec et al. [4] as the appearance of a new problem or solution in the explored design space. Similarly, Liu et al. [5] suggested that this change in the current products happens through a cycle of actions that serve to develop solutions by agents' proposing, analysing, and comparing alternatives. Finally, Huet et al. [2] suggested that editing the current product happens only through managing the changes, such as prioritising goals, resolving conflicting interests, decomposing the work, and scheduling.

While definitions of actions slightly differed among the reviewed classifications, a consensus is that three actions describe the transitions [2, 5]: understanding, evaluation, and planning. Although a more fine-grained distinction of actions exists [127, 141], design researchers have usually agreed that these three actions can be used to describe transitions [4, 109]. The actions differ by their focus on the current design (i.e., understanding and evaluation) and the future design (i.e., planning). Moreover, understanding action describes changing the state of the agent, while evaluation and planning focus on the product being designed. This focus on both the product and the agents aligns with the multifaceted nature of design [59, 110, 142]. Therefore, multifacetedness is also present in transitions, which are reviewed in the following section.

2.3. Multifaceted nature of transitions

As design can be observed from various aspects, the two design paradigms [57, 110] were often augmented with the three facets: evolutionary, agent, and social. The first two facets could be identified from the micro-scale description (see previous section), as transitions are viewed as a sequence of actions that change the product being designed and the agent. Therefore, evolutionary [4, 35–38, 40, 136] and agent [143–148] facets are relevant for transitions.

The social facet is mainly shaped by Bucciarelli's work described in *Designing Engineers* [149]. More specifically, Bucciarelli [57, 149] suggested that design is a social construct between designers, i.e., a product being designed exists only in a collective sense. This notion contradicts the current state of design research that is mainly based on studying individuals [52]. Prior findings thus have limited value for a design practice that mainly utilises teams [53, 54] – two or more agents who interact through specified roles as they work towards shared and valued goals [150, 151]. Working in teams does not mean that agents always work together but rather that there is an alternation between individual and teamwork [152]. Nevertheless, specific design activities are often conducted in a synchronous team setting (e.g., during a meeting). Transitions are one such activity, as they often include designers meeting various stakeholders (e.g., users and managers) to negotiate the design [66, 68, 153] and make many important decisions [2, 3]. Therefore, social aspects also play a role during transitions [57, 58, 154].

Given the importance of the three facets in the transition context, each facet is explored further in the following subsections. As these facets have rarely been investigated in the context of transitions, the findings from related activities can provide the background for studying transitions as multifaceted. In the design discipline, the development activities received much more attention. Although these activities differ from transitions as they have different purposes, both of them can be described with the same transition state and actions [4, 41]. Therefore, findings from general design activities can be utilised to describe the multifaceted nature of transitions.

2.3.1. Evolutionary facet of transitions

The evolutionary facet is one of the most influential descriptions of design activities [37]. This facet proposes that designers develop problems and solutions in parallel [136] until a satisfactory product is created [102]. On the one hand, co-evolution is from the rational problem-solving paradigm seen as an iterative process in which designers focus on the current problem space and propose solutions, followed by evaluating that solution (e.g., *this solution did not work, let's refine either the problem or the solution*) [40]. On the other hand, co-evolution from the reflective practice paradigm involves reflection on one's action (e.g., *this approach was not fruitful, I should try another approach*) rather than the output of these actions [40]. That way, actions influence the designers and, consequently, the execution of subsequent actions [155].

Following the evolutionary view, transitions are moment-by-moment activities during which the final output evolves [5]. For example, agents can execute transitions by following a provided checklist. Checklist items might be addressed through a sequence of the abovementioned transition actions [2, 5], suggesting the evolving nature of the final transition state. More specifically, teams usually start addressing a checklist item with an understanding of design intent, followed by evaluating whether the solution meets the problem [5]. Optionally, the transition team might work on proposing new solutions or even problem-solution pairs for issues they identify [156]. Although transition models usually do not capture this co-evolving nature [2, 5], experimental findings suggest that design problems are also considered during these transition activities [131, 157]. Hence, transition output is built moment-by-moment through actions that co-evolve the design problem and solution.

The evolution of the design problem and solution in transitions depends on various aspects, such as the design phase [131, 158], the design field [63, 159, 160], and the transition team [156]. In terms of the design phase, Reymen et al. [158] suggested that the early phases are characterised by the co-evolution of problems and solutions, while the later ones are solution-oriented. This suggestion has been partially confirmed by Martinec et al. [131], who found that the amount of problem-space items decreased in later activities. Furthermore, various authors suggest that the design field might affect co-evolution. Yilmaz and Daly [63] found that transitions in mechanical design were oriented towards convergent feedback (i.e., solution-focused), while industrial design transitions towards both divergent and convergent feedback. This difference might be due to the kind of tasks, as they are often more open-ended in industrial than mechanical design; the focus of the latter ones is on practicality and performance [110, 160, 161]. Although the evolutionary facet provides insights into the evolving nature of transitions, this aspect largely depends on the transition team [156], as their background determines what constitutes a problem [110]. Therefore, an agent-based facet might provide additional insights into the multifaceted nature of transitions.

2.3.2. Agent-based facet of transitions

As agents in the observed transitions are humans, these activities come with the characteristics and biases of human minds [162], such as those described with the dual-process theory of human reasoning [162, 163]. The first process (often referred to as System 1 processing) is characterised by rapid and unconscious processing, usually connected to intuition and association, whereas the second process (often referred to as System 2) is described as reflective, deliberate, slow, and conscious processing. These two systems resemble the main elements in the Concept-Knowledge theory [164–166], suggesting that design is a cognitive process. Moreover, Kannengieser and Gero [72] adapted the dual-process theory to design thinking, suggesting that searching for ideas is usually a System 1 process, while reflection and assessment are usually a System 2 process. As transitions involve a search for ideas and assessment (see an overview of transition actions in Subsection 2.2.2), they utilise both types of human reasoning. Moreover, several researchers have provided empirical evidence that supports the dual process theory [167, 168], suggesting that studying design as a cognitive process provides insights into the design work.

The design cognition view suggests that transitions are driven by agents' cognitive actions [169]. For example, researchers have found that agents' preferred way of solving problems (i.e., cognitive style) was linked to design performance in individuals [170] and to verbal communication in teams [171]. This view supports both design paradigms, suggesting that design cognition is an adaptive combination of structured (related to rational problem-solving) and opportunistic (related to reflective practice) approaches [60, 100].

Furthermore, following the reflective practice paradigm, design cognition also includes continuous monitoring and control of cognition, known as metacognition [172]. Studying metacognition in design has been mainly influenced by the notion that agents tolerate, engage with, and resolve uncertainty [173]. Uncertainty has been described as agents' awareness of the limitations of their current knowledge or understanding [143, 146]. As such, the perception of certainty/uncertainty drives monitoring and control processes in thinking and reasoning [172]. Studying uncertainty provided insights into various design aspects, such as partially explaining disciplinary differences [174], analogies [146], mental simulations [146], and the co-evolution of problems and solutions [175]. Therefore, uncertainty might explain much of the work that is happening during transitions.

Despite explaining its various aspects, the cognition approach failed to comprehensively explain the design process. Most notably, Paletz et al. [144] failed to predict the success of design teams with uncertainty. The design teams' success was significantly predicted only when they combined uncertainty and micro-conflict [144]. Conflict often includes cognitive and affective components [176], suggesting that cognition might be augmented with affect. Affect plays an important role during transitions [177–179], as agents often have to consider emotional responses that designs provoke [97, 126, 180] and as affective reactions of agents influence how teams work [181–183]. In addition, emotional engagement was found to be related to reframing in design [148] – an important notion in the reflective practice paradigm. These suggestions, coupled with the well-documented impact of affect on cognition [184–186], suggest that design cognition might perform better when combined with affect.

Affect might be even more important in teams, as they were found to have a higher level of affect than individuals [187]. There is also a difference between individuals and teams in the source of affect fluctuations. For individuals, the virtual content was the main source of affect fluctuations. Contrarily, the main source of affect fluctuations for teams was communication [187]. Given this effect of communication on affect, it is not surprising that moment-by-moment fluctuations in affective tone between agents influence the design process [147]. As transitions are mainly executed in a team, these fluctuations in affect can influence the way transitions are executed. More specifically, Dong et al. [147] found that a positive affective tone assisted groups in generating alternatives, while a negative one inhibited the generation of alternatives. In addition, they also found that negative assessments co-occurred with the detailed technical analysis (e.g., *energising the entire printout is quite demanding*). In contrast, positive assessment co-occurred with the focus on the overall evaluation (e.g., *this is nice*). This difference between positive and negative assessment is consistent with the suggestion that positive affect promotes attention to global information and negative to local information [188]. Finally, Jung et al. [189] found that teams with a balanced interaction in terms of positive and negative affect outperformed teams with an unbalanced interaction. Altogether, these findings suggest that affect might play a significant role in team transitions.

2.3.3. Social facet of transitions

The social facet proposes that each agent has their own view on the design, depending on knowledge, skills, experience, roles, etc. To complement different viewpoints, agents interact with each other. Gero and Kannengiesser [190] suggested that this interaction occurs with agents having mental models of each other. Therefore, each agent has been described through several mental models, one of itself and one for each agent that it has interacted with. Each mental model has been described with the FBS [98] description of the design, thus being focused on the design-related aspects. These constructed FBS models differ for each agent [191] and depend on the common ground [73] between them. The common ground is knowledge, beliefs, and suppositions that agents know are mutual between them [73, 74]. It consists of two parts: fixed (pre-existing common ground based on, e.g., professional background) and built-up through interactions between team members [73, 74]. Hence, common ground is built moment-by-moment, suggesting that agents in transition build common ground through interaction. This view can describe the differences between transitions conducted with different stakeholders, as users might have different mental models than representatives from a production department. Therefore, acknowledging the moment-by-moment build-up of the common ground is important for describing transitions.

Through interaction, agents influence each other's thoughts and rationales [45, 191–194]. This interaction has often been modelled as one-to-one, where each pair of agents has an interaction tunnel [190]. The number of interaction tunnels in this model increases exponentially as the number of agents increases, thus providing a limitation with larger team sizes. As a response, a model with the external world [193] through which agents interact has been proposed. In this model, each agent has its own tunnel to the external world and can thus interact with any other agent. The number of interaction tunnels in this model increased linearly with the increase in the number of agents, making it more suitable for larger team sizes. However, this model does not describe a malleable formation of sub-teams and all-together work – an important aspect of transition activities [154] that affects the ways teams work [195].

The interplay of working in a sub-team or all-together during the transitions can be depicted by analysing communication between agents. More specifically, Clark and Brennan [74] suggested that communication is a joint action that involves two or more people, where listeners provide grounding cues to the speaker. These grounding cues are essential in communication as they enable the speaker to acknowledge the listener's understanding. Three categories of grounding cues are usually distinguished [74]: acknowledgements (e.g., uh-huh), relevant next turn (e.g., answering a question, repeating the content), and continued attention (e.g., eye gaze). Grounding cues from any category can be used to provide evidence of common ground.

In addition to grounding cues, several researchers point out the importance of boundary objects (e.g., sketches, drawings, 3D models, physical prototypes) for transitions [134, 135, 196]. These objects aid communication and the development of common ground among various product stakeholders [68] and have a mediating role in directing and maintaining shared attention [197]. By focusing on boundary objects between agents, Detienne and Visser [198] tried to capture individual work and teamwork. They suggested that two members work together if they focus on the same contextual element (e.g., working on a particular problem), even if the members perform different actions (e.g., one member performs evaluation and the other planning). Therefore, the use of boundary objects is important in transitions [67, 68, 199, 200] and can be used to develop a common ground.

Studying each of these facets resulted in various factors that might affect transitions. For example, the evolutionary facet suggests that the execution of transitions depends on the design problem and the current design phase. Next, the agent-based facet proposes that the characteristics of agents also affect the execution of transitions. Finally, the social facet provides insights into the effect of teams on transitions. While these factors are important for understanding transitions at the micro-scale, they are also relevant at the meso-scale. Moreover, understanding transitions at the meso-scale is important for integrating their activity-level performance into the broader design performance (see Figure 2.1). Therefore, the following section provides an overview of the transitions at the meso-scale. Given the almost exclusive use of teams during transitions, the focus will be on transitions executed by teams (team transitions).

2.4. Meso-scale description of team transitions[4]

The meso-scale description of transitions includes factors characterising the activity without considering what happens after each action. This description is usually depicted by the inputs, mediators, outputs, and outcomes (Figure 2.4). In micro-scale terms (Figure 2.3), inputs and outputs represent the first and last transition states, respectively. Inputs and outputs are thus a set of values for all the characteristics that describe the transition state (e.g., characteristics of the product being developed and agents). Furthermore, a sequence of actions at the micro-scale is represented by mediators, described as the means that transfer inputs into outputs. Hence, the outputs largely depend on the inputs[5]. To examine the performance of transition teams, the relative change between the transition state at the beginning and the end of the activity, depicted by the outcomes, is more important. Outcomes are related to the differences between outputs and inputs over the course of that activity. Therefore, Subsection 2.4.1 provides an overview of the transition team outcomes, while Subsection 2.4.2 reviews the relationships between inputs and outcomes. Given the multifaceted nature of the transitions, it is assumed that many relationships can be identified. An overview of factors that describe transitions has thus been provided in Subsection 2.4.3.

[4] In the rest of the thesis, both transitions and team transition terms will be used interchangeably. In cases when the focus is solely on transitions executed by individuals, the term individual transitions will be used. Readers interested in individual transitions might also benefit from this section; they should just neglect the team aspect (e.g., team composition, communication, collaboration).

[5] Colloquially known as *garbage in, garbage out*.

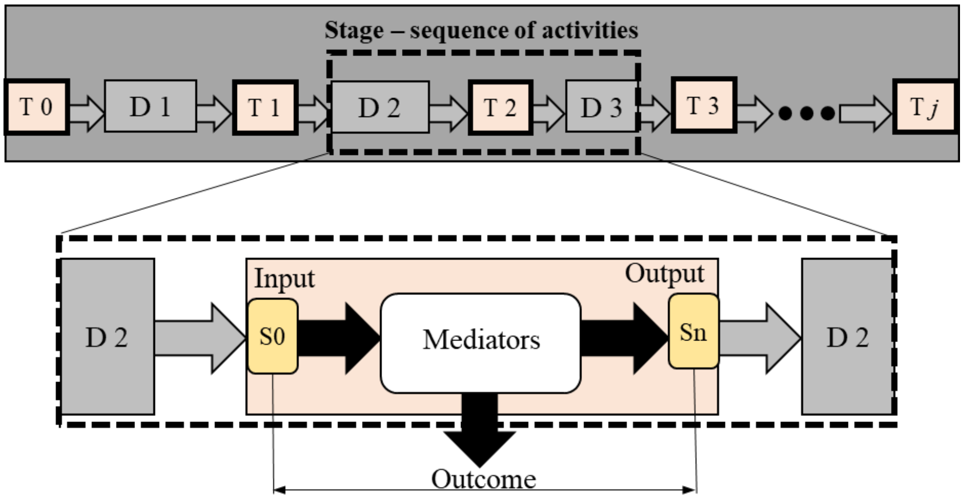

Figure 2.4 Transitions at a meso-scale

2.4.1. Transition team outcomes

The main indicators that can describe the outcomes of activities are efficiency and effectiveness [201]. Efficiency corresponds to the outcome that teams produce per unit of resource [201], while effectiveness is the extent to which the outcome meets the activity goal [201]. Combining efficiency and effectiveness results in a goal-related efficiency indicator, described as the goal-related outcome that teams produce per unit of resource. An overview of these three indicators is provided in Table 2.2.

Table 2.2 Indicators and metrics that can describe outcomes of transition teams

	Efficiency	Effectiveness	Goal-related efficiency
Definition	The outcome that teams produce per unit of resource.	The extent to which the outcomes are related to the transition goal.	The goal-related outcome that teams produce per unit of resource.
Example of metrics	Number of identified issues, Transition time	Perceived effectiveness, Assessed by judges (experience + controlled designs)	Number of correctly identified issues, Number of issues for a specific context

The outcomes can be described through the relative changes of any element in the transition state, such as the relative changes in the design space and agents. Regarding the design space outcomes, researchers explored all three indicators. While exploring the efficiency of transitions, researchers utilised metrics such as the number of identified issues [31, 202] or transition time [26, 30, 153, 203]. In addition to measuring the number of issues the team identifies, Linhares et al. [153] proposed a metric that captures each member's contribution by assessing the number of arguments (utterances that give strength to a position) they produced during transitions. Moreover, Sato and Yamada [202] suggested normalising the number of identified issues by the complexity of the design under transition (e.g., lines of code in software design). Furthermore, the transition time has been used as a metric to depict the time until the transition finishes [202] or until the transition team identifies specific issues (often made on purpose by the researchers) [204]. For example, in software design transitions, Sato and Yamada [202] suggested a metric that describes resources used (e.g., person-hours) normalised by the complexity of the design (e.g., lines of code). In contrast, Satter and Butler [204] measured the time it took to find and repair an error in the design created by the researchers. They used this measure to compare individual and team transitions.

In terms of the effectiveness indicator, several metrics were developed. Ostergaard et al. [7] measured effectiveness using a questionnaire, i.e., perceived effectiveness. Astaneh Asl and Dossick [205] measured team effectiveness by having judges assess a team's final decision on the design created by the researchers. Similarly, Hannah et al. [206] also created their own designs, but the effectiveness was measured by the percentage of correct answers to the questions posed by the researchers (e.g., does the design satisfy the requirements related to mass?). Furthermore, Liu et al. [33] also utilised the assessments from the judges, but for a different purpose. In their study, judges categorised verbal communication into actions and assigned a transition goal contribution value for each communication action. They assigned a value of zero for actions unrelated to the transition goal, a value of four for the decision-making action, etc. Their effectiveness was then the sum of all the multiples of actions and their duration, divided by the transition duration.

Furthermore, researchers estimated the goal-related efficiency of transition teams using the number of correctly identified issues [7, 133] and the number of issues in specific contexts [28, 75]. Wetmore et al. [133] and Ostergaard et al. [7] utilised a pool of judges in order to identify issues related to designs in transition. The issues that the judges identified were considered comprehensive and used to compare the transition outcomes. More specifically, issues identified in each transition were compared to the ones made by the judges, and only the correct issues were counted to measure the goal-related efficiency of transition teams. Furthermore, Wolfartsberger [28] and Rigutti et al. [75] used designs with intentionally placed issues to estimate the goal-related efficiency for particular contexts. Wolfartsberger [28] differed between three types of issues: ergonomics (e.g., accessibility of parts), CAD modelling (e.g., collisions or inaccuracies), and logic (e.g., wrong circuit logic). Contrarily, Rigutti et al. [75]

differentiated issues based on affordance (e.g., door handle on the same side as the hinges) and perceptual (e.g., misaligned handrail) violations. Finally, Tea et al. [32] calculated the difference between the number of correctly and incorrectly identified issues divided by the number of incorrectly identified issues in order to determine the outcomes. They also used intentionally placed issues to calculate the goal-related efficiency of transition teams.

Outcomes related to agents have rarely been explored on both an individual and team level [207]. Metrics related to the individual-level outcomes included assessments of engagement [208], satisfaction [207, 209], and learning [209–211]. These metrics are usually based on surveys, interviews, or observations [210]. For example, Newton et al. [208] used the adapted version of the job engagement survey [212] to assess physical, cognitive, and emotional engagement and test the effect of engagement on subsequent development activity. Next, satisfaction has been measured on a general level (e.g., satisfaction with working in a team) [211, 213] or in a specific context (e.g., satisfaction with using VR for transitions) [27, 29]. Moreover, learning is especially salient in educational transitions (e.g., design studio, design critique), as it is the main focus of these activities. This outcome has usually been assessed via questionnaires [211, 214].

Team-level outcomes are estimated by aggregating individual-level outcomes [210] or using dedicated metrics. Aggregation can be accomplished by the measures of central tendency (e.g., mean, median, mode) [215, 216] or the distance between team members (e.g., inter-quartile range) [209]. Besides aggregating individual-level outcomes, team-level outcomes include collective metrics. Astaneh Asl and Dossick [205] measured the time to reach an understanding of the disciplinary constraints and the time to build a shared understanding of the final design alternative. Another approach is by using concept maps [217–219], where members at the end of the transition would have to report transition outcomes using a concept map, representing a mental model of each team member. The concept maps across team members can be compared to assess the common ground of the transition team. Several researchers in the design discipline utilised this approach to assess shared understanding within a team [220–222].

In line with the multifaceted nature of transitions, researchers assessed various team outcomes. Outcomes related to the efficiency, effectiveness and goal-related efficiency of the design space are usually oriented towards the number of identified issues. These issues are identified throughout the transitions, thus supporting the evolutionary facet. Next, researchers also assessed outcomes from the agents' viewpoint (e.g., learning, satisfaction), thus supporting the agent-based facet. Finally, collective team-level outcomes (e.g., level of common ground) acknowledge the social facet, as they are developed through the interaction between agents. Given the multifaceted nature of transitions, various antecedents might affect the transition team's outcomes.

2.4.2. Antecedents to transition team outcomes[6]

Design researchers identified various influencing factors during transitions, such as team composition and structure [65–69], the product being designed, representations of the current transition state (artefacts) [67, 206, 223], the environment used to represent the artefacts [200, 224], and other contextual factors (e.g., design field, transition goal). The composition and structure of teams were found to influence collaborative design [225] and transitions [65–69]. In this context, various classifications of agents' roles within a team have been proposed. Ichida [76] divided the roles into internal (only agents that worked on the design) and external (none of the transition agents worked on the design). Next, Lauff et al. [68] suggested a distinction between design team agents (i.e., internal), other agents within a company (e.g., managers), and agents outside the company (e.g., users). Alabood et al. [69] provided a more fine-grained classification of roles in order to include educational transitions. These roles include [69]: students, end-users, field experts, and designers. Moreover, D'Astous et al. [66] differentiated three classifications of the roles: project (e.g., supervisor, developer), meeting (e.g., author, reviewer), and task (e.g., direct or indirect involvement). Researchers also found that the size of the team influences transitions [153], as larger teams might find it more challenging to reach a consensus.

Furthermore, researchers also identified the effects of the product being designed on the transitions. In this context, researchers identified that the transition might be affected by factors such as size [23, 33], complexity [23, 33], and quality (e.g., the number of issues in the design before the transition) [65] of the product being designed. A product being designed is usually represented with design artefacts. Several factors related to these artefacts were found to affect transitions, such as fidelity, quality of the artefact, and system extent [67, 206, 223]. Fidelity is one of the major characteristics observed in the prototyping literature [67, 200, 206, 226, 227], describing the extent of similarity between the artefact and the anticipated final product [228]. However, the effect of fidelity on review outcomes is still unclear, with researchers suggesting that it is moderated by the transition context, such as goal, design phase, and review strategy

[6] Given the various outcomes of transitions, coupled with the various elements that describe their state, a complete overview of identified relationships would not be feasible. Therefore, this subsection focuses on the most influential findings, while the next one provides an overview of the models that group the factors relevant to transitions.

[229]. Artefact quality (i.e., the precision and robustness of design artefacts) was also found to affect interaction with artefacts [223, 230, 231]. System extent is another artefact characteristic, described as the proportion of functions of the product being designed represented by the artefact [68, 224]. This characteristic has been found to affect the design process. However, the findings are inconclusive, as researchers suggested starting early with integrating functionalities [232] and delaying the integration until later phases [233]. Therefore, to reduce the effect of the product being designed on transitions, researchers often conduct studies with controlled artefacts [25, 26, 75, 234].

Another characteristic that has been investigated is the environment used to represent the artefacts [200, 224]. Using various environments (e.g., virtual reality, augmented reality) also has a significant effect on transition mediators [18, 128, 235, 236] and outcomes [27, 28, 32]. The environment is often distinguished between virtual and physical artefacts. The main rationale for this distinction is 2D and 3D dimensionality [68], the opportunity to control the environment [224], and the resources needed for creation [237]. In this context, foam models were perceived positively in terms of creativity, comfort, and aesthetics compared to CAD models [238]. Furthermore, researchers also investigated design understanding and found decreased transition performance when using 3D physical artefacts compared to 3D virtual artefacts [239]. However, another study failed to identify the effect of the environment on contextual design understanding [240]. These contradictory findings are somehow expected, given that researchers hypothesise a complex effect of artefacts on transitions [241].

Other contextual factors can also affect transitions. For example, researchers identified the effect of the design field on transition mediators, such as convergence/divergence of the feedback [63, 64], focus on problems or solutions [95], contribution to the transitions [242], etc. Next, Wetmore et al. [133] suggested that sharing transition documents in advance might increase the effectiveness of the transitions. Next, several researchers pointed out the importance of transition goals [2, 78, 132]. Oh et al. [43] suggested that the type of transitions (e.g., one-on-one, group, formal or informal) might affect their execution. In this context, Ostergaard et al. [7] found that group transitions were approximately twice as effective as individual ones.

This brief overview showed that a large number of factors influence transitions. While this bottom-up approach resulted in various factors influencing transition team outcomes, providing a comprehensive overview of the identified relationships would not be feasible. A comprehensive overview might be provided utilising a top-down approach, as various models that holistically group all the factors relevant to transitions have been developed.

2.4.3. Factors describing team transitions

Several models have comprehensively captured the factors describing team transitions at the meso-scale (Table 2.3). These models are common in the management discipline, where the focus is on understanding the implications of transitions on the meso-scale. In this context, Tannenbaum et al. [243] suggested that outcomes (i.e., team changes, team performance, and individual changes) are influenced by input, throughput, and organisational characteristics. Inputs include task (e.g., task organisation, type, and complexity), work structure (work assignment, team norms, communication structure), individual (e.g., knowledge, skills, abilities, motivation, personality), and team characteristics (e.g., power distribution, member homogeneity, resources, cohesiveness). These inputs affect outcomes directly and through team processes (e.g., coordination, communication, conflict resolution, decision-making, etc.). Moreover, organisational and situational characteristics (e.g., reward system, organisational climate, and competition) affect all other characteristics of teams (i.e., inputs, throughput, and outcomes). Finally, in this model, team outcomes affect team inputs through a feedback loop. The feedback loop is also emphasised by Ilgen et al. [244], who proposed an input-mediator-output-input model in order to emphasise the effect of outputs from one activity on inputs of the subsequent activity [245]. Grossman et al. [246] built on Ilgen et al.'s [244] model to describe the mediators that transfer inputs (i.e., organisation context, team characteristics, task context, and member characteristics) into outcomes (i.e., performance outcomes and team member affect). They classified mediators into behaviour, cognition, and affect. Affective mediators reflect relationships among team members, motivational characteristics of team members, and affective reactions (e.g., team moods and emotions). Cognitive mediators reflect what teams think. Finally, behavioural mediators indicate what team members do—actions primarily focused on accomplishing objectives. In the management literature, two aspects of team behaviour have been considered [50, 247]: taskwork and teamwork. While taskwork represents what agents are doing [50, 247], teamwork depicts how agents are doing it with each other [50, 247]. Finally, Grossman et al. [246] also suggested that both mediators and outcomes affect the inputs of subsequent activities.

Researchers later suggested that the relationship between inputs, mediators, and outcomes is not linear but that various interactions exist [244], such as the interaction between inputs and mediators, within mediators, etc. This interrelatedness was emphasised by various researchers, such as Salas et al. [248], Dinh et al. [249], and Mathieu et al. [250, 251]. More specifically, Salas et al. [248] and Dinh et al. [249] proposed nine factors that affect team outcomes: context, composition, culture, cooperation, conflict, coordination, cognition, coaching, and communication. The first three factors (i.e., context, composition, and culture) provide influencing conditions that describe the context for the other six factors (i.e., teamwork processes and emergent factors). To emphasise the complexity of the interrelatedness between the factors, they do not assume any specific relationship between them. Similarly, Mathieu et al. [250, 251] also embrace complexity among factors, dividing them into four categories: organisational structure and culture, team structural features, mediating mechanisms, and compositional features. In addition, they also suggested that specific factors might be a combination of the two categories (e.g., structural and mediating features).

Table 2.3 Overview of factors describing team activity

Discipline	Reference	Inputs	Mediators	Outcomes
Management	Tannenbaum et al. [243]	Task characteristics, work structure, individual characteristics, team characteristics, organisational and situational characteristics	Team processes, team interventions	Team changes, team performance, individual changes
	Grossman et al. [246]	Organisational context, team context, members	Affect, behaviour, cognition	Multiple criteria
	Salas et al. [248] and Dinh et al. [249]	Context, culture, composition	Cooperation, conflict, coordination, cognition, coaching, communication	Team effectiveness
	Mathieu et al. [250, 251]	Structural features, compositional features, organisational structure and culture	Mediating mechanisms	Team effectiveness, individual reactions, learning
		Structural and mediating features, compositional and mediating features		
Design	Takai and Esterman [209]	Task characteristics, work structure, individual characteristics, team characteristics, team formation, design problem	Intermediate evaluation, team collaboration, design process	Team performance
	Maier et al. [225]	Information, representation, individual, team, organisational	Design communication	-
	Kleinsmann et al. [252]	Actor level (e.g., language used, applicable experience), project level (e.g., efficiency of information processing, division of labour), company level (e.g., organisation of resources, allocation of tasks)	Shared understanding	-

In contrast to the management discipline, design researchers rarely capture the factors describing transitions in a coherent model. Most notably, Takai and Esterman [209] proposed a design team effectiveness model that is mainly based on Tannenbaum et al. [243]. More specifically, inputs are organised around the task, work structure, individual, and team characteristics. The inputs affect outcomes directly or through team processes. Finally, team processes consist of collaboration among team members and the design process. In design, models more commonly describe factors influencing a specific mediator, such as design communication [225] or shared understanding [252]. For instance, Maier et al. [225] proposed factors affecting engineering design communication. They identified factors in five levels of influence: information (availability of information about product specifications, procedure, company and competitors), representation (product representations and terminology), individual (knowledge of information needs, use of capabilities, education and training, an overview of the sequence of tasks in the design process, the autonomy of task execution), team (collaboration, common goals and objectives, team identity, design reviews, lessons learned, best practice), and organisation (mutual trust, roles and responsibilities, handling of conflicts, activity at interface, transparency of decision making, application of corporate vision, use of procedures, and hierarchies).

The overview of the models shows that various factors have been proposed to describe team transitions, commonly divided into inputs, mediators, and outcomes. Inputs usually represent factors that can be manipulated in order to get the desired mediators and outcomes. However, not all inputs can be manipulated at the initial transition state (i.e., a moment before the transition starts). For instance, changing the organisational culture or team expertise is possible only in the long run, while the environment in which they execute transitions can be easily changed (e.g., virtual reality, a desktop monitor). More specifically, agents can decide which environment to use before the transition starts. For example, they can choose one environment for the transitions oriented towards assessing the manufacturability (perhaps an environment that can simulate manufacturing procedures) and another for assessing the functionalities (e.g., an environment that enables taking a stance from the viewpoint of users). That way, the environment is a factor that can be manipulated for each transition in order to elicit desired mediators and outcomes. Recently, a new type of environment enabled by VR technologies has shown great potential to change the way transitions are executed [9]. These technologies are actively used in industry to support transitions [20], and investigating their effects might have large implications for the design practice. Given the easy manipulation of the environment factor and the notion that VR might greatly influence transitions [27, 28, 32], the next section provides an overview of the VR effect on transitions.

2.5. Virtual reality (VR) and transitions

Virtual reality is the experience of virtual content through natural sensorimotor contingencies, thus providing the illusion of being present in another environment [253, 254]. This illusion is often referred to as telepresence or spatial presence [255–257]. In order to provide this experience, VR technologies have been developed. These technologies are described as human-computer interface that seeks to perfect a VR experience [10, 11, 258, 259].

Typical VR technologies are differentiated by their visual simulation devices [260]: screen-based, projector-based, and head-mounted displays (HMDs). Screen-based VR technologies (e.g., Powerwall) utilise large flat or curved desktop monitors and track users' head position and rotation. Projector-based (e.g., cave automatic virtual environment – CAVE) VR technologies render images on each surface of the empty room (i.e., walls, floor, and ceiling) based on the current position of the user within the room. Finally, HMD VR technologies consist of a helmet-like device that is directly attached to the user's head. This device can track the user's head and position and render a separate image to each eye based on this tracking information. VR technologies might provide various interaction possibilities with the virtual content and other users during the transitions. These possibilities are described in the next subsection through the affordances [261] that VR technologies provide to users (Table 2.4).

2.5.1. Virtual reality affordances for transitions

VR affordances for transitions are actionable properties between the virtual environment and the user [261–263] enabled by VR technology. They can be divided into a perception of the environment, interaction with the virtual content, and interaction with the agents (Table 2.4). The affordances related to the perception of the environment include those related to spatial cues and navigation types. The perception of the environment related to spatial cues is covered by immersion [11, 258], which describes the extent to which technology simulates various sensory cues [15, 264, 265]. For example, tracking the user's head supports motion-based cues, such as motion parallax [15, 266]. These cues enable the user to perceive depth by moving, as the position of virtual content in the viewed frame changes faster for the content closer to the user than the one that is further away. Moreover, rendering separate images to each eye of the user supports binocular cues, such as stereopsis [15, 266]. These cues enable users to perceive the depth of the virtual content by combining different viewpoints from each eye. As the extent to which VR technologies present content through natural sensorimotor contingencies is their distinctive feature [267], they are usually considered high-immersion. Contrarily, traditional technologies (e.g., a desktop monitor) are considered low-immersion as they usually do not support spatial cues such as motion parallax and stereopsis. This difference in supported spatial cues might result in transition teams focusing on different aspects of the product being designed.

Another characteristic that differentiates VR technologies is their navigation affordance—the movement of the user within the environment [268–270]. While body-track navigation [13, 14] has been commonly utilised in high-immersion environments [271], VR technologies can also support other navigation types, such as point and teleport [272, 273], grab and move [274–276], map-based [277, 278], and fly navigation [279, 280]. Recent research recommended that VR should support various navigation approaches so that users can select the one they prefer [281]. For example, map-based navigation might be relevant for transitions related to buildings so that different floors can be quickly assessed. However, this navigation type might not be efficient for smaller products (e.g., office chairs).

Table 2.4 Overview of the main VR affordances for transitions[7]

Perception of the environment		Interaction with virtual content		Interaction with agents	
Types	Examples	Types	Examples	Types	Examples
Spatial cues	Motion parallax	Manipulation	Rotating	Direct	Verbal
			Changing the scale		Gestures
	Stereopsis	Representation	Measuring dimensions		Facial expressions
			Representing clearance	Referencing[8]	Pointing
Navigation type	Body-track	Editing	Edit position		Sectioning
			Edit metadata		Hiding
	Map-based	Creation	Add new artefacts	Indirect[8]	Sketching
			Record video		Direct design editing

Besides perception and navigation, VR technologies provide new ways of interacting [12] with virtual content, such as 3D models [282, 283], documents [284, 285], and various metadata

[7] This table has largely been shaped by our systematic literature review of developed VR functionalities; see [271].
[8] Referencing and indirect interaction with agents can be accomplished using shared interactions with virtual content. Therefore, the examples might overlap with the virtual content interaction affordances.

[286, 287]. The interaction with virtual content is based on the environment affordances agents have at their disposal [271]: manipulation, representation, editing, and creation. Manipulation and representation affordances enable users to change the information they receive from the virtual environment, such as measuring dimensions [14, 288], analysing clearance between artefact elements [28, 278], changing the scale [289, 290], isolating artefact elements [291, 292], or sectioning artefacts [286, 293]. These affordances provide an opportunity to gather relevant information from the environment that can support the evaluation part of the transitions. Editing and creation affordances enable users to change the virtual content or add new information to the environment. For example, they might enable agents to edit artefacts [34, 294, 295], add new artefacts [296–298], and record video or audio information [292, 299, 300]. These affordances support the planning part of the transitions, as users can work on design alternatives and record the decisions.

VR technologies also provide new ways of interacting with agents, differing in the number of supported social cues [16, 301]. The interaction with agents can be divided into direct, indirect, and referencing [302]. Direct interaction involves verbal communication and gestures that can be augmented with reference points in the virtual environment. This kind of interaction plays a significant role in design [8, 198, 303]. Therefore, verbal communication is almost always supported by various environments [271, 304, 305]. Furthermore, gestural modalities can be supported by providing social cues using hands [306], facial muscles [307], or the whole body [308]. Furthermore, indirect interaction techniques represent interaction through virtual content [302]. This type of interaction can be supported by sketching functionalities or direct design editing [271], thus supporting the development of common ground during the planning part of the transitions. Finally, referencing is conducted by acts such as pointing [74] and shared viewing [134, 139] or interaction techniques such as sectioning and hiding [271]. These affordances help agents build a shared understanding around the virtual content [309], as they can efficiently describe the communication context throughout transitions (e.g., pointing to a specific part of the virtual content and saying *look at this*).

The proliferation of VR technologies has the potential to change the way agents execute transitions [9] in various design phases [6]. Given that VR technologies provide spatial and social affordances in the transition context, their use has been explored for individuals (based on spatial affordances) and teams (based on social affordances). The following two subsections provide an overview of the findings related to the VR effect on individual (Subsection 2.5.2) and team (Subsection 2.5.3) transitions.

2.5.2. Virtual reality and individual transitions

The effect of VR technologies on individual transitions has been manifested through the change in supported spatial cues. Therefore, many researchers focused not only on the effect of VR on outcomes (e.g., the number of identified issues) but also on mediators, such as understanding of the virtual content (Table 2.5).

Studies in the design discipline analysing the effect of VR on mediators have mainly considered its effect on design understanding [310], observed as a general construct [311] or through its specific dimensions [23]. Design understanding as a general construct has been explored mainly through self-reported studies. For example, Kandi et al. [312] showed that the use of VR improved students' design understanding compared to 2D drawings.

Studies that observe specific design understanding dimensions can be categorised using the FBS ontology [98]. These categories may include understanding the structure of a design artefact and understanding the behaviour from structure (i.e., attributes that can be derived from the structure of the design artefacts). The design understanding of structure can be further divided into context-independent (e.g., understanding the artefact's dimensions) and context-dependent (e.g., understanding the artefact's function).

Table 2.5 Overview of the observed concepts in individual transitions

Mediators			Outcomes	
Understanding of structure		**Understanding behaviour from structure** (e.g., identifying folding steps)	**Goal-related efficiency**	
Context-independent (e.g., spatial perception)	**Context-dependent** (e.g., counting specific parts)		**General** (e.g., time to find intentionally planted issues)	**Categorical** (e.g., time to find issues of specific category)

Context-independent understanding has been explored through spatial perception and the perception of non-geometric attributes. In terms of spatial perception, both self-reported studies [23, 29] and studies based on objective measures (e.g., relative error when estimating dimensions) [17, 22–24] reported better design understanding (e.g., dimension estimation) using VR technologies as compared to low-immersion technologies (e.g., a desktop monitor). In terms of non-geometric attribute perception (colours, surface transparency, and area darkness), a recent study reported that users had a better design understanding in VR than in a low-immersion environment [313].

Furthermore, context-dependent design understanding of artefacts' structure requires the categorisation and transformation of sensory inputs (e.g., visualisation of the foldable vehicle design) into thought concepts (e.g., wheel, seat, handle) [314]. Those concepts are then compared to previous knowledge [314]. When studying the context-dependent understanding of the structure, self-reported studies suggested a better understanding of the spatial arrangements of the components [29] in VR than in a low-immersion environment (e.g., a desktop monitor). In addition, researchers found that the context-dependent design understanding of artefacts' structure depends on the tools available in VR [34].

In the studies that focused on understanding behaviour from structure, researchers measured design understanding using self-assessments or objective assessment methods. Studies based on self-assessment methods captured students' perceptions of the construct and have reported improved design understanding in terms of buckling modes [315] and assembly processes [316]. However, studies based on objective assessment methods reported contradictory findings. On the one hand, Fogarty et al. [315] showed that representing buckling modes in VR results in a more accurate understanding after the high-immersion experience. On the other hand, multiple studies did not find significant differences in understanding the behaviour of the design from the artefact structure between VR and a low-immersion environment [25, 26, 317]. These studies assessed design understanding through the number of correctly identified folding mechanisms [318] and assembled designs that correspond to a particular exploded view [26] or through the description of the implementation of various functions in the design [317]. In terms of the duration required to solve these tasks, studies reported that users spent significantly more time in the high-immersion environment as compared to the low-immersion one [26]. In general, the effect of VR on understanding behaviour from structure remains inconclusive. This contradiction might be due to other factors that might have affected the findings, such as expertise in design and the technology used [21, 319–322].

Researchers also explored the effect of VR on design space outcomes. The studies have measured the number of identified issues [234] or the time spent on identifying the issues [26, 30] in transitions with design artefacts that have intentionally introduced issues [234]. Regardless of the utilised metric, the effect of VR on individual transition outcomes remains inconclusive. On the one hand, Satter and Butler [30] and Bhonde et al. [323] found that participants in VR require significantly less time to perform the given task (e.g., find and repair an error) than in a low-immersion environment (e.g., a desktop monitor). On the other hand, de Casenave and Lugo [26] found that participants spent more time in VR. Contradictory findings have been reported concerning the number of identified issues, indicating that VR reduces [25], increases [324], or does not affect [234] the number of identified issues. Finally, researchers have also investigated the context of issues reported during transitions. Rigutti et al. [75] found that VR helps identify affordance errors (e.g., door handle on the same side of the hinges), but it does not support recognition of perceptual errors (e.g., misaligned handrail).

The effect of VR on individual transitions in literature is consistent only with respect to spatial perception. Findings remain inconclusive regarding the effect on contextual understanding and outcomes. Nevertheless, VR shows great promise in supporting specific aspects (e.g., affordance errors, spatial perception) of individual transitions.

Although the effect of VR on individual transitions has been extensively studied, transitions are often conducted as a team activity. Therefore, studying the effect of VR on team transitions might have implications for both theory and practice. The following subsection provides an overview of the effect on team transitions.

2.5.3. Virtual reality and team transitions

Scholars investigated the effect of VR on team transition mediators and outcomes and on the broader design context (Table 2.6). In these studies, teamwork has been supported in two ways: presenter view and active participation. The presenter view includes only one participant in VR, while other members are passive observers in the low-immersion environment [28, 203]. This approach is usually accomplished with one member in VR while others observe their viewpoint via a desktop monitor. Another implementation is that all members use VR technology, but only one can adjust their viewpoint, while others are passive observers in the VR [29]. For example, if all members use a Cave Automatic Virtual Environment (CAVE), only one participant is being tracked [325]. The view that is rendered in CAVE is thus optimised for the tracked participant. In contrast, the active participation mode provides all team members with views based on their navigation input [27]. This way of working needs to be supported with one VR technology set for each participant, thus requiring several CAVEs or head-mounted displays (HMDs). Most of the findings regarding the effect of VR on transitions are based on the VR technologies that enable a presenter view. Only a few studies utilised VR technologies that enabled active participation, such as Cárcamo et al. [31], Zaker and Coloma [27], Tea et al. [32], and Sopher and Dorta [242].

Table 2.6 Overview of the observed factors in studies related to team transitions

Mediators	**Team behaviour**	**Communication** (e.g., sketching, conversational turns)
		Actions (e.g., divergent and convergent)
		Working mode (e.g., participation in team actions)
	Cognitive aspects (e.g., spatial understanding, understanding of context)	
Design space outcome	**Perceived outcome** (e.g., interviews, survey)	
	Effectiveness (e.g., assessed by judges)	
	Efficiency (e.g., number of identified issues)	
	Goal-related efficiency	**General** (e.g., number of identified intentionally planted issues)
		Categorical (e.g., number of identified issues of specific category)
Broader design context	**Design team behaviour**	**Actions** (e.g., number of actions before the transition)
	Design process fit (e.g., design phase, integration to the design process)	

The effect of VR on mediators in team transitions has been identified for team behaviour (i.e., what team members do) [27–29, 32] and cognition [29, 32]. Team behaviour has been explored through communication, actions, and working modes. Self-reported studies found that VR positively affects communication within transition teams [28]. Objective measures partially supported this claim, as the studies reported that VR affected the number of conversational turns [236], sketching [19], and gesturing [19]. However, these findings are still inconclusive, as Beaudry et al. [19] point out that VR might not affect design conversations. Similarly, studying the effect of VR on divergent/convergent actions also provided contradictory results [46, 235]. Furthermore, the effect of VR on working modes suggests that using VR results in higher participation of individuals [29] compared to traditional approaches. This participation is especially emphasised in educational transitions, as recent findings suggest that VR increases students' engagement during transitions [46].

The effect on cognitive aspects has weak evidence, usually in the form of teams reporting an improved understanding of various aspects. For example, teams reported improved overall spatial understanding [32], understanding of product assembly steps [29], and understanding of spatial relationships between parts [29].

Researchers studied the effect of VR on transition team outcomes as perceived by the transition team [27, 326] and in terms of efficiency [31], effectiveness [33], and goal-related efficiency [28, 32, 33]. The perceived outcome was mainly positive. Zaker and Coloma [27] compared a two-member collaboration and reported that high-immersion environments are perceived as beneficial for internal and mixed design reviews. Another study supported this finding, where participants reported that using VR contributed to their redesign projects [326].

Objective measures of outcomes resulted in conflicting results. In terms of efficiency, Cárcamo et al. [31] reported a significantly higher number of identified issues in the VR review with 3D models compared to the traditional collaborative revision of 2D plans. Contrarily, Liu et al. [33] reported lower effectiveness of teams working in VR than in a low-immersion environment. Finally, goal-related efficiency was usually improved by VR for the overall number of identified issues but not for all types of issues (i.e., context). Wolfartsberger [28] reported a higher number of identified issues when teams had an active member using VR technology rather than a desktop monitor. Tea et al. [32] compared high-immersion (i.e., VR) and low-immersion environments as preparation for transitions and found that VR positively affected the goal-related efficiency (i.e., the number of issues identified on a controlled design) of the follow-up real-world building inspection. In addition, Wolfartsberger [28] suggested that the high-immersion environment supported the identification of design- and ergonomic-related issues, while the identification of circuit logic issues was not affected. Therefore, VR might help improve only specific aspects of the transition [327].

A broader design context has also been found to be affected by introducing VR in transitions. Sopher et al. [328] reported an increase in the development rate of the design before the VR transitions. They also suggested that VR better supports the later phases of the design process. However, this finding has not been consistent, as later work showed that VR might better support early phases [46].

2.6. Research implications

The overview of design paradigms supported the focus on transitions as a distinguishable type of activity in the design process. While VR has great potential to improve transitions, the findings regarding the effect of VR on transition mediators and outcomes are inconclusive. The reason behind this might be the oversimplified description of transitions, as the effect of VR was mainly studied on a meso-scale without considering other factors that might alter this relationship. Hence, a multifaceted description of transitions might be necessary to understand the effect that VR has on these activities. However, the overview of transitions shows that the multifaceted description of transitions is lacking on both micro and meso scales. Therefore, there is a need to comprehensively describe transitions (meso-scale) and transition processes (micro-scale). The next chapter presents the two developed models.

3. THEORETICAL MODELS

Based on the literature review, this chapter presents two theoretical models. The first model is developed from the micro-scale definition of transitions and describes team transition processes. The model consists of transition states that describe the current characteristics of transitions and actions that agents execute to change the transition state. This generic model is then elaborated by providing a more comprehensive description of the transition state and actions. The second model is developed by mapping the micro-scale model elements to the meso-scale level and grouping them using the meso-scale models reviewed in the literature.

The proposed hypothesis of this thesis has two main parts. While the first part of the hypothesis relates to understanding the transitions, the second part relates to their execution. Hence, as a theoretical basis for the first part of the hypothesis (*VR technologies augment understanding of transition processes*), a micro-scale model is developed (Section 3.1) with transition actions at its core. For the second part of the hypothesis (*VR technologies improve the execution of evaluation/planning activities*), a team transition model is developed (Section 3.2).

3.1. Theoretical model of team transition processes[9]

Following the micro-scale description of transitions, an initial model is presented in Figure 3.1. The model consists of a transition state before the action, a transition action, and a transition state after the action. The transition state describes elements (e.g., a product being developed) that might affect actions or that are affected by actions [41]. An overview of the literature (see Subsection 2.2.1) suggests that three transition state elements are usually distinguished: design space, agents (i.e., transition team), and information content. The *design space* element represents a set of all possible design solutions for the problem at hand [41]. The *agents* element describes a transition team that executes actions [4, 41, 329]. An agent within the transition team is described as an adaptive system that interacts with the information content and other agents in the same transition state [330, 331]. Finally, *information content* (IC) is introduced following Hubka and Eder's [115] notion that agents have only a subset of information available (e.g.,

[9] Transition processes correspond to transition actions. Although this inconsistency has already been discussed, it is worth noting again that these two terms will be used interchangeably.

design solution artefacts might not represent the whole design space). In addition to these three elements, the transition state might be described by other elements. Even though they are not explicitly modelled, these elements are described by characteristics that are relevant for transitions (e.g., transition goal). These characteristics are not depicted by the design space, information content, or agents and are, therefore, part of the other transition elements.

Transition actions change the current transition state to a new one [41]. Actions usually last a few seconds [93, 130] and resemble other similar concepts in design, such as design operations [4] and design moves [329]. The outputs from the action are the new state of the design space, information content, agents, and other transition elements. The following sections provide a more detailed explanation of the basic model.

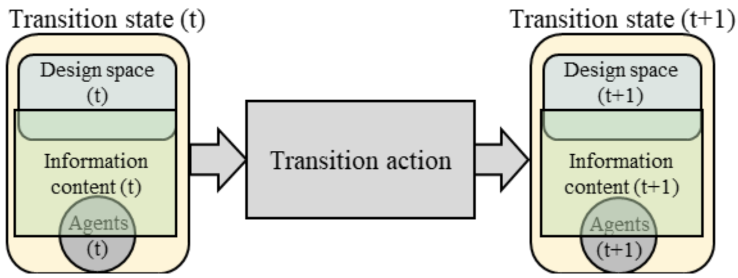

Figure 3.1 Basic micro-scale description of transition action; Note: the other transition elements are depicted by the uncovered area of the transition state

3.1.1. Elaborating the transition state

Providing a more comprehensive description of the transition state involves the elaboration of the design space, information content, and agents. The design space consists of entities that describe the state of the design. More specifically, these entities describe the design problem and solution [4, 41] of the current work and of all future states. Therefore, design space can be divided into spaces related to the current design (CDS) and the future design (FDS). This distinction is of particular importance for transitions, as agents evaluate the conducted work (current design) and plan future actions (future design) [2, 5, 50]. Therefore, modelling design space provides an opportunity to study the transitions through the changes in the product being designed. These changes in the transition state are accomplished by agents.

Elaborating on the agents element provides a better understanding of how the design space advances throughout transitions. Based on the review of the agent-based perspective (see Subsection 2.3.2), the cognitive characteristic that emerged is uncertainty, described as agents' awareness of the limitations of their current knowledge or understanding [143, 146]. Uncertainty is a central element of metacognitive monitoring and control that agents use to regulate time and effort throughout the design activities [172]. More specifically, based on their uncertainty level, agents decide which action to execute [60, 143, 146]. They constantly monitor the execution of actions (e.g., automatic assessment of the appropriacy of the strategy), thus updating uncertainty to a new state. This updated uncertainty then serves as a driver for the subsequent action. The metacognitive monitoring and control view corresponds to the reflective practice paradigm [60], in which agents constantly reflect on prior actions and plan future ones. Hence, uncertainty is integral to design [332] and one of the main drivers of the design work [60, 143, 146].

Focusing solely on uncertainty might provide a limited view of transitions from the agent-based perspective [105, 333, 334]. The well-documented impact of affect (i.e., agents' experience of emotional intensity [335]) on cognition [184] suggests that this characteristic is also relevant to these activities. Based on metacognitive monitoring and control, the current affective state might drive the decision about which action to execute [336–339]. Similar to uncertainty, this affective state is updated once the action has been executed and serves as a driver of subsequent action. The relevance of the affective mechanisms might be especially emphasised in a team, as stress is released while negotiating ideas in this context [340]. More specifically, the affect is transmittable between agents [335] and has an important role in relating an agent with other agents [335]. Therefore, affect is another driver of design work [147], and it plays a significant role in team transitions due to its transferability.

Both uncertainty and affect are team characteristics whose values fluctuate throughout the transition [147, 172]. While various team characteristics might have values that fluctuate [246], these two emerge as the most prominent in the context of team transitions (see Subsection 2.3.2). Therefore, based on the importance of uncertainty and affect in transitions, agents are elaborated by these two characteristics (Figure 3.2).

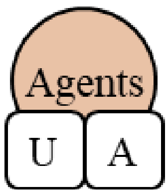

Figure 3.2 Agents with uncertainty (U) and affect (A)

Information content, another element in the transition state, serves as a medium between the agents, design space, and other transition elements [134, 302, 330, 331]. Therefore, the IC can be described as a layer that makes the transition state characteristics available to agents and is divided into design problem and solution artefacts, transition goal description, minutes, and avatars (Figure 3.3). Based on the overview of transition state descriptions (see Subsection 2.2.1), the existence of IC related to the current design (i.e., design problem and solution) is important in transitions, as they are also knowledge carriers [341] that can aid agents in this activity [68]. They also serve as boundary objects to aid communication between agents [77, 132]. The design problem and solution IC might be changed by agents (e.g., by deleting a portion of the solution, adding a new problem to the description, or sketching new ideas). However, due to the large amount of resources that might be needed to actually change the current design, these changes are often implemented in a subsequent development activity [2, 77]. Therefore, agents utilise IC that captures decisions they make throughout transitions [2]. These decisions are captured in minutes and describe the current design (e.g., a description of what is wrong with the current design problem and solution) or the future design (e.g., a description of an alternative design problem and solution).

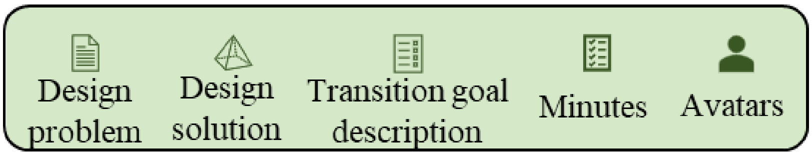

Figure 3.3 Elaborated information content (IC)

In addition to the design problem and solution artefacts, agents that worked on creating the current design (i.e., designers) might hold additional information not captured by the artefacts [57, 149]. Therefore, agents that evaluate the design (i.e., reviewers) might interact with the creators (i.e., designers) in order to understand and negotiate the decisions. In this context, the agent's IC (i.e., their avatar) is an important factor affecting this interaction between agents [8]. For example, in face-to-face work, agents' avatars include the IC that agents can perceive about each other (e.g., verbal communication, gestures, facial expressions, odour, etc.). In virtual work, this IC depends on the technology used (e.g., audio conferencing, video conferencing, virtual reality, etc.).

Besides IC related to the design space and agents, the IC of other transition elements might also be available to agents. As transitions are goal-oriented activities, the IC content describing the transition goal is often available to agents (Figure 3.3). This content can be general and applicable to various transitions (e.g., is the solution possible to manufacture) [77] or specific to the current transition and product being designed (e.g., does the solution adhere to the specified weight) [133]. Combining these five IC characteristics with the design space and the agents elements results in an elaborated transition state (Figure 3.4).

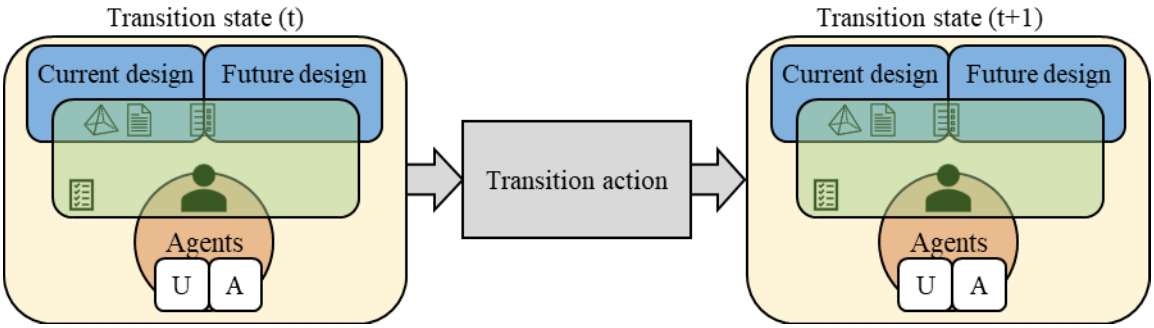

Figure 3.4 Elaborated transition state

3.1.2. Elaborating the transition action: Team behaviour

Transition actions change the value of transition state characteristics. This change can be observed from two perspectives: taskwork and teamwork [50, 247]. The taskwork aspect of transition actions[10] depicts what agents do [50, 247] in terms of what characteristics of the transition state are changing (Figure 3.5), while teamwork depicts how agents work while executing actions (Figure 3.5) [50, 247]. For instance, actions that change the design space (i.e., taskwork) can be executed by one member or by collaboration in a team (i.e., teamwork). Additionally, agents have the ability to execute taskwork that alters the state of the avatar IC (i.e., taskwork). This can be done by the agents themselves or by other agents (i.e., teamwork), such as muting the microphone of others during a conference call. These two perspectives are thus complementary and serve as a basis for elaborating transition actions.

The taskwork goal of actions is to change one or more elements in the transition state. For example, agents may execute actions to change the state of the design space, such as proposing a new solution or understanding the current solution. Other actions might aim at changing the state of the agent (e.g., moving in the physical space), the state of the information content (e.g., rotating a physical artefact, sectioning a virtual artefact, switching off a camera in virtual work), or the state of other transition elements (e.g., changing the transition goal).

Furthermore, actions might change the state of more than one transition element. For instance, agents could execute actions that primarily change their own state (e.g., the agent moves around to get a better view) and, consequently, the state of their avatar also changes (e.g., an avatar

[10] The taskwork aspect of transition action is the only one that has been identified in prior work on transitions (Section 2.2.2). Therefore, transition action in the prior studies has been conceptualised only from the taskwork perspective. However, the background work about the social facet of transitions suggests that transition actions also consist of a teamwork aspect. This suggestion is supported by the management literature that describes team behaviour (a concept related to transition actions) in terms of taskwork and teamwork.

representing an agent changes its position). Next, agents might execute actions to change the state of the design solution IC (e.g., create a sketch, delete part of the solution, etc.), which results in changing the state of the design space as well. Therefore, although presented as separate actions, the taskwork aspect of actions usually changes multiple elements of the transition state.

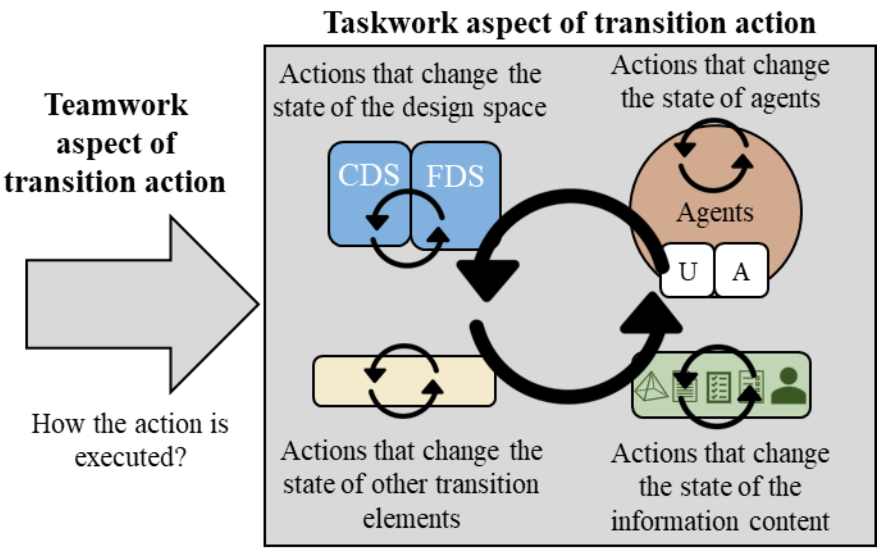

Figure 3.5 Teamwork and taskwork aspect of transition actions

The taskwork aspect of transition actions (i.e., what elements in the transition state they change) can vary in frequency and extent. For example, actions that change the state of the transition goal are rare, as transitions are usually conducted with goals that the transition team can assess (e.g., the manufacturing goal of transitions would involve an agent with manufacturing knowledge) [5, 68, 76]. In contrast, actions that change the viewpoint of the agent might be executed almost always. Furthermore, actions differ in their extent, as they can change only the subsequent state, a number of states, or all states that follow. Changing only the subsequent state is common for actions executed through verbal communication, as the voice quickly dissipates. Actions could also be executed through information means that do not dissipate as quickly, such as slower physical processes (e.g., emptying a tank with water to evaluate the drain duration) or pre-programmed in a virtual environment (e.g., self-deleting messages). Finally, turning off the camera in virtual work changes the state of the avatar until an agent executes another action to turn on the camera.

Although the taskwork aspect of transition actions suggests that various elements of the transition state can be changed, actions related to the changes in the design space are related to the definition of transition (evaluation/planning of design work) and the main ones that have been studied in the literature (see Subsection 2.2.2). Based on the two general transition goals (evaluation of the current work and planning of the future work), actions that change the design space are evaluation and planning [2, 5]. The evaluation action is the assessment of the current design regarding the design goal and the utility assessment of these goals (Figure 3.6) [2, 5]. The result of this action is the change in preference regarding entities (design problem and solution, see Subsection 3.1.1) in the current design (depicted as the modified size of an entity in the current design in Figure 3.6). Planning relates to discussing a future design and involves the creation of alternatives to the current design (e.g., alternative requirements or alternative solutions) or evaluating these alternatives [2, 5]. Therefore, planning action results in changes related to the future design (depicted as a new entity or as the changed size of an entity in the future design in Figure 3.6). Of course, as these actions change the design space, they also change the agents (e.g., uncertainty). However, to keep the simplicity of the modelled actions, only their main aim has been visualised in Figure 3.6.

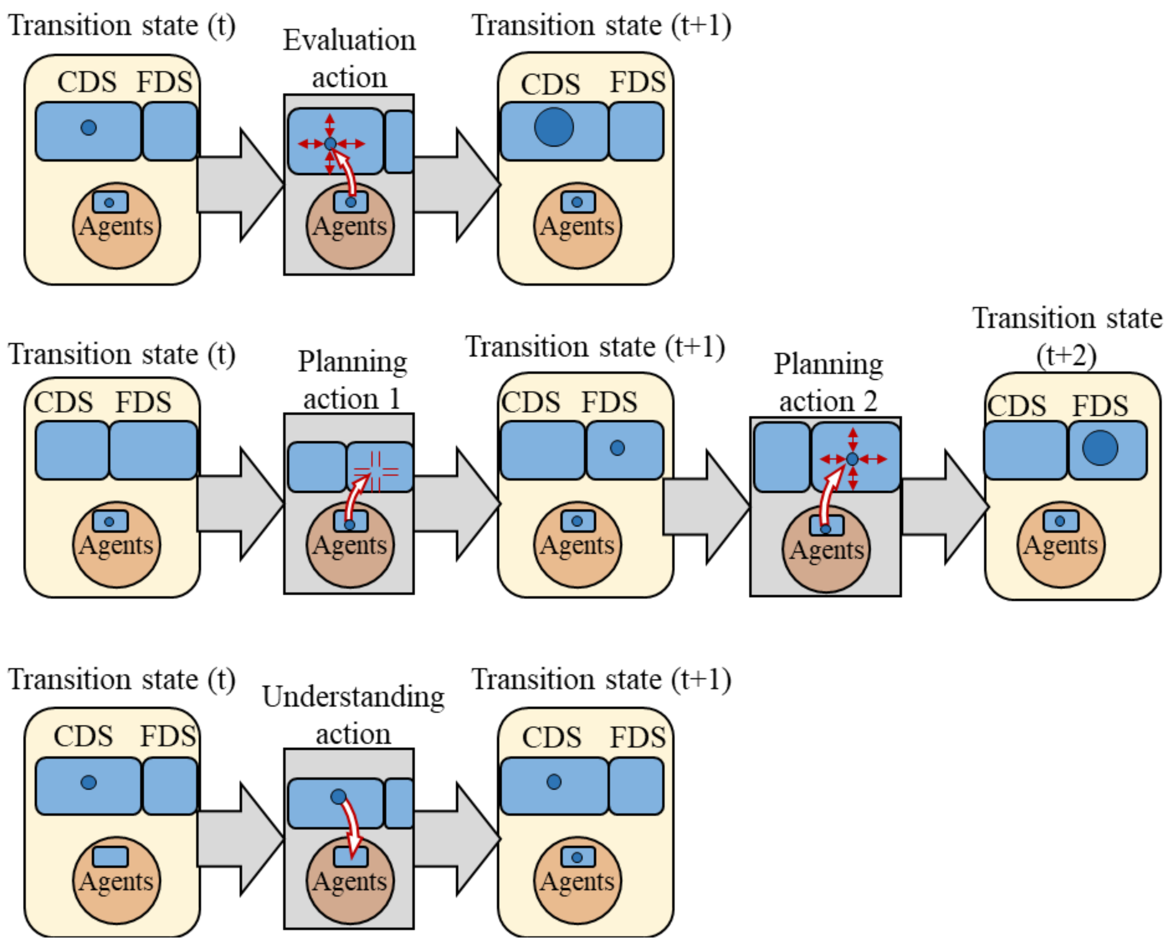

Figure 3.6 Evaluation, planning and understanding actions; CDS – current design, FDS – future design

In addition to evaluation and planning actions, researchers often point out the importance of understanding action [2, 5]. The aim of the understanding action is to comprehend any design aspect through interaction with the transition team [5] or interaction with the design artefact [21]. Therefore, this action enables the establishment of common ground related to the current design (depicted as an explored entity of the current design in Figure 3.6), thus changing the state of agents. Although the understanding does not directly contribute to the outcomes of the evaluation/planning-oriented activities (transitions), it helps agents create a basis for goal-directed actions [127].

Based on the social facet (Subsection 2.3.3), a teamwork aspect relevant to team transitions is the agents' participation in action execution. More specifically, the action executed by all agents can increase the common ground among them, thus enabling transition teams to build shared understanding and make collective decisions [73]. This building of shared understanding is critical for teams, as it is related to group performance [342]. However, agents do not always participate in actions all-together [154], as they form sub-teams [191] that can work in parallel with the aim of increasing efficiency. Although enabling parallelisation, sub-team work might result in decisions that are not agreed upon by all agents, thus forming a gap that could influence subsequent actions and activities. Therefore, the malleable formation of sub-teams is important for transitions. To capture this aspect of transitions, teams can execute the transition actions by the whole team (all-together) or by sub-teams (Figure 3.7).

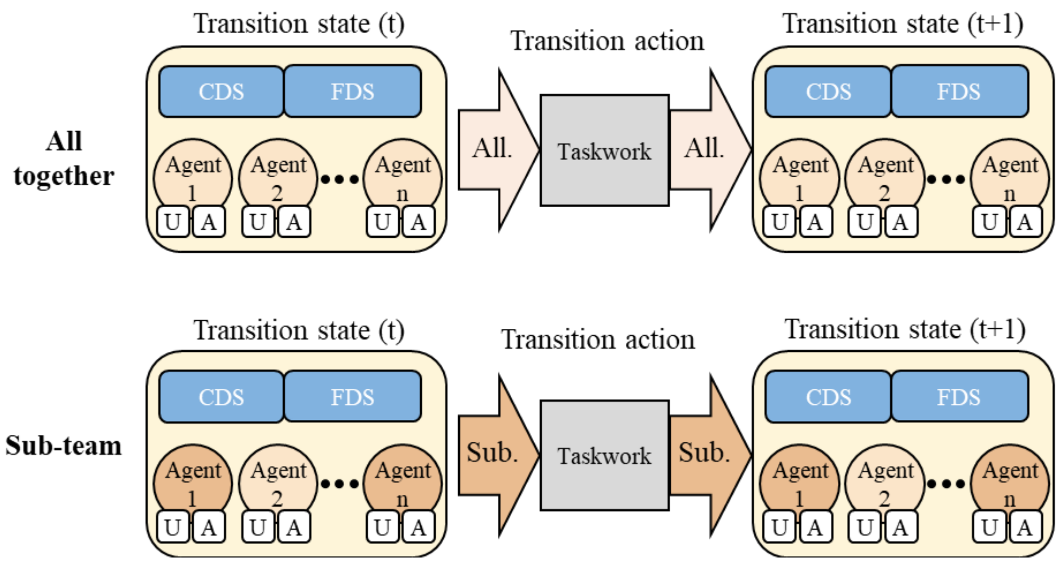

Figure 3.7 All-together and sub-team working mode

By combining the elaborated transition state (Figure 3.4), the transition action taskwork (Figure 3.6), and the transition action teamwork (Figure 3.7) into the basic model (Figure 3.1), a micro-level model of team transition actions is proposed (Figure 3.8). This model of transition action represents only one sequence in the transition activity. Therefore, the next subsection implements this model in the transition activity.

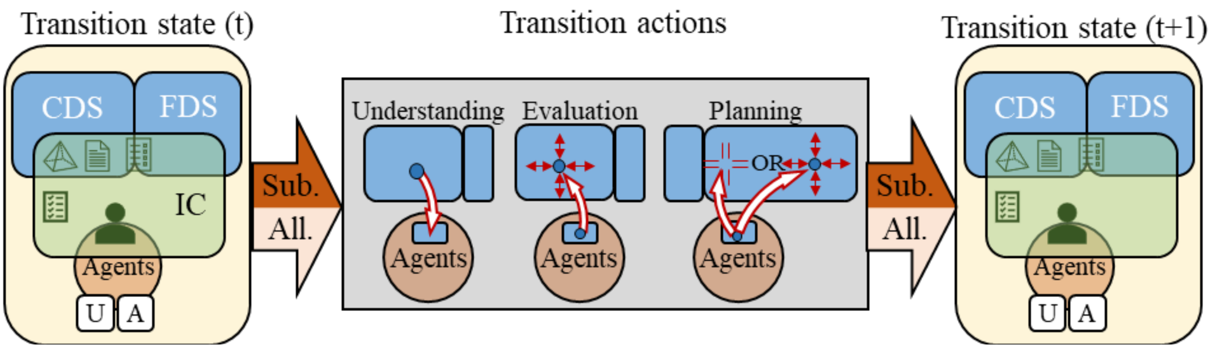

Figure 3.8 A micro-level model of team transition actions

3.1.3. Transitions in the context of evaluation/planning activities

Following the basic description of transition activity as a sequence of actions that consecutively change the transition state (Figure 2.3), the elaborated transition action model (Figure 3.8) has been scaled to the activity level (Figure 3.9). The transition activity starts with the initial transition state (t) resulting from the previous activity (see Figure 2.3). Similarly, the last transition state (t+n) describes the output that the subsequent activity uses as input. In line with the definition of activity as a sequence of goal-oriented actions, an overall transition goal has been added as an orientation for the actions. In specific instances of transitions, this goal can be related to focusing on various aspects, such as manufacturing, ergonomics, or users. This in-depth description of transitions enables the development of the team transition model.

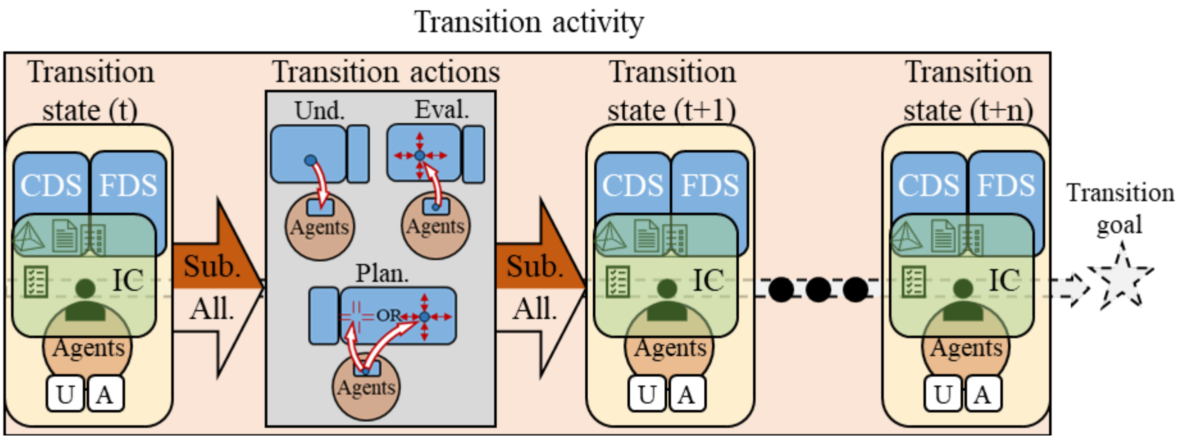

Figure 3.9 Micro-scale theoretical model of transitions

3.2. Theoretical model of team transitions

The team transition model is developed on the meso-scale level in order to describe the factors that characterise transitions (Figure 3.10). The model is developed based on the common division of factors into inputs, mediators, outputs, and outcomes of transitions (see Section 2.4). This division was used to map elements from the micro-scale to the meso-scale level. The mapping involved the alignment of inputs to the transition state (t) and outputs to the transition state (t+n). Inputs and outputs are thus described by the same characteristics; they just differ in the values of these characteristics. Although the four elements of the transition state are intertwined, the team transition model considers them separately to provide factors that describe each element.

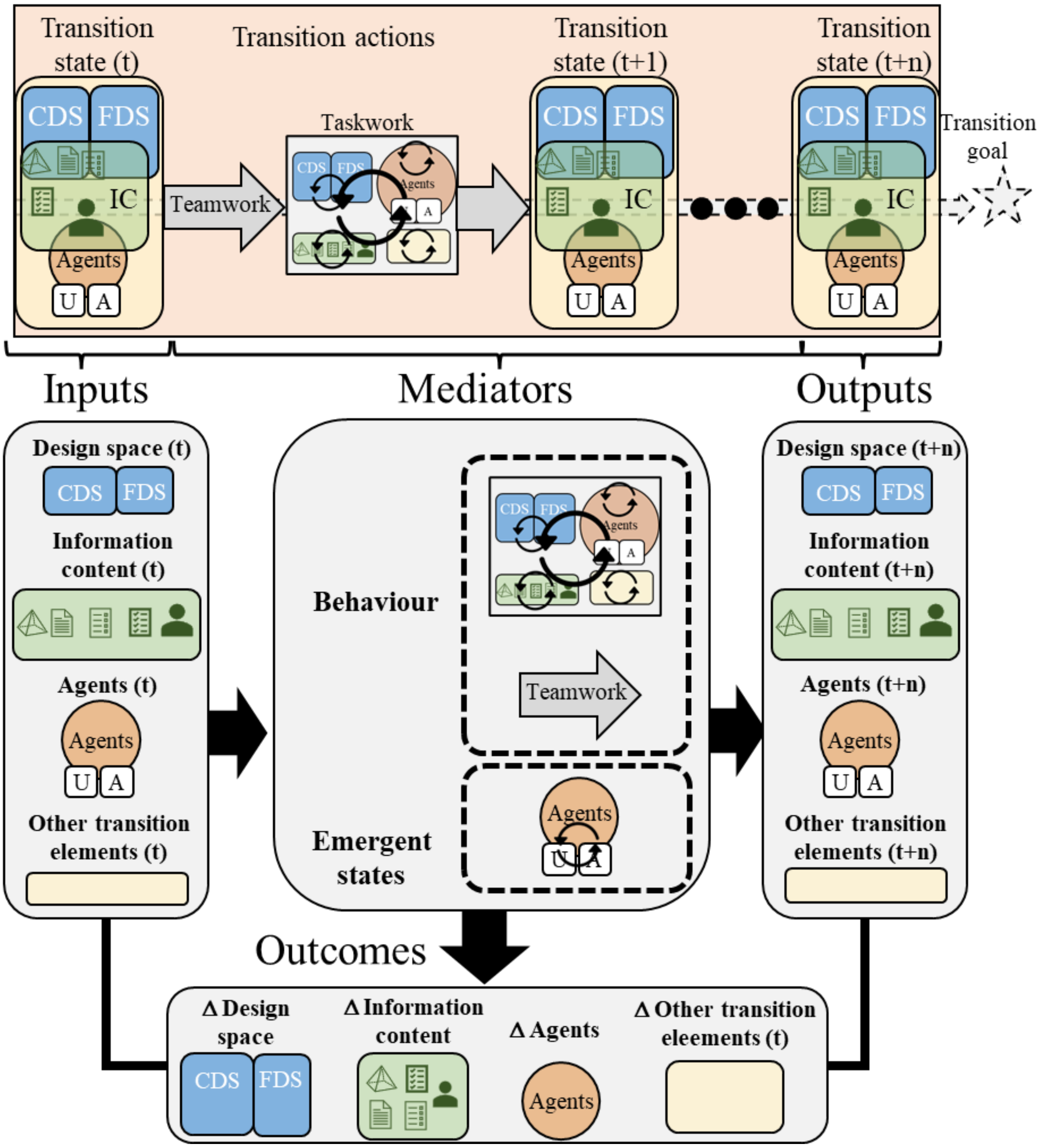

Figure 3.10 Mapping the micro-scale model elements to meso-scale

In the team transition model, mediators describe how inputs are transformed into outputs [244]. This transformation is in the micro-scale model described through teamwork and taskwork of transition actions. The taskwork aspect of transition actions suggests that various elements of the transition state can be changed, thus representing this aspect of behaviour with the generic actions presented in Figure 3.5. Moreover, while the micro-scale model points out the importance of working mode (e.g., all-together, sub-team), this teamwork characteristic of transition actions is abstracted and depicted as a generic description introduced in Figure 3.5. In addition to behaviour, mediator variables in the micro-scale model include the agent's uncertainty and affect. Although these two characteristics are prominent in the transition activity, researchers point out that other ones might also be transition mediators (e.g., cohesion). These characteristics emerge from the agents' interaction with the transition state elements and represent another group of mediators, often divided into cognitive and affective [246]. Following this distinction, uncertainty is a characteristic of the cognition factor, while affect is a characteristic of the affective factor. Although these factors have values at the initial and final transition states, their dynamic nature throughout the session makes them much more relevant as mediators [50, 246].

Finally, outcomes are the results of a transition activity that depict the relative changes of inputs to outputs [250, 343]. Therefore, the uppercase symbol Δ has been used to denote differences between the two states (i.e., output and input). To better describe elements of the team transition model, the following subsections provide examples for inputs/outputs (Subsection 3.2.1), mediators (Subsection 3.2.2), and outcomes (Subsection 3.2.3). Even though an extensive literature review has been provided to understand the factors (see Section 2.4), the characteristics of the factors in the team transition model are not an exhaustive list. Instead, they serve as illustrations of each factor in the developed model.

3.2.1. Transition inputs and outputs

To ensure that inputs and outputs in the team transition model represent a relevant transition element, the reviewed meso-scale models (see Subsection 2.4.3) were mapped onto the transition state elements (Table 3.1). The factors in the reviewed models can broadly be categorised into composition, context, and culture [248, 249]. These three categories are used to ensure that the proposed factors provide a comprehensive list.

Table 3.1 Mapping the input and output categories from management to team transitions

Management discipline [248, 249]	Team transition element
Composition, task context 1 (structural characteristics of the team)	Agents
Task context 2 (characteristics relevant to the design)	Design space
Physical context	Information content
Task context 3 (Characteristics relevant to transitions), organisational context, culture	Other transition elements

The composition in Salas et al. [248] and Dinh et al. [249] includes characteristics of the agents that are relevant to the team's performance, both on individual and team levels. Individual-level characteristics describe agents by considering their traits, such as knowledge, skills, abilities, and personalities. Team-level characteristics are related to the configuration of these individuals in the team, such as similarity or diversity between agents. The composition category is thus mapped to agents in the team transition model (Table 3.1).

The context in Salas et al. [248] and Dinh et al. [249] includes situational characteristics that affect mediators, divided into task, physical, and organisational contexts [249]. Task context represents the work to be performed and how it is performed. More specifically, it describes the structural characteristics of the team that performs the activity (e.g., team size, hierarchy) and the characteristics of the task (e.g., complexity). Task context is a broad category that has been divided into subcategories in order to enable distribution across inputs and outputs. Firstly, the structural characteristics of the team describe another factor in the team transition model (Table 3.1). Next, as the transitions usually have specific goals that are a subset of the design goals, characteristics are further decomposed into characteristics relevant to the design and characteristics relevant to the transitions. Characteristics relevant to the design are thus related to the design space, while characteristics relevant to the transition goal are related to the other transition elements (Table 3.1). Furthermore, physical context represents features of the working environment [248, 249], such as tools, information displays, and workspaces. More generally, the physical context in Dinh et al. [249] describes the information that surrounds the agents, thus representing an information content group (Table 3.1). Finally, the organisational context describes environmental settings determined by the organisation, such as a reward system, training, managerial support, etc. [248, 249]. Although they are unlikely to be affected by transitions, they are still relevant for describing other transition elements (Table 3.1).

Finally, the culture in Salas et al. [248] and Dinh et al. [249] includes assumptions about relationships between agents and the environment in which they work. More specifically, while context is related to the environmental setting for teams, culture describes broader societal and interpersonal dynamics that drive members' values, norms, and behaviours [249]. Therefore, culture is another factor describing the other transition elements. This mapping of elements (Table 3.1) is considered while elaborating on each input/output category, i.e., design space, information content, team, and other transition elements.

The mapping of inputs and output categories from management literature to the team transition model ensured that the factors describing each group were comprehensive. Therefore, the rest of the subsection elaborates on each element, namely design space, information content, agents, and other transition elements.

Design space inputs/outputs represent factors related to the current and future design (Table 3.2). *The current design factor* represents characteristics relevant to the design problem and solution (i.e., framing) under transition. As characteristics of this factor, the size and complexity of the current design were found to affect mediators [23] and outcomes [33]. In addition, the quality of the current design also affects transition outcomes [65]. For example, if the current design is of lower quality, agents have a lot of opportunities to improve it. However, if the current design is of higher quality, the relative change that the agents can make from the current to the future design is much lower.

The future design factor represents characteristics relevant to creating alternatives and solving issues during transitions. In this context, a definition of the design goal (e.g., what functionalities the product should have) and the design constraints (e.g., what manufacturing technologies can be used) might affect the execution of transitions [2].

Table 3.2 Factors related to design space inputs/outputs

Element	Factors	Example of factor characteristics
Design space	Current design	Size [23, 33]
		Complexity [23, 33]
		Design quality [65]
		…
	Future design	Design goal [2]
		Design constraints [2]
		…

The IC element depicts characteristics of the environment and artefacts (Table 3.3). Therefore, VR would be one instance of the environment factor supporting various digital artefacts. Other instances of the environment factor could be traditional user interfaces (mouse, keyboard, monitor) supporting digital artefacts or even physical environments supporting physical artefacts. *Environment* characteristics depend on the affordances that agents have at their disposal and can be broadly categorised into [271]: navigation, manipulation, type of available information, editability, reversibility, creation, and collaboration. Navigation in an environment and manipulation of objects are general characteristics relevant beyond transitions [268–270]. In the real-world environment, navigation and manipulation are determined by physical laws.

In the virtual environment, these affordances largely depend on the technology used (see also Subsection 2.5.1 and [271]). Next, the type of information describes what IC is supported by the environment. This IC can be imported into the environment [271], such as physical models for the real-world environment [230] and digital documents for the virtual environment [284, 285]. In addition, the IC can also be provided by the environment with additional tools, such as a ruler to measure the size in a physical environment or a collision detector to measure the clearance between objects in the virtual environment [28, 278].

Table 3.3 Factors related to information content inputs/outputs

Element	Factors	Example of factor characteristics
Information content	Environment	Navigation (e.g., navigation type, navigation restriction) [268–270]
		Manipulation (e.g., object) [268–270]
		Type of information (e.g., 3D models, dimensions) [28, 230, 278, 284, 285]
		Editability and reversibility (e.g., editing artefacts) [34, 237, 271, 294, 295, 344]
		Creation (e.g., creating new artefacts, recording decisions) [292, 296–300]
		Collaboration (e.g., communication modalities, view types) [8]
		Immersion [267]
		…
	Artefact	Fidelity [67, 200, 206, 226, 227, 345]
		Dimensionality (e.g., 2D, 3D) [31, 68]
		Extent (e.g., subsystem level, whole design) [224]
		Scale (e.g., reduced, increased) [224]
		Composition of artefacts (e.g., similarity, difference) [132]
		…

Furthermore, environments could also provide an opportunity to edit the IC [237, 271, 344] or reverse the actions that changed the state of the IC [346]. For example, they might enable agents to edit design space artefacts [34, 294, 295] or the IC related to the agents' avatars. Editability and reversibility characteristics often distinguish physical from digital content, with the latter usually being more editable and reversible [344, 346]. However, physical objects could also be editable (e.g., LEGO) and reversible (e.g., smart materials) to a certain extent, sometimes even more than digital objects (e.g., digital content with read-only rights). Therefore, the digital/physical distinction does not determine editability and reversibility characteristics. Following this premise, digital LEGO prototyping that simulates its physical characteristics (i.e., editability, reversibility, physical laws, haptics, and type of interaction[11]) in a high-immersion environment might elicit the same effect on the transition mediators and outcomes as physical LEGO prototyping. Another example would be sketching, which is almost indistinguishable between physical and digital [347].

Creation is an environment characteristic that enables agents to externalise the future design [296–298] or evaluate the current design [292, 299, 300]. For example, sketching could be used to describe the future design while taking pictures (or screenshots) to capture the evaluation of the current design. These externalisations are an important part of transitions, as they can support the creation of boundary objects that support collaboration. The support for collaboration is another characteristic, described as the affordances that help agents build common ground. For instance, agents might utilise verbal communication, the main mode of information exchange in design activities [8]. In addition to verbal communication, sharing other communication modalities (e.g., gestures, facial expressions) or viewpoints among agents might affect the execution of transitions. Finally, environment characteristics are sometimes depicted by the broad concept of immersion [267], described as the extent to which the environment presents content through natural sensorimotor contingencies [11, 258]. Immersion accounts for various affordances and is thus a helpful characteristic for understanding the effects of environments.

Artefact factor is another type of IC input [224], describing characteristics such as fidelity, dimensionality, extent, scale, and composition. The fidelity of artefacts describes the extent of similarity between the artefact and the anticipated final product [228]. Fidelity is commonly observed in the prototyping literature [67, 200, 206, 226, 227] and was found to affect interaction with the design [345]. From an agent IC perspective, fidelity can describe how similar the avatar is to the agent (e.g., face-to-face work is usually high fidelity). A closely related characteristic is the dimensionality of artefacts (e.g., 2D and 3D), which has been commonly found to affect transitions [31, 68]. Furthermore, the extent of the artefacts (i.e., the proportion of functions represented by the artefacts) might not represent the whole design but instead focus on specific subsystems [224], thus representing another input that could affect transitions. Artefacts can also vary in scale, an often utilised characteristic in small (e.g., circuit

[11] At the moment of writing this thesis, there does not seem to be a technology that enables this level of immersion. For example, while VR technologies could enable real-world perception (e.g., HMD devices with six degrees of freedom), natural interaction with the digital content (using, e.g., hand tracking), and touch-feeling the digital objects (e.g., using haptic devices), they still do not enable the immersive sense of gravity (e.g., the weight of digital objects). Nevertheless, this technology might become available in the future.

boards) or large designs (e.g., buildings). Finally, the composition of artefacts used (e.g., using both drawings and 3D models) can also affect transitions.

The team input/output element represents team composition and team context (Table 3.4). *The composition* involves members' characteristics that can be divided into demographic and psychological [249]. Demographic characteristics characterise the surface level of agents (e.g., age, ethnicity [249]). Psychological characteristics are deep-level, divided into expertise-related (e.g., knowledge, skills, and abilities) and personality-related (e.g., big five [348], problem-solving style [349, 350]). Both expertise (e.g., design ability [351] and expertise [110, 352]) and personality characteristics (e.g., problem-solving [171, 353] or cognitive style [170, 354]) have been utilised in the design. These characteristics can be used to configure teams by assessing members' diversity/similarity, such as reducing relative distance in characteristics [171].

The team context describes the structural characteristics of the team [207, 248, 249, 355], such as the number of agents, hierarchy, leadership, and interdependence between team members. For example, team size affects communication and parallelisation of work [356, 357]. Moreover, as the team size increases, hierarchy and leadership become more important [1]. Team context also includes the interdependence of tasks, as teams work differently on independent tasks than interdependent ones [358].

Table 3.4 Factors related to agents inputs/outputs

Element	Factors	Example of factor characteristics
Agents	Team composition	Demographic characteristics (e.g., age, ethnicity) [249]
		Psychological characteristics (e.g., expertise, personality) [110, 170, 171, 348–354]
		Configuration of characteristics (e.g., diversity/similarity) [171]
		…
	Team context	Number of agents [356, 357]
		Hierarchy [1]
		Leadership [1]
		Interdependence [358]
		…

The last input/output category relates to **other transition elements**, divided into the design process context, transition task context, organisational context, and culture (Table 3.5). *The design process context* factor describes the inputs/outputs that characterise the transition from the broader design context, such as integration into the design process, the current design phase, etc. Integration of transitions into the design process workflow [271, 359] could affect their efficiency, as transitions last longer if more time is needed to import and export the IC. The design field (e.g., industrial design, engineering design) is another input/output that affects the agents' approach during the transitions [63]. Similarly, the design phase also affects the execution of transitions [5, 43, 77], as early phases focus on different aspects than the later ones. These design process inputs/outputs set the scene for the specific transition task context inputs/outputs.

Table 3.5 Factors related to other transition inputs/outputs

Element	Factors	Example of factor characteristics
Other transition elements	Design process context	Integration into the design process [271, 359]
		Design field [63]
		Design phase [5, 43, 77]
		…
	Transition task context	Transition goal [77, 132]
		Transition working approach [76]
		Transition duration [49]
		…
	Organisational context	Organisational resources [207, 249, 250]
		Market characteristics [207, 249, 250]
		…
	Culture	National culture [249, 250]
		Organisational culture [249, 250]
		…

Transition task context inputs/outputs describe characteristics from the transition activity perspective, such as transition goal [77, 132], duration [49], and working approach [76]. A transition goal describes a specific aim that agents consider while executing a transition. This characteristic is found to significantly affect transition mediators and outcomes [65]. Furthermore, agents have limited time to execute transitions, ranging from a few seconds [360] to a few days [77]. The available time is thus another input that affects both mediators and outcomes [49]. Agents could have different working approaches to reach the transition goal, such as utilising design methods, decision-making approaches, and the extent to which they want to have formal transitions [76]. For example, these less formal transitions might happen when designers ask a colleague for feedback. However, agents could also be involved in formal transitions, such as milestones between the design stages (e.g., design reviews) [2, 77, 361].

Another factor is related to *the organisational context*, described through characteristics such as organisational resources and market competition [207, 249, 250]. Organisational resources include the technology and budget an organisation can provide to agents executing transitions [207]. In addition, organisational human resource policies (e.g., reward system, training) can influence mediators such as affective or team behaviour factors [207, 249]. Next, the characteristics of the market for which the product is being developed could also influence mediators. For example, if the market is highly competitive, agents might make different decisions than if it is uncompetitive.

Finally, *culture* represents another transition input/output factor, acting as a driving force for agents' values, norms, and behaviours in a specific context. The culture affects the approach that teams take and, consequently, the outcomes [362]. Various characteristics describe the culture, such as national, organisational, or team culture [249, 250].

3.2.2. Transition mediators

Transition mediators are usually divided into emergent factors and behaviours [50, 207, 246, 250, 251]. **The emergent element** reflects shared team characteristics that unfold over time through dynamic interactions among the agents [50, 246], consisting of cognitive and affective factors (Table 3.6) [50, 246]. *The cognitive factor* is based on the cognitive actions at the team level [246]. This emergent factor is the most prevalent in the design discipline [60] and is often identified as a driver of the design work [60, 143, 146]. For example, shared understanding has been found to be a prerequisite to evaluation [127]. This cognitive characteristic is found to be affected by various inputs (e.g., team composition), and it has often been linked to team outcomes [246]. Furthermore, the transactive memory system describes collective knowledge within a team and a perception of the knowledge that other agents within the team have [363]. This characteristic is also affected by various inputs (e.g., team member familiarity) and is linked to team performance [363]. Uncertainty is another characteristic describing a cognitive factor that has been linked to other mediators [146]. Moreover, uncertainty has been linked to outcomes in conjunction with affective characteristics [144].

The affective factor depicts the motivational and emotional aspects of team members and is described as agents' experiences of emotional intensity [335]. Although this factor was also found to drive the design work [336–339], it was rarely considered in the design context [148]. This factor is largely influenced by team interactions [195, 335] and is thus dynamic throughout the transitions. The transferability of affect between agents and its fluctuations over the course of transitions have been found to influence the execution of actions [147] and team performance [144]. Similarly, team cohesion—a social or task bonding among agents that drives them to remain together [364]—has also been linked to team outcomes [246]. Therefore, despite not being the main focus in the design discipline, the affective factor is also identified as a critical component in the design work.

Table 3.6 Factors related to emergent mediators

Element	Factors	Example of factor characteristics
Emergent factors	Cognitive	Shared understanding [127, 246]
		Transactive memory system [363]
		Uncertainty [144, 146]
		…
	Affective	Cohesion [246]
		Affect [144, 147]
		…

Behaviour describes what agents do—actions primarily focused on accomplishing objectives. Two behaviour factors are commonly distinguished [50]: taskwork and teamwork (Table 3.7). *The taskwork factor* represents what it is that agents are doing, usually depicted by the actions that transform the inputs into outputs. For example, the taskwork factor could be characterised by transformations of the design space, such as the actions described by the design ontologies [138, 365, 366]. These actions are affected by various inputs, such as design context [367] and design field [137], and influence team outcomes [368]. Similarly, transition actions (see Subsection 3.1.2) are found to differ across teams [63] and transition goals [4]. Moreover, they influence the execution of other transition actions [127] and team outcomes [33]. For instance, if agents focus too much on understanding actions, they might have less time to make decisions [33].

The teamwork factor describes how agents are doing taskwork with each other (Table 3.7), such as coordination style [249] and working mode. While various coordination styles exist, they all drive team performance [249] due to the ability of coordinated teams to easily exchange information and quickly move between activities [369]. Furthermore, the working mode characteristic describes how teams distribute their work and execute actions, such as working in sub-teams or all-together. Working in sub-teams enables teams to parallelise actions and be more efficient [92], while working all-together supports collective decision-making [198]. Teams usually employ both working modes, with flexible changes between the two [154, 370]. The utilisation of different working modes depends on the team and the nature of the activity [371] and affects team outcomes [92, 371].

Table 3.7 Factors related to behaviour mediators

Element	Factors	Example of factor characteristics
Behaviour	Taskwork	Design space actions [138, 365, 366]
		Agent actions [2, 5]
		IC actions
		Transition actions [4, 33, 63, 127]
		…
	Teamwork	Teamwork actions (e.g., coordination) [249]
		Working mode (e.g., all-together, sub-team) [154, 191]
		…

3.2.3. Transition outcomes

Transition outcomes describe differences between outputs and inputs, thus representing what the transition team achieved during the activity. However, not all characteristics of the input factors change throughout the transitions [4, 41]. Consequently, specific factors are unlikely to change during transitions. For example, the organisational context and culture are unlikely to be affected by transitions. Therefore, outcomes describe the factors and characteristics that might change throughout the transition. This possibility of being changed during a transition has been identified by reviewing the characteristics of each input/output factor together with the definition of factors. Furthermore, as transitions can differ in their goals (e.g., educational and practice-based transitions), the relevance of transition outcomes depends on those goals. Therefore, the review also included consideration of various transition goals. Based on this review, input/output factors and characteristics were reduced to those that might be changed. The included and excluded factors are discussed in the rest of the subsection, organised around design space, agents, information content, and other transition elements (Table 3.8).

As the main goal of transitions is to evaluate the current design and propose future actions, most of the outcomes are related to the design space [41], as presented in Table 3.8. **Change in the design space** can be depicted through changes in the design context aspects [2, 5], such as size, complexity, design quality, and design goal. These aspects change through actions that agents execute during the transitions. For example, if agents identify various issues during the transitions, they are reflected in the design quality change. This change in the design quality might also affect the size and complexity of the design. Furthermore, based on the insights gathered during the transitions, agents might also change a design goal. Hence, evaluation and planning actions might result in changing various aspects of the design context.

Table 3.8 Factors related to transition outcomes

Elements	Factors	Example of factor characteristics
Δ Design space	Δ Current design	Change in size [2, 5]
		Change in complexity [2, 5]
		Change in design quality [2, 5]
		Design goal change [2, 5]
		…
Δ Agents	Δ Composition	Change in surface-level characteristics (e.g., KSAOs) [207, 250]
		Change in surface-level composition (e.g., KSAO diversity/similarity) [207, 250]
		…
Δ IC	Δ Artefacts	Change in fidelity [271]
		Change in extent [271]
		Change in dimensionality (e.g., 2D, 3D) [271]
		Change in scale (e.g., smaller, enlarged) [271]
		Change in composition [271]
		…
Δ Other transition elements	Δ Design process	Change of the design field [361]
		Change in the design phase [361]
		…

The change in agents (Table 3.8) is mainly related to the changes in the expertise-related characteristics of agents [207, 250], referred to as learning [250]. These outcomes are especially salient in educational transitions (e.g., design studios, design critiques), as their goal involves learning [43, 160] in addition to the improvement of the design space. A change in the expertise-related characteristics of the members consequently results in configuration changes for the team. Other characteristics, such as demographics or personality, are usually stable over time [372]. Similarly, characteristics describing the structural factor (e.g., number of agents, hierarchy) are also unlikely to change over the transition activity. Therefore, demographic and personality characteristics and the team structure factor were not included in the transition outcomes.

The IC outcomes are usually related to changes in artefact characteristics such as fidelity, extent, composition, etc. (Table 3.8). More specifically, as agents might edit existing artefacts during the transitions [271], the characteristics of these artefacts might change. For example, agents might detail elements in the artefact, thus increasing their fidelity. Moreover, agents might also add new objects to existing artefacts in order to explore the possibilities of underdeveloped functions (e.g., sketching). That way, agents can change the extent of the functions that artefacts represent. Changes in the characteristics of the environment are rare, as the context in which agents work is usually constant throughout the activity (e.g., conference room, VR environment).

Other transition elements rarely change throughout the transition [4, 41]. For instance, organisational context (e.g., resources, market characteristics) and culture (e.g., national culture) are unlikely to be affected by transitions. Nevertheless, design process characteristics might be affected (Table 3.8). More specifically, the decisions and new solutions arising from the transition might affect the design fields necessary to develop the product (e.g., adding electronics to a mechanical device). Moreover, in the stage-gate design process [361], transitions are the means of transferring from one phase to another (e.g., design review). Therefore, the outcome of transitions might also be a change in the design phase.

3.3. Chapter conclusion

Developed models provide a theoretical basis for testing the hypothesis. More specifically, the micro-scale model aims at understanding transitions and is used for testing the first part of the hypothesis (*VR technologies augment understanding of transitions*). Furthermore, the team transition model is used for testing the second part of the hypothesis (*VR technologies improve the execution of evaluation/planning activities*). The following chapters provide evidence for validating the theoretical models through design review case studies. As previous studies related to transitions often had many assumptions that restricted their implications for PD practice, it is necessary to understand the consequences of the assumptions researchers are making while planning the studies. For example, the use of VR technologies introduces new concerns that researchers need to account for, such as the experimental setup of the equipment for the whole team and potential problems with using the technology (e.g., cybersickness). The following chapter serves as a guide for planning and executing VR-supported transitions by consolidating the considerations that have to be taken into account during the process.

4. EXPERIMENTAL FRAMEWORK

In this chapter, an experimental framework to study VR-supported transitions has been developed. The framework is built upon experimental, theoretical, methodological, and implementational considerations. The experimental considerations include research ethics, resources, reliability and replicability, and validity. Theoretical considerations are divided into research questions and transition factors. Methodological considerations include factor measurements, sample definition, experimental setting, and data analysis. Implementational considerations consist of the experimental setup and the experimental procedure. Finally, pilot studies are suggested to fine-tune aspects of the experimental planning. Each of these aspects is considered throughout this chapter.

This chapter develops an experimental research framework, defined as a particular set of considerations [373] that enable researchers to systematically study VR-supported transitions. The experimental framework can also be used to test the developed theoretical models [374] and to build new theories [375]. Moreover, as experiments engender confidence in the trustworthiness of causal findings [86], they provide an opportunity to test the team transition model. Although experiments are mainly based on the positivist epistemological orientation and focus on objectiveness [85], they also enable the use of data collection approaches related to interpretivism, such as case studies [376]. Given these properties, it is not surprising that experiments are commonly utilised in design research [377].

The developed experimental framework is built around four groups of considerations (Figure 4.1): experimental, theoretical, methodological, and implementational. Experimental considerations describe research principles and constraints that are necessary to account for while planning and executing experiments supported by VR technology. These considerations include research ethics, resources at disposal, reliability of the measurements, replicability of the experiment, and experimental validity. Theoretical considerations describe how to decide on research questions and transition factors. These considerations can be largely based on the theoretical models developed in the previous chapter. Methodological considerations depict design-of-experiment (DoE) principles for conducting a VR-supported experiment that is reliable, replicable, and valid. They include factor measurements, sample definition, experimental setting, and data analysis. Implementational considerations describe the development of experimental setups and procedures for VR-supported transitions. Their development includes consideration of the VR technology specificities that need to be taken into account while planning the experiments. It is suggested to conduct pilot studies in order to improve the proposed aspects of the experimental planning and execution. Each of these consideration groups is further decomposed in the following sections and subsections.

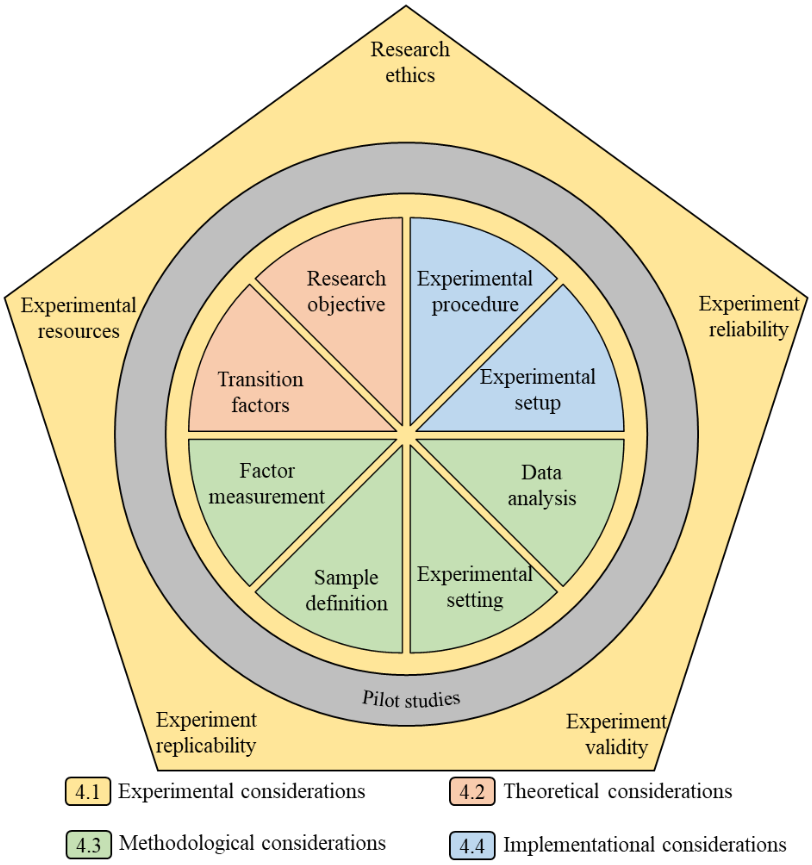

Figure 4.1 Experimental framework to study VR-supported teamwork for transition processes

4.1. Experimental considerations

The experimental considerations for studying transitions are divided into [85, 86, 378]: research ethics (Subsection 4.1.1), experimental resources (Subsection 4.1.2), experiment reliability (Subsection 4.1.3), experiment replicability (Subsection 4.1.4), and experiment validity (Subsection 4.1.5). These considerations are related to the three research properties [378]: ethical, feasible, and appropriate. While ethical and feasible properties directly correspond to the research ethics and experimental resources subsections, the appropriate property has been divided into the three elements of research rigour [85, 86]: reliability, replicability, and validity. Therefore, the following five subsections describe each experimental consideration.

4.1.1. Research ethics

Although ethical considerations in research have roots in medical research, they can be applied to any research involving human subjects. Therefore, studying VR-supported transitions also raises ethical concerns that have to be considered. These considerations are based on the four intertwined principles of ethics in research [379, 380]: beneficence, nonmaleficence, autonomy, and justice[12].

The beneficence principle describes the obligation to act for the participant's benefit, such as protecting their rights, preventing harm, and rescuing them from danger [379, 380]. Therefore, this principle suggests that a researcher has to protect the rights related to the anonymity and privacy of the participants. This includes anonymising the names of participants and any other personal details that might lead to participants' identities [381]. Furthermore, in order to prevent physical harm while using VR, it is suggested that the physical space be free from objects on which the user can step as well as from walls into which participants can collide. Another prevention of harm is maintaining hygiene (e.g., disinfecting the equipment and providing hygienic masks) in cases when multiple participants use the same equipment. Next, as the use of VR might result in cybersickness [382], another prevention of harm includes an examination of the potential causes. For example, this issue is emphasised in specific applications where participants have the perception of moving but actually stand still (e.g., flying simulators). Therefore, researchers should carefully examine the VR applications and navigation techniques provided to participants [383]. Another contributing factor to cybersickness might be the lower-quality equipment that tracks fewer degrees of freedom [384] or has higher latency between action and perception cycles [385]. As the occurrence of cybersickness depends on the individual [386], it is necessary to have a procedure for stopping the VR experience (i.e., rescuing from danger), such as closing eyes and calling a researcher [387]. Finally, another suggestion to prevent harm is to limit the length of the VR experience [388]. Researchers usually suggest that sessions be a maximum of 40 minutes long [389], which might also contribute to other ethical considerations, such as derealisation [388].

Closely related to beneficence, the nonmaleficence principle suggests not inflicting harm on others, such as incapacitating or causing pain or suffering [379, 380]. In this context, VR's potential to simulate high-immersion environments can lead to depersonalisation and

[12] These concerns are based on several declarations and regulations, such as the Declaration of Geneva [510], the Declaration of Helsinki [511], the Belmont Report [512], and the General Data Protection Regulation [381].

derealisation [388, 390]. Hence, it is necessary to compare the VR experience with a real-world scenario and execute only those experiments that are ethical to conduct in the physical environment [390]. For example, simulating the well-known trolley problem [391], in which participants are given an ethical dilemma, might be harmful to participants [388].

As another ethical principle, autonomy proposes that researchers provide participants with all the relevant information about the research and allow them to withdraw from the experiment at any point [379, 380]. This principle also suggests that the researcher should not deceive participants or observe them without their consent. To ensure that participants have time to understand all the provided information, researchers have to obtain consent at least one day before the experiment begins [85]. Informed consent has to contain all relevant information about the research project, i.e., what participants will be asked to do, what kind of data will be collected, who will process the data, and how the data will be processed, analysed and used. Furthermore, in informed consent, participants are usually given the explicit notion that their participation is voluntary and that they can withdraw at any time. Withdrawal in VR can be accomplished by participants verbally requesting to stop and closing their eyes [388, 390]. Based on this request, a researcher would immediately stop the VR experience and finish the session.

Finally, the justice principle suggests that researchers provide equity among participants [379, 380]. This principle suggests that researchers distribute benefits, risks, costs, and resources [379, 380] among the participants. For example, if the experiment compares VR technology with traditional one, participants that were assigned to the VR group might benefit from using this emerging technology. In that case, participants that were assigned to the traditional technology group might be given an opportunity to use VR technology after the experiment, thus giving them similar benefits from participating.

As the principles are context-dependent, it is difficult to decide if an experimental study meets them. It is thus necessary to anticipate the threats to ethical issues by conducting pilot studies (Subsection 4.5). Moreover, it is also necessary to get approval for conducting an experiment from the ethics committee at the responsible institution. For this approval, the documents describing the experiment (e.g., setup, procedure, measurement methods) have to be prepared and submitted to the ethics committee. As this approval might be a decisive factor that keeps the research from execution, it is necessary to consider the ethical aspects of the research from the beginning [85].

4.1.2. Experimental resources

Most experiments have to be conducted with limited human and technical resources [378, 392]. These constraints are important for the feasibility of experimental designs and should be accounted for while planning experiments. In this context, researchers have to consider the knowledge needed to conduct the experiments and plan the necessary education if needed (e.g., through the available knowledge resources or consulting with experts). Next, they have to consider the equipment necessary to execute the planned studies (e.g., VR equipment and software licences). Of course, researchers' expertise and working environment largely affect these constraints. For example, more experienced researchers might have to spend less time learning about transitions, VR technology, etc. Moreover, researchers working in an environment with all the necessary equipment may have to spend fewer resources on the apparatus needed to conduct an experiment. Furthermore, considering experimental resources also includes the researchers' and participants' efforts [393] while collecting the data. For instance, data collection using interviews would require more effort from the researcher than questionnaires [393].

4.1.3. Experiment reliability

Experimental reliability is the first element of research rigour [85, 86], describing the extent to which a measurement method provides consistent results. This consideration comprises three criteria: stability, inter-rater consistency, and internal reliability [85, 86].

Stability refers to the repeatability of the measure over time so that a measurement at multiple points provides consistent results [86]. For example, measuring the personality of agents using standardised tests is usually stable. The usual approach to measuring stability is thus a test-retest approach [394], where the same test is conducted twice with a lag in time [395], and the results between the two tests are compared.

A similar test, but with at least two different raters, is conducted when the measurement is largely based on subjective judgements (e.g., protocol analysis). In this case, the second criterion of reliability [85, 86]—inter-rater consistency—has to be calculated by having two or more raters of the same measurement [394]. Suppose the researcher would like to measure the frequency of understanding actions in the transitions. In that case, it is necessary that two or more raters measure this variable on the same sample. Then, the agreement between the two or more raters is compared.

The third reliability criterion relates to multiple items that measure one factor. These measures have to be assessed for internal reliability – the extent to which multiple items point to the same factor [394]. To test internal reliability, researchers typically utilise a split-half approach [396]. This method involves randomly dividing multiple items into two groups. The factor is then measured using each group separately, and an association between these two groups is calculated. For example, measuring design ability using a 14-item questionnaire [351] would require dividing the items randomly into two groups. The design ability would then be measured for each group, and the results would be compared across respondents. Given the large number of participants needed to conduct this test, it is usually advisable to use measures that have already been tested and accepted regarding internal reliability (e.g., already developed questionnaires).

4.1.4. Experiment replicability

Reliability in measurements is closely related to another aspect of experimental considerations – replicability. Replicability describes the extent to which the conducted study can be repeated [86], thus requiring the reliability aspect to be satisfied. More specifically, the experiment cannot be replicated if measures are not stable over time or among people. Furthermore, scholars often point out transparency by clearly reporting the experimental study [397]. Therefore, experimental variables, measures, a sample, setup, and procedure have to be comprehensively described. In order to accomplish that, researchers might provide supplementary materials in addition to reporting the results of the study. These materials can include a detailed experimental setup and procedure, together with all the information that was given to participants. Additionally, anonymised raw data from the experiment might also be provided.

4.1.5. Experiment validity

Experimental validity is the third element of research rigour that concerns the integrity of the conclusions drawn from the research [398]. As conclusions cannot be drawn without experiment reliability, this element of research rigour is a prerequisite for experiment validity. Experiment validity comprises three criteria [86]: measurement (construct), internal, and external validity.

Measurement validity refers to the extent to which the measurement reflects the underlying factor. For example, many researchers measure the transition team’s performance by counting the identified issues. This measure is valid when all designs in the sample have the same issues to be identified, as it can describe how efficient agents were. However, the validity of this measure becomes questionable when having a sample with designs of different quality, as the number of identified issues can then relate to the design quality rather than to transition team performance. There are several complementary approaches to addressing measurement validity [85, 86, 398]. One approach is face validation, which is based on asking experts to assess the comprehension (i.e., includes different aspects relevant to the factor) and purity (i.e., does not measure something else) of the measure [399]. Another approach is concurrent validation, which compares the measure to other validated measures of the same concept on the same sample [399]. Moreover, predictive validation includes the comparison of the measure's predictions with an outcome that occurs in the future [399]. Finally, convergent validation involves comparing and combining measures of the same concept based on different data collection approaches (e.g., interviews), sometimes also referred to as triangulation [400]. Usually, the combination of various approaches can be utilised (see Subsection 7.3.2 for a discussion about the measurement validity of the conducted studies).

Internal validity is another criterion of experiment validity that describes the trustworthiness of the identified causal relationships [401]. Although experimental designs can provide a clear direction of causality, suggesting high internal validity [84], there are still obstacles that influence internal validity (e.g., the effect of participants' backgrounds, the learning effect during transitions, and the placebo effect). Most of them can be addressed by having experimental and control groups with randomly assigned participants [86]. In random assignment to conditions, experimental activities before intervention (e.g., a tutorial with the experimental procedure and used technology) have the same effect on both experimental and control groups. Similarly, the maturation effect of participants (e.g., learning during the experiment) should also affect both groups in a similar manner. Next, the participants' background effects (e.g., different education and culture) unrelated to the manipulation of the independent variable are also eliminated with randomisation [86]. Furthermore, having a fixed experimental design with a fixed number of participants can overcome other threats related to internal validity, such as problems with changing instruments for measuring variables and dropping participants from the study [85]. Next, keeping the participants unaware of the research aim might also help internal validity, as they will not know how to change their behaviour to match the research hypothesis. Finally, equalising the treatments so that the control group receives a similar experimental effect can neutralise the placebo effect [402].

External validity refers to generalising the study findings beyond the experimental context [401]. Threats to this aspect are not addressed by experimental design per se, but they have to be individually examined for each experiment [85, 86]. Firstly, it is necessary to consider the generalisation to other participants, such as those of different gender, ethnicity, social class, personality, experience, etc. Another generalisation to be considered relates to the experimental setting. More specifically, researchers have to examine to what extent the results are applicable outside the experimental setting, also known as ecological validity [403]. This applicability is closely related to the influence of experimental settings on participants, usually described as the Hawthorne effect [404]. This effect suggests that participants change their behaviour when they know they are being observed. Similarly, participants might also change their behaviour if they were involved in pre-testing – a procedure that is rarely utilised in the real world, thus affecting the external validity of the findings. Finally, it is also necessary to examine if the results are applicable to various environments. This is especially emphasised in the transitions, as they largely depend on the technology and design methods that change rather quickly [405].

The experimental considerations provide constraints for each step while planning and executing experiments. The next subsection thus shows how they are taken into account while considering theoretical aspects of experimental design.

4.2. Theoretical considerations

Theoretical considerations are related especially to the transition perspective, ensuring that experimental findings are relevant [79–81]. More specifically, these considerations involve determining the research objective (Subsection 4.2.1) and transition factors (Subsection 4.2.2). These two considerations are the main ones connecting an experimental study to transition-related theories and are usually the first step in planning research [85, 86, 378].

4.2.1. Research objective

Consideration of the research objective usually includes the formulation of research questions and/or hypotheses. Research questions are the main questions that an experiment seeks to answer. They help to define the project, set boundaries, give direction, and define success criteria for the experiment [85]. If it is possible to assume the relationship between the factors under observation, it is advisable to develop hypotheses [375]. Hypotheses should specify the direction of the relationship and be clear and testable [398]. Depending on the epistemological stance, various approaches could be utilised to devise research questions and/or hypotheses. For example, researchers might employ a theory-driven approach in which the research questions and/or hypotheses relate to developing a new theory or testing existing theories [129]. A similar approach could be gap-spotting from the literature review, such as identifying competing explanations of a phenomenon or an overlooked area [406]. For example, the contradictory findings related to the effect of VR on transition outcomes (see Section 2.4.3) suggest that this relationship should be further explored. Researchers could utilise a pragmatic paradigm and choose the objective that is of interest to them [85].

In the design discipline, the criteria for good research questions and/or hypotheses are usually divided into conceptual and methods criteria [378]. Conceptual criteria require that the research questions and/or hypotheses are relevant, interesting, and novel [378]. More specifically, research questions and/or hypotheses should focus on answering currently underdeveloped areas of transitions and adding knowledge to current theoretical debates grounded in design research (e.g., rational problem-solving and reflective practice) [81, 378]. Furthermore, methods criteria require that the research questions and/or hypotheses are appropriate, feasible and ethical [378]. From the appropriateness criterion, it is necessary to ensure that research questions and/or hypotheses can be accomplished with the methods that can answer/verify them. Next, the feasibility of the experiment criterion includes the consideration of the resources available to the research, such as the volume of the data needed to reach the objective. Finally, following the research ethics consideration, the research questions and/or hypotheses have to be formulated so that they are ethically feasible. The developed research questions and/or hypotheses set the main factors to be investigated in the context of transitions.

4.2.2. Transition factors

Theoretical considerations also include a selection of the factors that will be analysed in the study. Transition factors are abstract descriptions of the transition characteristics that are relevant to the research objective [407]. Depending on the research objective, these factors can be unidimensional (depicting one transition characteristic) or multi-dimensional (consisting of multiple transition characteristics). The main factor in this thesis is a transition environment, which is multi-dimensional as it consists of editability, simulated sensory cues, simulated social cues, etc. In contrast, if research aims to understand the effect of the current design size on the transition execution, a design size would be a unidimensional factor (e.g., the largest dimension).

The developed theoretical models (see Chapter 3) can be used to choose factors for the experiment. For example, the micro-scale model can be used to investigate the interplay between states and actions. In this context, agents are the ones who execute actions. Therefore, their states (e.g., uncertainty and affect) might be related and predict the type of action that is executed (e.g., understanding, evaluation, and planning). In addition, the agents' states would transfer to the team level only if they participated in the action, suggesting that working mode (i.e., all-together or sub-team) might also explain variation in the executed action. These relationships are explored in Section 5.5. Furthermore, the team transition model can be used to investigate relationships, such as how inputs affect mediators and outcomes and how mediators affect outcomes. For instance, the environment factor might be chosen to test its effect on transition mediators (e.g., the teamwork aspect of how participants communicated) and outcomes (e.g., the number of identified issues). These relationships are explored in Sections 5.3, 5.4, 6.3, and 6.4. While these models propose only main (e.g., direct effect between environment and verbal communication) and mediating (e.g., indirect effect between environment and transition outcome) effects between the factors, each of the factors can also be investigated for the interaction (i.e., moderation) effect. In the latter case, a moderator factor affects the strength of the relationship between the two factors [398]. For example, a previous study found that VR might be more beneficial to agents with less experience in understanding the design than to agents with more experience [21]. In that case, the experience of participants affected the relationship between environment and design understanding, as the relationship was weaker for a high-experience group and stronger for a low-experience group. Studying various effects between factors can thus result in a better understanding of transitions and, consequently, better support for these important activities in PD.

4.3. Methodological considerations

Based on the transition experiment objective and study factors, researchers have to take methodological considerations into account. These considerations describe design-of-experiment (DoE) principles for conducting experiments, such as factor measurement (Subsection 4.3.1), sample definition (Subsection 4.3.2), experimental setting (Subsection 4.3.3), and data analysis (Subsection 4.3.4).

4.3.1. Factor measurement

To measure any of the transition factors, researchers need to operationalise them by defining which variables will be used to describe them [407]. Variables are measurable aspects of the factors that exhibit change across the unit of measurement [85, 398]. For example, design size is a factor that can be depicted with variables such as largest dimension, volume, etc. The largest dimension and volume can be measured, and they exhibit changes across design sizes. Another variable related to the design size might depict only *small* and *large* sizes. Therefore, each factor can have variables of different types, which can be classified into (Figure 4.2): dichotomous, categorical, ordinal, interval, and ratio [86]. Dichotomous variables have only two categories (e.g., gender). Categorical variables consist of categories that cannot be ordered by ranks (e.g., type of transition action: understanding, evaluation, planning). Ordinal variables can be ordered by ranks, such as technology expertise measured on a Likert scale. In interval and ratio variables, distances between the categories are the same across the range, with the ratio variable also having a value of zero aligned with a true zero. For example, the number of identified issues for measuring the design outcome is a ratio variable, as zero, in this case, means that there are no issues. Moreover, using Likert scales for measuring design ability might be considered an interval variable, as zero does not reflect that there is no ability. The selection of the variable type depends on the research objective and experimental considerations. If the objective is the identification of a new, previously unknown relationship, the suggestion is to choose a variable with two levels that differ from each other (e.g., low and high) [408].

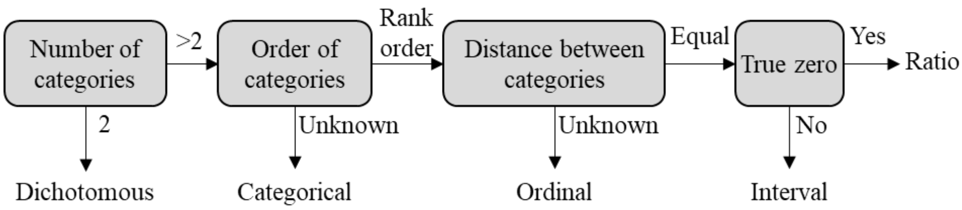

Figure 4.2 Types of variables

The chosen variables, coupled with the experimental considerations (e.g., the researcher's and participants' effort [393]), largely determine the data collection approach. There are various approaches to collecting the data required in the study, such as interviews, observation, tests (e.g., the mental rotations test [409]), and questionnaires [85]. These approaches differ in their epistemological stance, affecting various assumptions of the study, such as subjectiveness level [410]. Subjectivity is supported by the interpretivism paradigm, suggesting that it is necessary to understand the factors better [410]. This paradigm acknowledges the effect of subjectivity on data collection and aims to understand its influence on the results [85, 86]. Subjectivity in data collection is related to both the researcher and the participants [411]. The researcher's subjectiveness usually results from the qualitative data collection approaches (e.g., interview, observation), while the participant's subjectiveness results from the obtrusive measurement methods (e.g., questionnaire). Furthermore, objectivity is supported by the positivism paradigm, thus contrasting interpretivism. Researchers following this paradigm mainly utilise data collection approaches that are more objective and unobtrusive, such as tests (e.g., the mental rotation test [409] to measure participants' spatial ability), biometric measurements, and keystroke tracking. Given its technology-oriented nature, VR-supported transitions can utilise unobtrusive approaches like eye-tracking, viewpoint tracking, and movement behavioural data. Moreover, recording the viewpoints and behaviours of participants is less obtrusive than in the real world, as the device that records them is not visible to participants. Both subjective and objective data have advantages and disadvantages, and the data collection approach used in the experiment depends on experimental and theoretical considerations. For example, if the experiment aims at examining the satisfaction of members with the execution of transitions (a subjective factor), subjective data could be collected. Contrarily, if the experiment aims at examining the efficiency of the transition, objective data might be better suited.

Based on experimental, theoretical, and methodological considerations, several metrics to assess the effect of VR on transitions have been proposed (Table 4.1). The metrics depict characteristics of mediator and outcome factors from the team transition model. Based on the effect of VR on the transition teams, metrics related to mediators are developed for both teamwork and taskwork team behaviour. Both aspects are usually measured using a protocol analysis approach, which consists of dividing the transition activity into segments that can be utterances or actions. After the segmentation, each segment (unit of analysis) is labelled with a code. For example, for the amount of verbal communication, segments would be verbal utterances, while the code would be a team member that produced these utterances. As another example, for the frequency of actions metric, codes would be the actions described in the team transition process model: understanding, evaluation, and planning. In addition to its effect on mediators, VR might also affect outcomes. These outcomes can be measured based on the output that the transition team produces (e.g., based on the report) or on the observations of teams executing the transition. Using the output that the transition team produces as a measure of outcome is common in studies of the effect of VR (see Section 2.4.3), as the corresponding inputs are usually zero (e.g., the number of identified issues). Analysing outputs (e.g., reports or meeting minutes) usually requires less effort from the researchers than observing the teams during transitions. Moreover, they can provide insights into the efficiency, effectiveness, and goal-related efficiency indicators of transitions based on the relative changes in the design space. However, the value of these indicators largely depends on the inputs, as it might be easier to identify the issues in a low-quality design than in a high-quality design. Therefore, the execution of transitions might also be measured by observing the teams and identifying the number of design product aspects they discuss during the activity [412]. Finally, besides measuring efficiency, effectiveness, and goal-related efficiency, a thematic coding analysis of the outputs or protocol analysis of the transition activity can be used to provide insights into the context of the issues (e.g., problem space, solution space).

Table 4.1 Examples of metrics to measure the effect of VR on transitions

Metric name	Metric description	Related factor
Duration of verbal communication	The overall time spent talking during the transition.	Teamwork team behaviour
Count of verbal communication sequences	The number of verbal communication turns after different team members.	Teamwork team behaviour
Count of working all-together	The number of actions executed by all team members.	Teamwork team behaviour
Count of transition actions	The number of actions related to understanding, evaluation or planning.	Taskwork team behaviour
Number of feedback items	The number of suggestions that the transition team reported during the transition.	Design space outcome
Proportion of goal-related feedback items	The ratio between the goal-related and overall number of feedback items.	Design space outcome
Number of identified goal-related feedback items	The number of goal-related suggestions that the transition team reported.	Design space outcome
Number of discussed issues	The number of issues that the transition team discussed.	Design space outcome
Proportion of discussed goal-related issues	The ratio of the number of goal-related issues and the overall number of issues that the transition team discussed.	Design space outcome
Number of discussed goal-related issues	The number of issues that the transition team discussed.	Design space outcome
Proportion of problem space context of feedback items	The ratio between the number of problem space feedback items and the overall number of feedback items.	Design space outcome
Proportion of extrinsic context of feedback items	The ratio between the number of extrinsic (i.e., the relation between the design solution and the context) and the overall number of feedback items.	Design space outcome

As mentioned in the experimental considerations (see Subsection 4.1.3), the reliability of the chosen measurement has to be assessed in terms of stability, inter-rater reliability, and internal consistency [86]. Assessment of stability and inter-rater reliability depends on the type of variable (Table 4.2). In the case of ordinal, interval, or ratio variables, a correlation coefficient between the two observations can be calculated. For ordinal values (i.e., only the order of values is known, not the distance between the two values), researchers can utilise either Kendall's τ or Spearman's ρ statistics. For interval and ratio variables (i.e., both the order of values and the extent between the values are known), researchers can utilise Pearson's r statistics. In the case of categorical scales, Cohen's kappa [413] measures consistency for two raters, while Fleiss' kappa [414] is applicable for more than two raters. Next, Krippendorff's alpha [415] is a reliability coefficient that accepts any number of raters. Moreover, it is applicable to categorical, ordinal, and interval types of variables. Although these indices are commonly used, they have a large number of assumptions [416] that should be considered before using them.

Table 4.2 Common inter- and intra-rater reliability measures for different types of variables

Measure name	Variable type
Pearson's r	Interval
Kendall's τ	Ordinal
Spearman's ρ	Ordinal
Cohen's kappa	Categorical, Dichotomous
Fleiss' kappa	Categorical, Dichotomous
Krippendorff's alpha	Interval, Ordinal, Categorical, Dichotomous

Testing internal consistency is only necessary when there are multiple metrics that measure the same factor (common in questionnaires). This aspect is often measured using Cronbach's alpha [417], which calculates averages of all possible split-half results. However, this measure provides a limited understanding of internal consistency [418], and other measures have been suggested [419], such as omega [420].

4.3.2. Sample definition

Based on experimental and theoretical considerations, it is necessary to define the target population and sample. This is achieved through five steps [421]: 1) defining the required characteristics of the sample; 2) defining a scope; 3) defining the generalisation and abstraction approach; 4) defining the sample schema; and 5) determining the sample size.

Defining the required characteristics of the sample depends on theoretical considerations, i.e., the intended contribution to knowledge [129, 422]. More specifically, if the study intends to develop a theory, the aim of this step would be to identify a particularly interesting sample [421]. For instance, theory related to environments in transition aims to describe how these activities are affected (i.e., mediators and outcomes) by different environments. In that case, a particularly interesting sample would need to have a specific level of factors relevant to this context, such as design expertise (e.g., participants have a basic design education), age (e.g., more than 18 years old), etc. However, as variation in these factors (e.g., high expertise or low expertise, young or old) might also affect the transition execution, it is suggested that researchers neutralise their effect and utilise methods that can provide data capturing the transition context (i.e., qualitative). That way, researchers have a controlled sample with a lot of data, enabling them to induce a theory. Furthermore, if the intended contribution is related to testing a theory, it is necessary to have a statistically representative sample. For instance, if the aim is to test the theoretical predictions related to the effect of the environment on transitions, the sample should vary in other variables that might affect the transitions (e.g., design expertise). Therefore, a theory-testing experiment might provide an opportunity to understand the boundaries of the theory and support its future refinement [129]. The sample is thus defined by considering characteristics typical for the population that the theory describes [421–423].

Defining scope considers the generalisation of the findings from the sample to the population (generalisability) and generalisation to other settings (abstraction), such as location, time, and scale [421]. Based on the theoretical considerations, it is necessary to define which of the four generalisation approaches will be utilised [421]. The first approach is case-to-case transfer, in which generalisations (both generalisability and abstraction) from one case to another are based on making inferences from a detailed description of each specific case. This detailed description enables an understanding of its applicability to other contexts. The second approach is an internal statistical generalisation, which requires a mature theoretical definition of variables within a sample (e.g., design expertise in the case of transitions) to make generalisations from individuals to the sample. Thirdly, analytical generalisation uses theory (e.g., the developed theoretical models) to generalise from the specific case to other contexts. Fourthly, external statistical generalisations require a mature theoretical definition of variables relevant to the population/sample relationship to make generalisations from a sample to the population. As the theoretical definition of transitions is still not mature, the experiments should utilise a case-to-case or analytical generalisation. The utilisation of these generalisation approaches is even more emphasised if the studies examine the effect of VR on transitions, as theoretical definitions related to the environment (e.g., VR) are also scarce.

Depending on the generalisation approach and whether the probability of the selection is the same for everyone in the population, two sampling schemas are considered [85, 421]: probability and non-probability. The probability schema uses statistical rules to select the sample from the known population, such as random, systematic, or stratified. Using this schema allows statistical generalisation from sample to population [421], thus being more related to testing a theory [129]. The non-probability schema includes individuals based on various criteria. This approach is commonly divided into purposive (based on research purpose), quota (based on a stratified quota), and convenient (based on availability) sampling. For instance, in theory-building related to the effect of environments on transitions, purposive sampling might be utilised. This sampling would include the utilisation of participants that have characteristics of the population that the theory aims to explain (e.g., users with VR and design experience). In addition, this group would have to be homogeneous for all the factors that might influence this relationship. For example, while a certain amount of VR and design experience would be required in transition experiments, the theory-building sample should be homogeneous (e.g., having a combination of expert and novice designers might introduce additional variation in the experiment).

In line with the sampling schema, the sample size has to be determined. In case-to-case and analytical generalisation approaches, the sample size is usually smaller than in statistical generalisation [421]. The smaller sample size enables an in-depth investigation that can provide a detailed description of each case. However, the sample size for an in-depth investigation should also be large enough to enable the convergence of the findings (i.e., further data would confirm already identified results) [424]. While the exact numbers would vary from case to case, the usual rule of thumb for this type of generalisation is a sample size between one and 20. More specifically, if the aim is to investigate the potential use cases of VR in design, case studies in the industry might provide convergence with only a few cases. In contrast, if the experiment aims for statistical generalisation, a sample size should meet statistical requirements [421], such as the effect size that the researcher wants to identify [425] and the confidence interval that the sample is equal to the population [426]. Altogether, the sample size should reflect the research objective and the generalisation approach.

4.3.3. Experimental setting

Defining an experimental setting consists of choosing a type of experiment, an experimental design, and participation in different conditions. To choose a type of experiment, researchers can utilise thought, computational, or physical ones [375]. Thought experiments are rarely employed in the design discipline as they lack empirical evidence, are difficult to replicate, and are prone to the researcher's bias [427]. Computational experiments are becoming more popular as they can be used to get quick feedback on various hypotheses. In the transition context, agent-based models of designers are currently being developed [428–430] and used to compare various transition characteristics, such as virtual and face-to-face collaboration [431] and design space expansion [432]. Physical experiments are the most common type in the design discipline [375], often divided into laboratory and field experiments. Laboratory experiments are conducted in artificial settings to maximise control over a wide range of influencing factors [85]. However, laboratory experiments are often criticised due to their ecological validity, which prevents generalisation [433]. Field experiments are conducted in real-world environments and often involve observing practitioners in their working environment. As such, they can provide information on the behaviour and activities of practitioners in the natural environment [434]. However, these studies are more likely to lack internal validity as they do not have random assignment into groups. Moreover, they also lack control over the other variables, thus reducing the validity of the findings. Therefore, both types of physical experiments have advantages and disadvantages, and experimental considerations should be used to determine the more suitable type. For example, as studying the effect of VR on transitions includes the use of equipment that might not be available to the company in a natural setting, researchers should consider either a laboratory setting or investing in easily transportable equipment.

Furthermore, experiments can be formed around different experimental designs, commonly divided into true, quasi-experimental, and non-experimental [85, 86]. The highest internal validity has a true experiment [85] – a design in which participants are randomly allocated to two or more groups. These two or more groups can be tested for differences only after the treatment or both before and after the treatment. For instance, analysing the effect of VR on the final shared understanding could be measured by assessing the shared understanding after the treatment. However, the effect of VR on shared understanding might not be identified in cases of high initial shared understanding. Due to the high initial shared understanding, the differences in shared understanding between the treatment and control groups after the experiment might not be significant. Contrarily, using the pre-experiment and post-experiment measures of shared understanding would enable a comparison of the relative change in this characteristic. Measuring the relative change neutralises the effect of the initial level of shared understanding. Therefore, the analysis of VR's effect on shared understanding can be assessed regardless of its initial level. Another experimental design is the quasi-experiment [84, 375], which is employed when the random allocation to groups might not be possible. Although the internal validity of this experimental design is weaker than a true experiment, it can provide additional evidence for testing a hypothesis [375]. For example, researchers could observe teams throughout several transitions in which they use a traditional approach and then introduce VR technology to them. Researchers can again observe teams throughout several transitions but with the new technology. This approach can help identify the effect of VR technology on a particular group. Moreover, dividing the participants according to pre-test values into low- and high-score groups (e.g., low design expertise and high design expertise) could also provide valid insights. For instance, quasi-experimental findings could distinguish differences between the groups if the outcomes are different between the treatment (e.g., increasing trend) and control (e.g., without change, decreasing trend) groups while being consistent within each condition. The third approach is non-experimental – a design that does not involve the treatment of variables but focuses on studying the relationship between the variables within a specific context and observing the team behaviour of a particular group [85]. This experimental design is often used for descriptive purposes when the interest is in understanding or explaining a phenomenon. Focusing on descriptive purposes can provide insights to build a theory or develop testable hypotheses. For example, this approach can be used to understand how participants utilise VR technology during transitions (e.g., teamwork and taskwork behaviour) in order to develop hypotheses for future testing.

Participation in different conditions considers the allocation of study subjects to experimental groups, divided into between-subjects[13] and within-subjects[14]. The between-subjects approach is to have participants allocated to only one experimental group. This approach often consists of control and treatment groups, and the goal is to compare them [85, 86]. For instance, studying the effect of VR on transition might include a control group with technology that has a low immersion level (e.g., a desktop monitor), and the allocation of participants would be either to the VR or desktop monitor group. Furthermore, within-subjects is an approach where the same participant is tested under two or more treatments. However, this approach can only be utilised when order effects are unlikely, and the independent variable enables the allocation of participants into both groups (e.g., it is difficult to test the same person as a novice and an expert). Furthermore, if a known variable is associated with the dependent variable, it is possible to design an experiment with matched pairs [85, 398]. This approach is also treated as within-subjects, as the first member of the pair is randomly allocated to one treatment while the

[13] Also known as independent samples or between-groups
[14] Also known as repeated measures or within-groups

second member is allocated to another treatment. For example, participants in VR might benefit differently depending on their spatial ability [322, 435, 436], making it a potential variable to create matched pairs. Various experimental settings exist, and the chosen one largely determines the data analysis approach.

4.3.4. Data analysis

Considering data analysis early in the experiment planning process helps researchers decide on factor measures, an adequate sample, and the experimental setting [85, 408]. Data analysis largely depends on the chosen type of variable [86, 437]. On the one hand, describing the results of dichotomous and categorical variables consists of describing the frequencies and proportions. On the other hand, continuous (ordinal and interval) variables can be described using central tendency (mean, median) and variation (standard deviation, interquartile range).

Tests for analysing the differences between the treatment and control groups also depend on the chosen independent and dependent variables (see Table 4.3 for common parametric tests to analyse between-subjects experiments). More specifically, tests differ regarding the type (dichotomous/categorical, ordinal/interval, or combination) of variables, the number of variables, and the number of categories (only in the case of categorical variables).

For determining an association between categorical variables, a Chi-square test of independence can be utilised [86, 437]. This analysis can be used when observing taskwork of transition actions. More specifically, researchers might compare the number of understanding, evaluation, and planning actions between transitions in VR and low-immersion environments. These action counts can be compared using the Chi-square test.

Logistic regression (binomial or multinomial) is used to associate a categorical dependent variable with more than one categorical variable, with a combination of categorical and continuous variables, or with ordinal and interval variable(s) [86, 437]. For example, a multinomial logistic regression might be used to associate the taskwork of transition actions (i.e., a categorical dependent variable with understanding, evaluation, and planning categories) with the working mode (e.g., a categorical variable with the all-together and sub-team categories) or to the agents' states (i.e., uncertainty and affect interval variables).

Furthermore, a common experiment type with one or more categorical independent variables and one ordinal or interval dependent variable utilises a *t*-test, one-way analysis of variance (ANOVA), or factorial (e.g., two-way) ANOVA [86, 437]. Next, a one-way ANCOVA can be used in cases where one ordinal/interval type of dependent variable has to be associated with a combination of categorical and continuous variables. Finally, having independent variables of ordinal or interval type that have to be associated with ordinal/interval types of dependent variables involves the use of linear regression. In the case of more than one ordinal/interval dependent variable, multivariate equivalents can be used, such as multivariate analysis of variance (MANOVA), multivariate analysis of covariance (MANCOVA), and multivariate linear regression [86, 437].

Table 4.3 Common parametric tests for between-subjects experimental design; based on [86, 437]

<table>
<tr><th rowspan="2">Type of variable</th><th></th><th colspan="2">Dichotomous and categorical</th><th colspan="2">Ordinal and interval</th></tr>
<tr><th>DV / IV</th><th>1 variable with 2 categories</th><th>1 variable with >2 categories</th><th>1 variable</th><th>>1 variable</th></tr>
<tr><td rowspan="3">Dichotomous and categorical</td><td>1 variable with 2 categories</td><td colspan="2" rowspan="2">Chi-square</td><td>Independent samples t-test</td><td>Multiple t-tests with correction</td></tr>
<tr><td>1 variable with >2 categories</td><td>One-way ANOVA</td><td>One-way MANOVA</td></tr>
<tr><td>>1 variable with ≥2 categories</td><td rowspan="4">Binomial logistic regression</td><td rowspan="4">Multinomial logistic regression</td><td>Factorial ANOVA</td><td>Factorial MANOVA</td></tr>
<tr><td>Combination</td><td>≥1 categorical and ≥1 continuous variable</td><td>One-way ANCOVA</td><td>One-way MANCOVA</td></tr>
<tr><td rowspan="2">Ordinal and interval</td><td>1 variable</td><td rowspan="2">Linear regression</td><td rowspan="2">Multivariate linear regression</td></tr>
<tr><td>>1 variable</td></tr>
</table>

IV – independent variable, DV – dependent variable

Depending on the test, an additional analysis might be conducted (i.e., post hoc analysis) to understand the results better. For example, if the differences from a one-way ANOVA are significant, multiple *t*-tests can be employed to compare each combination of groups (also known as pairwise comparisons). These pairwise comparisons should usually be adjusted (e.g., Bonferroni correction) to prevent the occurrence of the Type 1 error (rejecting a null hypothesis that is true, i.e., a false positive). However, this adjustment may not be necessary in special cases of exploratory studies or when the necessity of avoiding Type 2 errors is highlighted [438]. Another example of post hoc analysis includes the calculation of the effect size – the magnitude of the difference between the two variables [439].

Besides the variable type, it is also necessary to consider the extent to which tests are applicable to the collected results. Firstly, almost all the tests depend on the relationship between experimental conditions (within-subjects and between-subjects). Therefore, it is necessary to utilise the correct alternatives depending on participation in different experimental conditions (Table 4.4). Secondly, the type of the utilised *t*-test might depend on the hypotheses (e.g., one-tailed, two-tailed). For example, a directional hypothesis related to the effect of VR on spatial perception might be derived from the notion that VR influences a higher number of sensory cues (i.e., VR improves spatial perception). Therefore, comparing VR and low-immersion environments in terms of spatial perception might utilise a one-tailed test. Thirdly, a common assumption of tests relates to the normality of the data, which can be tested (e.g., the Shapiro-Wilk test) prior to the analysis. If the data are not normally distributed, it is possible to conduct data transformations (e.g., Box-Cox) and test the data again for normality. The second approach could be to use non-parametric alternatives (see Table 4.4) that do not rely on the normality assumption. Fourthly, most of the tests (e.g., *t*-test, ANOVA) also assume that the variances between two or more groups are homogeneous. This assumption can also be tested (e.g., the Levene test) before the data analysis. Regression analysis often assumes that the predictor variables are not linearly dependent, which can be tested using, e.g., the variance inflation factor (VIF). Despite the test used, it is necessary to check the assumptions of any chosen test before interpreting the findings. Therefore, data analysis should be well-planned for each specific experiment.

Table 4.4 Statistical tests depending on the experimental design and normality assumption; based on [86, 437]

Between-subjects		Within-subjects (matched pairs)	
Parametric	Non-parametric	Parametric	Non-parametric
Independent t-test	Mann-Whitney U test (Wilcoxon rank-sum test)	Paired t-test	Wilcoxon signed-rank test
One-way ANOVA	Kruskal-Wallis Test	Repeated measures ANOVA	Friedman test
Factorial unrelated ANOVA	Use rank-transformations or generalised linear models	Factorial related ANOVA	Use rank-transformations or generalised linear models

4.4. Implementational considerations

Implementational considerations include aspects relevant to the execution of VR-supported transitions. They consist of the experimental setup (Subsection 4.4.1) and the experimental procedure (Subsection 4.4.2).

4.4.1. Experimental setup[15]

To conduct physical experiments, researchers have to develop an experimental setup. The setup consists of hardware (e.g., physical space, computer hardware) and software used to conduct transitions and measure relevant variables.

Teams conducting transitions using VR equipment can be co-located (i.e., in the same room) and distributed (see Figure 4.3). In co-located teams, participants can interact with virtual and physical environments (see Figure 4.3). The virtual environment usually includes interaction with the information content related to design space (e.g., 3D models), while the physical environment might be used to interact with other participants. This interaction in the co-located physical environment might occur in shared or separate physical environments. In the shared physical environment, all participants occupy the same area in a room. This approach is commonly used with projector-based VR (e.g., CAVE), where all participants view the same screens. However, this layout tracks only one participant for whom the current viewpoint is rendered [325]. This suggests that, even if other participants are standing still, their viewpoint changes as the active participant moves. Sharing physical space is not advisable for teams that utilise several HMDs (i.e., VR technology that is mounted on the head of each participant), as participants cannot see each other and could disturb each other during the experiment. Hence, in the case of co-located work, it is suggested that participants utilise separate physical environments, with each team member having their own VR technology. This setup is also preferred for distributed teams. Despite the layout (co-located or distributed), each VR working area should have compatible hardware and software. A stable internet connection is also often required, as the servers that manage the collaborative virtual sessions are usually accessed via the Internet.

To set up the hardware equipment, researchers have to prepare the VR technology and the physical environment. VR technology usually consists of a device that provides a VR experience (e.g., HMD, CAVE), interaction devices (e.g., hand-held controllers) and a working station. Depending on the communication between team members, headphones with a microphone might also be required. Furthermore, to set up the software equipment, researchers would have to utilise applications that connect the VR equipment to the working station,

[15] An experimental setup has been considered only for cases where more than one team member utilises the stereoscopic view that VR technologies afford. This is true in the case of CAVE devices and multiple HMDs. Due to limitations explained in Subsection 2.5.3, the case where VR is used only by one team member while others are viewing the content in a low-immersion environment (e.g., a desktop monitor) has not been considered.

visualise and provide interaction with the information content (e.g., design solution, design problem, avatars, etc.), and enable communication within a team. As the application functionalities might significantly affect the team outcomes [34], researchers should provide similar functionalities for both treatment and control groups.

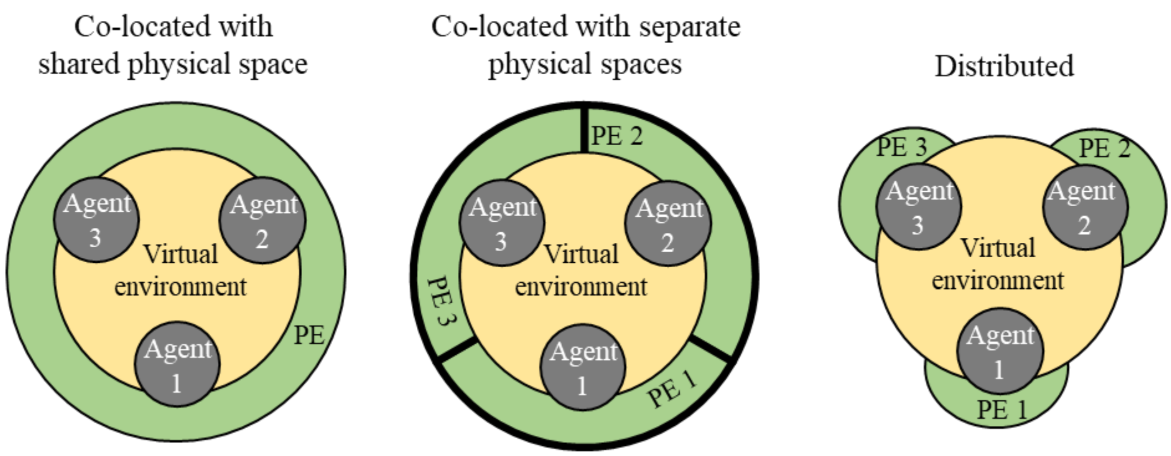

Figure 4.3 Different experimental setup layouts; PE – Physical environment

Besides the hardware and software necessary to conduct transitions, researchers might utilise other equipment that supports experiment execution, such as hardware and software for data management. Data managed during the experiment can be categorised into local and shared data (Figure 4.4). The local data are initially stored on the working station of the participant in the experiment (e.g., video recordings, screenshots taken). The shared data might be available on different servers, depending on the software utilised in the experiment (e.g., online questionnaire data, recorded communication through a conference tool). All the data should be uploaded to the server. The server upload might be accomplished automatically by choosing cloud-based software, with the main data server being in the cloud. However, some equipment still does not enable cloud work, so the collected data can be transferred to the data server using alternative approaches. One alternative could be to manually transfer files to a data server from each computer (e.g., via the Internet or USB). Another approach could be to automatically synchronise the data with a shared local network.

Finally, given that more than one experiment would usually be conducted on the same equipment, it is suggested to have a temporary folder on both the data server and local machines. This space is used to store the data from the experiment that is currently being run. After each experiment, the data from the temporary folder across several stations are saved onto the data server. This approach might prevent the automatic override and mixing of data from several experiments.

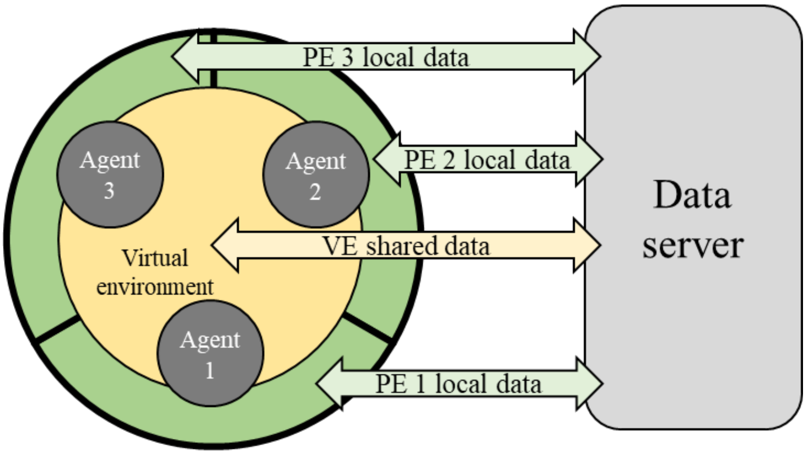

Figure 4.4 Data communication between the experimental setup elements and data server; PE – physical environment, VE – virtual environment

4.4.2. Experimental procedure

While developing the procedure for studying VR-supported transitions, several aspects should be taken into account, such as internal validity, research ethics, and factor measurements. Developing a procedure with high internal validity is based on the two suggestions for the experimental setting [408]: control and randomisation. More specifically, researchers should control team transition model factors (see Section 3.2) unrelated to the research objective. For example, as VR is still an emerging technology, it is possible that participants will have a diverse experience with this technology. Therefore, researchers usually plan the proper technology training before the experiment. As participants usually have to learn only a few functionalities, this training is usually about 30 minutes long [21, 389]. In addition, it is possible to provide participants with an information package (e.g., a description of the transition goal and a description of the design problem) before the experiment [77, 132, 133] so that participants have more time to prepare for the transition. To ensure that participants understood the provided information, researchers can check if participants familiarised themselves with the provided information using a short informal interview, specialised tests, or by going again through the information package.

Control of the variables may lead to limited generalisation. For instance, while transition experiments with the controlled design problem and solution can be executed, these would result in a limited generalisation to other design contexts. Therefore, researchers usually execute experiments with design products that can vary in several aspects, such as the complexity or quality of design solutions [23, 440]. In this case, the allocation of designs to the treatment should be randomised to neutralise these potentially confounding variables (i.e., design solution quality and complexity). The random allocation of participants is also necessary in the case of a between-subjects experiment. If the experiment is based on repeated measures, it is necessary to randomise the order in which the study treatments would occur.

Furthermore, the experimental procedure should follow ethical guidelines (see Subsection 4.1.1) related to anonymisation, session duration, and total experiment duration. Anonymisation requires that the data is captured without the participants' identities. Next, the session duration is limited to 40 minutes [389], as longer VR experiences might cause derealisation and cybersickness [382, 388]. Moreover, it is also necessary to consider the total experiment duration, especially its effect on participants' fatigue and experimental results. More specifically, if the procedure is too long, it is necessary to ensure that participants have breaks and treats (e.g., snacks, sweets, and drinks). The maximum experiment duration without a break highly depends on the experimental tasks and mental fatigue's effect on the results. The duration of transitions in a real environment might also be considered to address concerns related to ecological validity. For the micro-scale analysis, researchers in design usually investigate transitions from intervals of five minutes to 3.5 hours [441]. Therefore, the decision on breaks is highly contextual, and their timing should be established during the piloting.

The experimental procedure should also be developed by considering the data collection, such as connecting the data of the same participants and synchronising the various data sources at the same timestamp. Connecting the data from the same participants is based on the notion that multiple sources can be used throughout the experiment to collect the data. Therefore, it is necessary to ensure that multiple data sources can be connected by having identifiers in each source. This can be accomplished by giving participants aliases they can use throughout the experiment. Participants would write their aliases while filling out questionnaires or saving documents. In addition, a researcher might write the aliases on other recording data (e.g., interviews and video recordings). While participants could also use their names instead of aliases, ethical consideration suggests that data be connected anonymously.

In addition to connecting multiple data sources, it is necessary to enable their synchronisation across the experimental procedure, as multiple recordings might be used for the analysis (e.g., one video per participant). This synchronisation is especially salient for time-sensitive data that is recorded at each physical place (e.g., video recordings). In this case, it is necessary to have identifiers that enable data synchronisation (Figure 4.5). For example, researchers can share a screen with a timer for approximate synchronisation. However, for more precise synchronisation, other procedures should be utilised, such as the visual and audio recording of a clap. The clap procedure requires incoming sounds to be recorded for each participant. However, recording incoming sound on each participant's recording might increase the speaker diarisation process [442] – a common segmentation of communication in design [171, 353, 443, 444]. Therefore, researchers should record both incoming and outgoing audio during the synchronisation procedure (i.e., a clap) and continue recording only the outgoing sound. Given the many steps that are necessary to undertake, it is advisable to have a master recording that combines everything in one file.

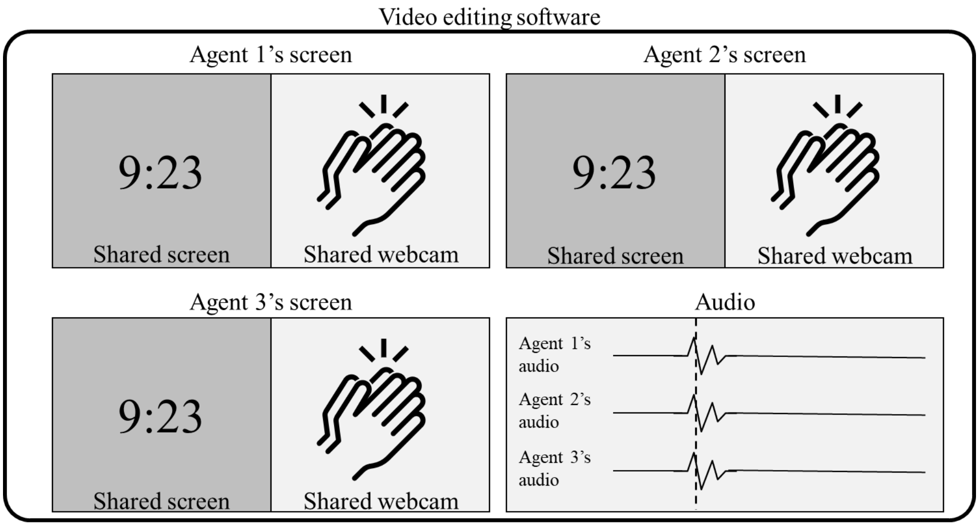

Figure 4.5 Synchronisation procedure with researcher sharing screen and clapping on webcam

In order to control the execution, a researcher can monitor the experiment (e.g., support with the VR technology setup, ensure that data are collected) in four different ways (Figure 4.6): without support, only virtual support, only physical support, and both physical and virtual support. Firstly, a researcher might prepare instructions to be used by participants during the experiment. This kind of control ensures that all the participants have the same information to work with, thus reducing the possibility that variations in procedure would influence the results. However, this approach does not allow researchers to help participants throughout the experiment or respond to unforeseen issues, thus raising concerns related to research ethics and experimental validity. For example, researchers might be unable to help participants stop the procedure in the case of cybersickness. Secondly, a researcher can provide participants only virtual support by entering the shared virtual environment. In that case, a researcher guides the participants through the experimental procedure and supports them through virtual interaction. Its flexibility to join or leave the transition environment might help with issues related to the Hawthorne effect [404], as participants might forget that they are in the experiment after the researcher leaves the virtual environment. Thirdly, a researcher can also support participants physically, which includes a researcher being co-located with participants to help them adjust the equipment and solve any problems they encounter. Physical support can also help with various data collection procedures, making it easier to start recording or change the recording settings. Finally, a researcher might also provide participants with a combination of virtual and physical support, thus utilising the advantages of both approaches. Hence, although experiments might be conducted without the researcher's physical presence, it is advisable to have at least one researcher who can access all participants.

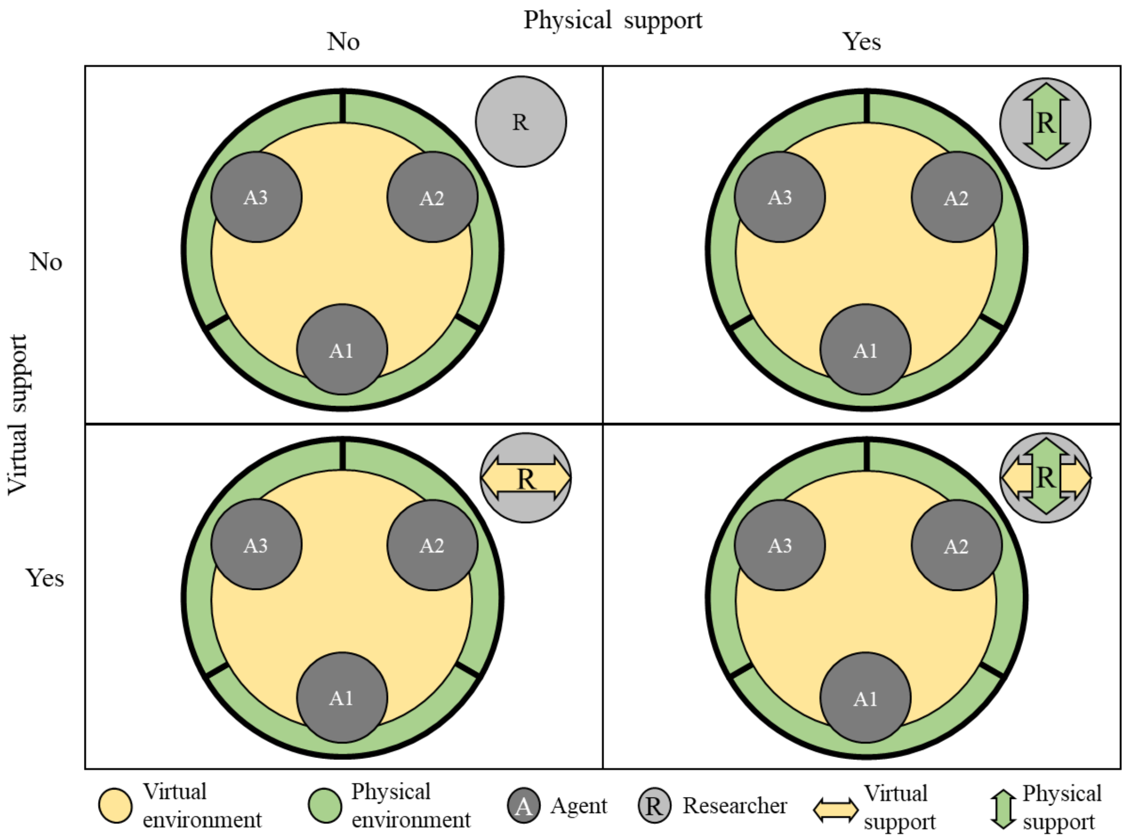

Figure 4.6 Researcher's support approaches for studying distributed teams

For more comprehensive physical support during the execution of the experiment, more than one researcher might be present (Figure 4.7). These researchers should be aware of the procedural steps and the experiment objective, thus providing physical support to each participant and helping with the measurement procedure. Furthermore, to ensure that various researchers work synchronously, it is advisable to provide another communication channel (e.g., instant messaging) available only to the researchers. In addition, one researcher might also join the virtual environment to ensure that the transition team follows the procedure.

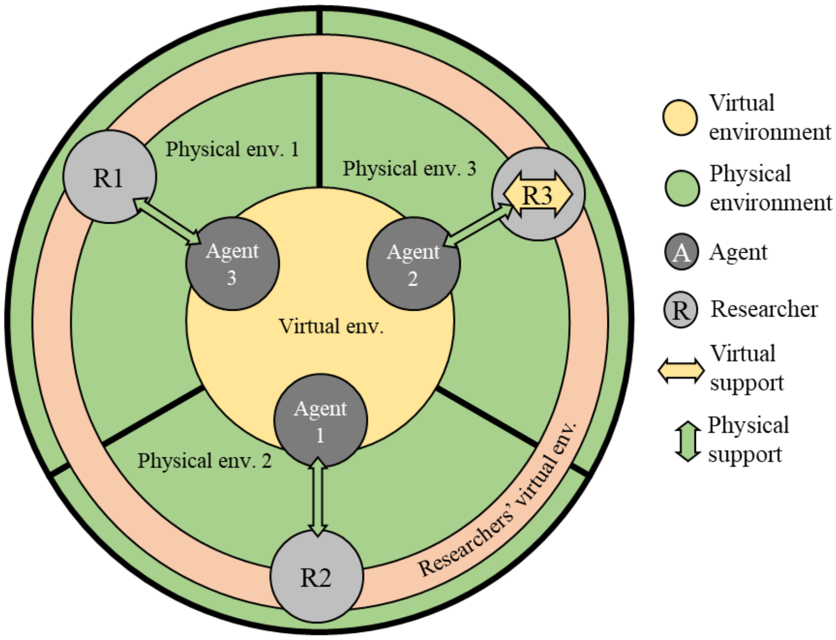

Figure 4.7 Researcher's support approaches for studying distributed teams

4.5. Piloting

Piloting a study is analogous to prototyping in design. Its goal is to fine-tune all the aspects of experimental planning [445]. More specifically, pilot studies help assess the experimental procedure's feasibility, estimate time and budget resources to conduct the study, assess the adequacy of data collection approaches and measures, and clear the research questions by getting preliminary data from the experiments and assessing ethical considerations [85, 445, 446]. Given the various goals, a pilot experiment might be identical to the final experiment (high fidelity) or be less detailed (low fidelity). Piloting can also be conducted on a part of the experiment (e.g., the data collection procedure) or on the whole experiment. Based on the piloting results, an experiment is adapted until it meets the experimental considerations, such as research ethics, experimental resources, experiment reliability, experiment replicability, and experiment validity.

4.6. Chapter conclusion

A developed experimental framework enables researchers to systematically plan and execute experiments related to transitions and thus contribute to their better understanding. The experimental framework has been used to collect evidence for validating the theoretical models through design review experiments.

5. FIRST DESIGN REVIEW EXPERIMENT

This chapter presents the experiment within a first case study in which ten three-member student teams designed everyday products as part of the CAD course. After the teams created a CAD model of the product, a design review (one type of transition) experiment was conducted. In the experiment, a transition team (i.e., two industry professionals and one designer) reviewed the design either in a low- (CAD) or high-immersion (VR) environment. This chapter initially describes the case and the design review experiment. Then, results are organised around three main analyses: the effect of immersion on verbal communication structure, the effect of immersion on the number of feedback items, and the interplay of uncertainty, affect, working mode, and transition actions.

The first study was conducted to test the main relationships of the proposed theoretical models and to check the usefulness of the experimental framework. The multiple aims of the empirical study require the use of various data sources, thus driving the decision to utilise an experiment within a case [376]. The case study is described in Section 5.1, while the experiment conducted as part of the case is described in Section 5.2. Finally, Section 5.3 provides the results of the experiment.

5.1. Case study description

The case study was conducted within a 15-week CAD course in the academic year 2020/21. The course consisted of 30 hours of lectures and 30 hours of exercises aimed at familiarising students with design in CAD software through active learning [447] and project design work. During exercises, an active learning approach was utilised for the first seven weeks, in which the instructor demonstrated the use of CAD features, which the students then repeated. A project design assignment was given to student design teams in the second week of the course. The project design assignment was to design a product based on the patent provided to the teams, i.e., their solution should have the same functionalities as those described in the patent. All the patents described products that use only human energy: foldable wheelchairs, weightlifting equipment, foldable baby strollers, foldable baby tricycles, and office chairs (Figure 5.1). These products were chosen as they are of a similar complexity level following

Hubka and Eder’s [440] classification and as they have a similar level of interaction with humans (e.g., all products use human energy, and all products enable humans to sit down).

In total, 30 third-year undergraduate mechanical engineering students (10 female and 20 male) participated in the case study. These students have been used to randomly compose ten three-member design teams. Each team was then randomly assigned one of the five products (each product was designed by two teams).

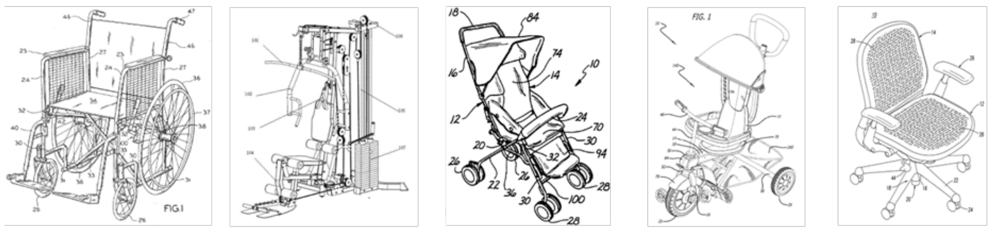

Figure 5.1 Tasks given to student design teams; Note: each design was assigned to two teams

The teams worked on the assignment in three phases (Figure 5.2), separated by transitions that served to evaluate the work and plan the changes to be incorporated until the next transition. In the first phase, teams had to describe the working principles and force distribution across the patent-based product. In the first transition, they received written feedback from the course instructor. Next, teams started with the second phase, where they had to address the comments provided by the instructor and deliver a CAD model together with basic calculations related to their design. In the second transition, their designs are reviewed as part of the experiment, where two industry professionals and one design team representative conducted a one-hour transition. The transition meeting was recorded, and the design teams received a feedback report consisting of issues related to their solution that they would need to resolve in the next phase. In addition to resolving issues, the last phase also included the creation of several technical drawings. At the end of the course, the instructor evaluated the final work of the student teams.

During the course, student design teams could work in a co-located or distributed manner. This flexible way of working was supported by cloud-based tools [448]. More specifically, each team was provided with a private Microsoft (MS) Teams[16] channel to enable distant communication (video conferencing, instant messaging), file sharing, and synchronous work

[16] *Microsoft Teams* – a cloud-based platform for team collaboration that integrates video conferencing, instant messaging, file storage and various software (e.g., document editing). Available at: https://teams.com/

on documents. In addition, each team also used collaborative CAD software (i.e., Onshape[17]) practised in the course. This browser-based CAD software enabled team members to work on an up-to-date version of the CAD model and to work synchronously, similar to the work in online documents. Furthermore, the use of Onshape enabled the automatic and unobtrusive collection of CAD action data throughout the course (Figure 5.2), which could be used to help in understanding team learning [449] and behaviour [450, 451].

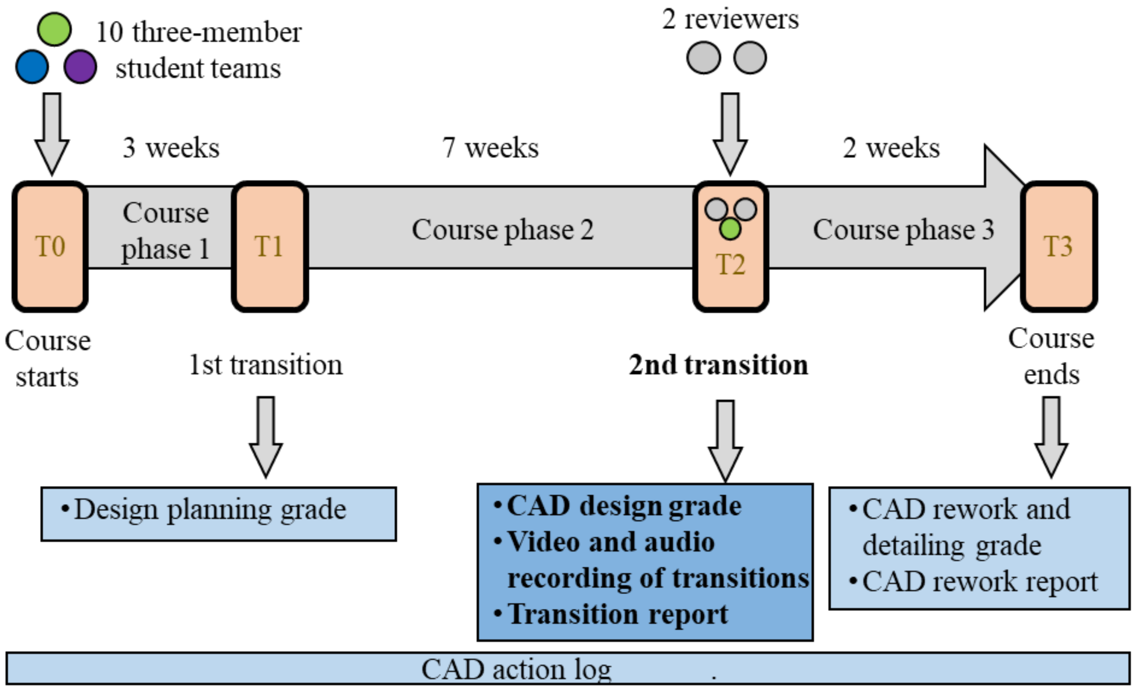

Figure 5.2 First case study overview

While various data have been collected throughout the course, the second transition was used to conduct a design review experiment. This transition was chosen as it aims at analysing the design in the form of 3D CAD models – a common representation used in this phase [135], thus providing an opportunity to utilise VR equipment that enables a natural perception of 3D models. This alignment between the VR affordances and 3D artefacts that describe the current state of the design drove the decision of many researchers to investigate the effect of VR on design activities. While the effect of VR might also help in other transitions, the visualisation in the early design phases is typically 2D [135]. Therefore, there might be a need to provide new visualisations in various design phases [452]. Nevertheless, as the second transition is an activity that already utilises the visualisations supported by VR technologies, it is used for the experiment.

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[17] *Onshape* – a cloud-native platform for product development that offers integrated product data management, full-featured CAD, and CAD action analytics in a single system. Available at: https://www.onshape.com/

5.2. Design review experiment

The experiment has been developed following the proposed framework. Firstly, experimental considerations have been taken into account: research ethics, experimental resources, experiment reliability, experiment replicability, and experiment validity. Research ethics were considered by limiting the duration of the VR experience (set to 30 minutes), providing participants with the cybersickness procedure (i.e., taking off the HMD equipment), and providing participants with informed consent. Consideration of the experimental resources was based on the type of available VR equipment in the laboratory, the course schedule, and the availability of participants. Of course, these resources were considered together with reliability, replicability, and validity. Reliability was ensured by using variables that have been reported to have high reliability (e.g., verbal communication duration, number of feedback items) or by reporting the reliability assessment (e.g., Cohen's Kappa for assessing the inter-rater reliability of taskwork of transition actions). Next, replicability was supported by a comprehensive description of the experiment. Finally, validity was supported by using already developed metrics (i.e., face validation of measurements), randomising the allocation of transition teams to conditions (i.e., internal validity), controlling for confounding variables such as design expertise (i.e., internal validity), and conducting the experiment as part of the course (e.g., external validity). In order to implement these experimental considerations, they are taken into account for other elements of the experimental framework: theoretical, methodological, and implementational.

Theoretical considerations included the description of the research objective and transition factors. The research objective was related to identifying the effect of VR on team mediators and outcomes to provide evidence for validating the team transition model. In addition, the objective was also related to identifying the relationship between characteristics describing team transition processes. Based on the definition of VR, the extent to which the environment presents content through natural sensorimotor contingencies can be used to describe this technology [267]. This aspect is covered by immersion [11, 258], operationalised as the number of simulated sensory cues [267]. Since the objective is the identification of a new, previously unknown relationship [408], immersion has been observed on two levels: low (traditional computer interface) and high (VR). These two categories are used as conditions for experimental treatment. o ensure that any changes in transition mediators and outcomes are caused by the immersion (internal validity), the experiment controlled most of the transition inputs (see Subsection 3.2.1). More specifically, it is necessary to set a constant value for factors that might introduce noise into the findings while maintaining variability in the factors over which the experiment aims to generalise. Firstly, as the main independent variable is related to the environment input (i.e., immersion level), the rest of the inputs (i.e., artefact factor and other characteristics of the environment factor) within this category were held constant. Furthermore, since the expertise might significantly affect the transitions [21, 318] and since relatively little is known about the exact effect of VR on transitions (see Subsection 2.5.3), the team inputs (composition and context) were also kept constant. Similarly, the other transition state inputs (PD task context, transition task context, organisational context, and culture) were also held constant within the experiment.

Following the methodological considerations, the effect of different designs has been neutralised by their random allocation to the experimental condition (low-immersion or high-immersion) and the order in which they were reviewed. Moreover, as there were two designs of each product type, one design of each type was randomly assigned to the low-immersion condition and another to the high-immersion condition (Figure 5.3), thus forming a matched pair experiment. This allocation procedure enabled the variation of designs to support the generalisation of findings across this characteristic while also neutralising the influence that different designs might have on the relationship between VR and transitions. The following subsections show how the task, sample, setup, and procedure were designed to adhere to the considerations in the experimental framework.

5.2.1. Experimental sample and task

Each design team executed one design review, making a total sample of ten transitions: five in the low-immersion environment and five in the high-immersion environment. The transition was conducted by a temporary transition team that included one internal (i.e., member of a design team) and two external (i.e., not part of a design team) members. This mixed team formation is common during transitions [68, 76]. An internal member of the transition team was a designer selected by the design team. Their role was to provide knowledge about the designs not covered by the artefacts [57], such as design rationale, materials, and strength analysis. The professional backgrounds of the ten internal members were very similar, with all of them being undergraduate 3rd-year mechanical engineering students enrolled at the same university. The two external members were working professionals (about one year of experience) with similar backgrounds: they were alumni of the same university and held a master’s degree in Mechanical Engineering (major: Engineering Design). Having experts in a laboratory setting provided the necessary control and helped overcome the issues related to the case where novices would evaluate the design [1]. The two external members remained constant throughout the whole experiment to reduce the effect of individual differences. For their participation in the experiment, each reviewer received financial compensation.

Figure 5.3 Designs reviewed in low- (up) and high-immersion (down) environments

This team design enabled the control of team inputs. More specifically, the same transition team size, hierarchy, and interdependence enabled the control of the team context inputs. In addition, the similar backgrounds of designers [453] and the same reviewers in each transition team enabled control of the team composition input. The potential small variations due to different design team representatives for each design were neutralised by randomly allocating transition teams to conditions. Furthermore, as all the reviews utilised the same external members, only one experiment was conducted per day.

In the experiment, a transition team had 60 minutes to review the design in one of the two environments. More specifically, the aim was to review the design regarding the design problem (i.e., context-specific requirements that the team developed), ergonomics, manufacturing, assembly, safety, maintenance, and functionality. These categories were derived from the common aspects of designs that have to be checked in this PD phase [77]. In order to assist the transition team, a checklist based on these transition goals has been provided to them during the experiment (Table 5.1). This checklist served as a guide for discussing the design during the transition.

While conducting the transition, the team members were instructed to capture their suggestions with screenshots that were later available to the transition team as a basis for writing the report (Figure 5.4). The report template was based on the prior recommendations regarding the form of this document [2]. The template consisted of the fields to add a checklist item code, the name of the participant that identified the issue, a description of the issue, a screenshot of the issue, and a description of how to solve the issue.

Table 5.1 Checklist provided to transition teams (translated from Croatian)

Category	Checklist items
1. Ergonomics	Have all human-design interactions been taken into account? Has the design been made in such a way that it corresponds to the capabilities and abilities of the user (dimensions, forces required from the user)? Does the construction look sturdy enough?
2. Safety	Have the factors that can affect the safety of the components been taken into account? Have factors that can affect user safety been taken into account? Have factors that can affect the safety of the environment been taken into account?
3. Assembly	Can the design be assembled according to the given principles? Can the assembly procedure of the design be simplified?
4. Manufacturing	Can the design be produced according to the given technology? Can the production of the design be simplified?
5. Maintenance	Can a simple inspection of the design be carried out during the product use phase? Can simple maintenance of the design be carried out?
6. General	Is the function of the product fulfilled? Are there additional functions that the product should have? Are the selected working principles adequate to achieve the desired function? Are the critical parts strong enough?
7. Requirements	Does the design meet the requirements prescribed by the team? Are there any requirements that the team misidentified? Are there any requirements that the team has not identified?

This setting of the CAD course, sample, and task ensured that factors related to other transition elements were controlled. Specifically, the same task description (i.e., goal, duration, working approach) for all the transitions ensured that the task context was held constant. Similarly, focusing on the second transition of the same course ensured control over a few PD task context aspects (e.g., PD phase). Finally, selecting one specific CAD course and having a similar background of participants ensured that these inputs were also controlled.

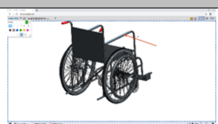
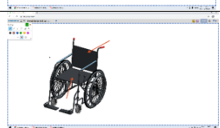
Date and time: 11.1.2021.16:00-18:00		**Design name:** Wheelchair (Onshape)	**Reviewers:** [Name removed], [Name removed]	**Designers:** [Name removed]
First TP session				
Checklist item	**Name**	**What is the issue?**	**Issue screenshot (optional)**	**How to solve the issue (if you have devised a solution)**
1a	[Name removed]	Shape, ergonomics, handle material		Ergonomic design, soft material (comfortable and adaptable)
1a	[Name removed]	Shape of the backrest, stiffness		The backrest is soft and adaptable to the body

Figure 5.4 Example of transition report (translated from Croatian)

5.2.2. Experimental setup

For the low-immersion condition, three physical rooms were equipped with a working station, a 22-inch monitor, headphones, a keyboard, a mouse, and an office chair. A working station and monitor with a mouse and keyboard is a common agent-computer interaction setup traditionally used by engineering designers. Although the use of a monitor already supports several depth cues (e.g., perspective and occultation), it is still considered low-immersion as it does not support binocular (e.g., stereopsis) or motion-based cues (e.g., motion parallax) [266]. Using a traditional computer has thus been a common comparison condition for VR in transition [22, 25, 28, 75], and it was used in this research as the equipment for the control group.

The low-immersion condition included Onshape (cloud-based CAD) for representing the design, Microsoft Teams for verbal communication, and Adobe Acrobat Reader[18] for representing the design problem (i.e., a list of requirements developed by the design team) and a transition goal (i.e., the checklist presented in Table 5.1). With Onshape, participants could interact with the same design representation synchronously and share their viewpoints (i.e., any participant could see what others were currently looking at). Moreover, participants could interact with the design representations using the standard CAD functionalities: using orbital navigation (i.e., pan, rotate, zoom), taking screenshots, measuring dimensions, using a digital pen to draw and highlight the issues, and making section cuts of the CAD model.

The high-immersion hardware consisted of a VR-ready working station and HMD VR equipment. HMD VR equipment tracks the user's head and position while rendering separate images to each eye of the user, thus supporting both binocular cues (e.g., stereopsis) and motion-based cues (e.g., motion parallax) [266]. Therefore, HMD equipment has been chosen for the high-immersion hardware, i.e., HTC VIVE[19] Pro and HTC VIVE. These HMDs are comparable as they have similar characteristics (see Table 5.2) and use identical controllers.

The software used for the high-immersion group included SteamVR[20] and Autodesk VRED Professional[21] for representing the design, Microsoft Teams for verbal communication and Adobe Acrobat Reader for representing the transition goal (i.e., the checklist) and design

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[18] Adobe Acrobat Reader – software to view Portable Document Format (PDF) files. Available at: https://www.adobe.com/acrobat/pdf-reader.html

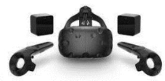
[19] *HTC VIVE* – a company brand that consists of VR-related equipment. Available at: https://www.vive.com/

[20] *SteamVR* – a platform that connects various VR hardware with VR applications. Available at: https://store.steampowered.com/app/250820/SteamVR/

[21] *Autodesk VRED Professional* – a professional 3D visualisation software that supports collaborative VR design review. Available at: https://www.autodesk.com/products/vred/

problem (i.e., requirements developed by the design team). The Autodesk VRED Professional enabled participants to utilise the following functionalities: taking screenshots, measuring dimensions, using a digital pen to draw and highlight issues, and making section cuts of the CAD model. The functionalities were thus similar to the ones in the low-immersion condition. Furthermore, the high-immersion condition enabled participants to walk around the virtual room (4x3 meters) and see each other's avatars and controllers. Transition sessions in low-immersion and high-immersion environments are shown in Figure 5.5.

Table 5.2 Comparison of the HMD devices used in the first experiment

HMD model	HTC VIVE Pro 	HTC VIVE 
Resolution	1440 x 1600 pixels per eye	1080 x 1200 pixels per eye
Field of view	Up to 110 degrees	Up to 110 degrees
Refresh rate	90 Hz	90 Hz
Controller input	Trackpad, Grip buttons, Dual-stage trigger, System button, Menu button	

This setup enabled the control of design space and environment factors that might impair internal validity of the experiment. More specifically, having artefacts (i.e., CAD model, transition checklist, list of requirements) with similar characteristics (e.g., fidelity, scale, dimensionality) in both conditions neutralised the potential effect of these factors. Moreover, paired designs enabled the control of design context aspects such as design size, complexity, and goal. In order to have higher external validity, design quality varied between teams. Nevertheless, the effect of this characteristic has been neutralised by randomising the designs to conditions. Furthermore, functionalities that participants could utilise in the high-immersion condition (e.g., screenshot, measure, section, marker) were similar to those in the low-immersion condition, eliminating the possible confounding variable of different toolsets [34]. Finally, the medium characteristics were also controlled, as none of the environments enabled editability or reversibility.

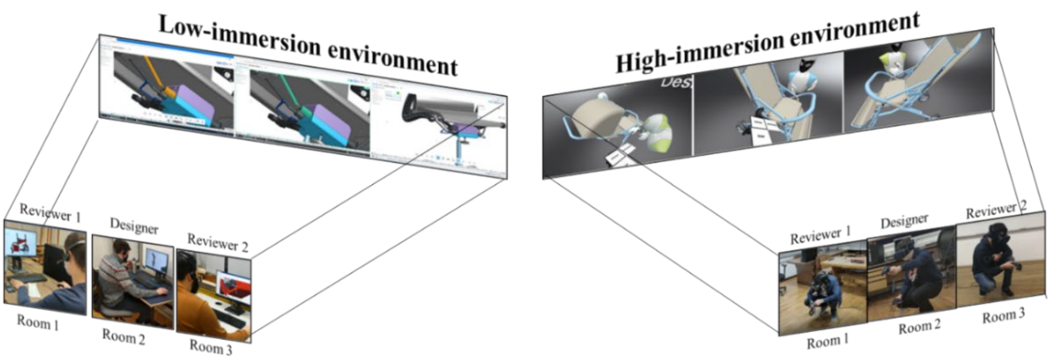


Figure 5.5 Transition in low-immersion (left) and high-immersion (right) conditions

5.2.3. Experimental procedure

The experimental procedure consisted of five steps (Figure 5.6): 1) Transition team preparation and introduction to the equipment; 2) First transition session; 3) Reporting the first transition session; 4) Second transition session; 5) Reporting the second transition session. The rationale for splitting the transition into two sessions was based on methodological considerations (i.e., duration of the VR experience) when designing experiments that use high-immersion equipment [389].

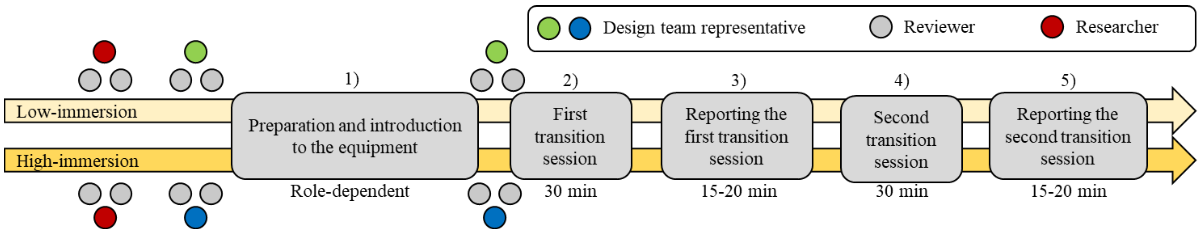


Figure 5.6 Experimental procedure

As reviewers were constant in all the sessions and as their role aligned with the goal of the transitions (to evaluate current and plan future work), the first step of the procedure lasted longer for the reviewers than for the designers. Reviewers were part of the two pilot experiments (one in each condition) lasting about one hour per condition that ensured a comprehensive introduction to the equipment and procedure. This duration is considered sufficient to tackle the issues related to lower experience with the equipment [21]. Reviewers also received an information package that included a list of requirements for the design under transition, a patent similar (but different) to the one given to students, a checklist to guide them during a transition (Table 5.1), a transition report template (Figure 5.4), and a set of *Design for X* guidelines (e.g., injection moulding, machining, sheet metal, welding, assembly, maintenance, safety, and ergonomics). On the day of the experiment, designers and reviewers briefly met in person before going into the dedicated physical working spaces. Each designer (i.e., design team representative) was then given a brief introduction (about 10 minutes) to the equipment for each functionality (screenshot, measure, marker, and section view). After this brief introduction, the transition team (a designer and two reviewers) met virtually and had about 20 minutes to prepare and repeat the functionalities that they had available.

Steps 2-5 comprise a transition activity that consists of two transition sessions (steps 2 and 4) and two reporting periods (steps 3 and 5). During the transition sessions (steps 2 and 4), transition teams had 30 minutes to review the design according to the provided transition checklist and a list of requirements. The transition team did not need to follow the checklist linearly but was given the option to work as they liked. They were also instructed to take one screenshot per identified issue that was made available to them in the reporting period. During each reporting period (steps 3 and 5), the transition team used a shared document on a desktop computer to provide written feedback for each screenshot they took. They were advised to agree on all the issues and remove all duplicates. Although members did not have time restrictions for reporting, this step usually lasted 15-20 minutes. The main data collected during the experiment were the participants' audio and the content displayed on each screen, recorded using the *OBS Studio*[22]. These data were synchronised using the suggestions from the experimental framework (i.e., a shared timer across the participants at the beginning and end of the experiment). Such collected data enabled follow-up observations that might provide insights into the mediator factors in the team transition model. Due to microphone problems in the second session of the baby stroller transition in the high-immersion condition, the second session of the baby stroller transition in both low- and high-immersion datasets was omitted from the further analysis.

The following sections present the results of the experiment. Sections 5.3 and 5.4 analyse the effect of immersion on verbal communication structure (a metric of team mediators) and the number of feedback items (a metric of the design space outcomes), respectively. These analyses provide evidence for evaluating specific relationships derived from the model of team transitions and for testing the second part of the hypothesis. Furthermore, Section 5.5 analyses the interplay between team mediators in two environments to provide evidence for evaluating the model of team transition processes and testing the first part of the hypothesis.

5.3. The effect of immersion on verbal communication structure[23]

The first analysis was based on the presumption that immersion would affect mediators due to the notion that high-immersion environments stimulate more sensory cues [15], transfer different social cues [16], and provide new ways of interacting [12] and navigating [13, 14] around the artefacts and environment compared to low-immersion ones. The effect of immersion on mediators is also supported by the social presence theory [454], which suggests that communication media affect the way other participants are perceived. Therefore, it was assumed that the effect of immersion would be pronounced on mediators.

[22] *OBS Studio* – free and open-source video recording software. Available at: https://obsproject.com/
[23] This section is based on the paper published and presented at the 17th International Design Conference [484].

As one aspect of teamwork, design researchers often study verbal communication - the most dominant mode of communication in design [8]. Such studies focus on the semantics or structure of verbal communication, using a unit of analysis that is either semantically determined or unrelated to the communication content. While both approaches were used to understand the design [68, 342], design researchers focused more on semantic analysis and rarely studied the communication structure. However, previous research has linked verbal communication structure to team creativity [455] and sub-team formation [342]. Moreover, the analysis of verbal communication structure with a content-independent unit of analysis yielded similar results to a content-dependent unit of analysis [443]. Since content-independent analysis is easier to execute than content-dependent analysis, verbal communication structure (i.e., type of content-independent analysis) can be used to identify related aspects of teamwork within transitions.

To provide early evidence for evaluating the team transition model and testing the second part of the hypothesis, the focus of this section is to analyse the effect of immersion (i.e., input) on verbal communication structure (i.e., mediator), as shown in Figure 5.7.

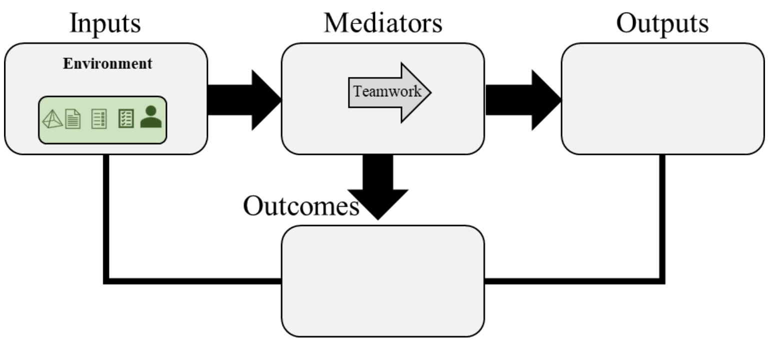


Figure 5.7 Factors considered when analysing the effect of immersion on verbal communication structure

5.3.1. Data analysis of the immersion effect on the verbal communication structure

The data for dependent variables that describe the communication structure were collected from the transition sessions using a protocol analysis approach [85]. Firstly, all the transitions were segmented into speaking and non-speaking portions. Then, each segment was coded with the transition team member who produced the utterance. Following similar approaches to segmenting verbal communication, pauses within the same speaker shorter than one second were ignored [8]. From the turn-taking model of conversation [456], two dependent variables commonly studied as part of verbal communication structure have been derived: the total duration of turns and the first-order turn sequences between team members. The total duration of turns is defined as the speaking time throughout the whole session. Furthermore, to identify the differences between the two conditions, the total speaking time of each member has been normalised to the team's overall speaking time. The first-order turn sequences between team members are defined as the total number of occurrences when a team member starts speaking after another member. They have also been normalised regarding the total number of first-order turn sequences in a transition session.

Before statistical testing for the group differences, the normality of the data was tested using the *Shapiro-Wilk* test, while the homogeneity of variances was tested using *Levene's* test. All the analysis has been conducted in *R*[24] using the *car* library.

5.3.2. Comparing the verbal communication structure

The speaking time of each session has been used to normalise the data and identify the ratio of the team members' total turns' duration. In all the sessions, except the wheelchair and weightlifting equipment in the low-immersion condition, the designer (D) had the highest ratio of total turns' duration, i.e., they spoke the most (Figure 5.8). Moreover, the highest ratio in both conditions was observed while reviewing foldable baby strollers (0.72 in low-immersion and 0.49 in high-immersion environments). The lowest ratio has been found for the first reviewer (R1), again while reviewing the foldable baby stroller (0.11 in low-immersion and 0.17 in high-immersion conditions).

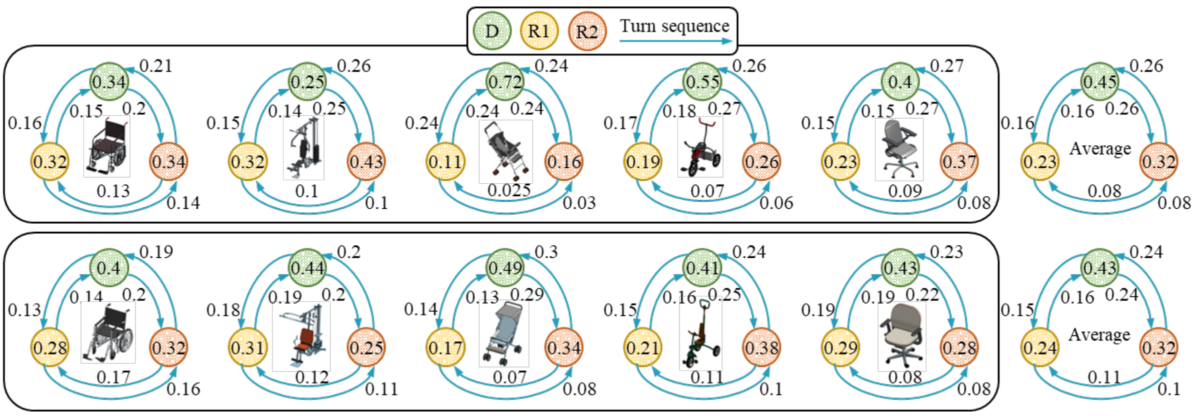


Figure 5.8 The ratio of total turns' duration (in circles) and first-order turn sequences (on arrows) for low-immersion (up) and high-immersion conditions (down); D - designer, R - reviewer

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[24] *R* – free software for statistics and graphics. Available at: https://www.r-project.org/

Furthermore, on average, the transition teams had 604 turn sequences between team members in the low-immersion condition and 580 in the high-immersion one. The number of turn sequences in each session has been used to calculate the ratio of the team members' first-order turn sequences. The highest ratio of the sequences was always between the designer (D) and the second reviewer (R2), i.e., R2→D and D→R2 sequences, ranging from 0.2 for a wheelchair in the high-immersion environment to 0.3 while reviewing a baby stroller also in the high-immersion environment. The lowest ratio of the sequences within sessions was usually amongst reviewers (the exception was a wheelchair in the high-immersion condition), with only 0.025 for the baby stroller in the low-immersion environment. Figure 5.8 presents the ratio of total turns' duration and the first-order turn sequences for each design.

While the designers verbally dominated the sessions in both environments, the comparison of the verbal communication proportions revealed that they had a slightly lower average ratio of turns in the high-immersion than in the low-immersion environment (Figure 5.9). However, the paired *t*-test did not reveal significant differences ($p = 0.81$), and the effect size was small (Cohen's $d = 0.12$). Comparison among reviewers suggests that, on average, R2 had a higher ratio of the total turns' duration than R1. Furthermore, both reviewers had a higher average ratio of the total turns' duration in the high-immersion condition. However, these differences were insignificant for the R1 ($p = 0.44$) and the R2 ($p = 0.96$). The effect sizes were also small, i.e., Cohen's d is 0.38 for R1 and 0.02 for R2. Finally, the total turns' duration ratio for each team member had lower variation in high-immersion compared to low-immersion conditions.

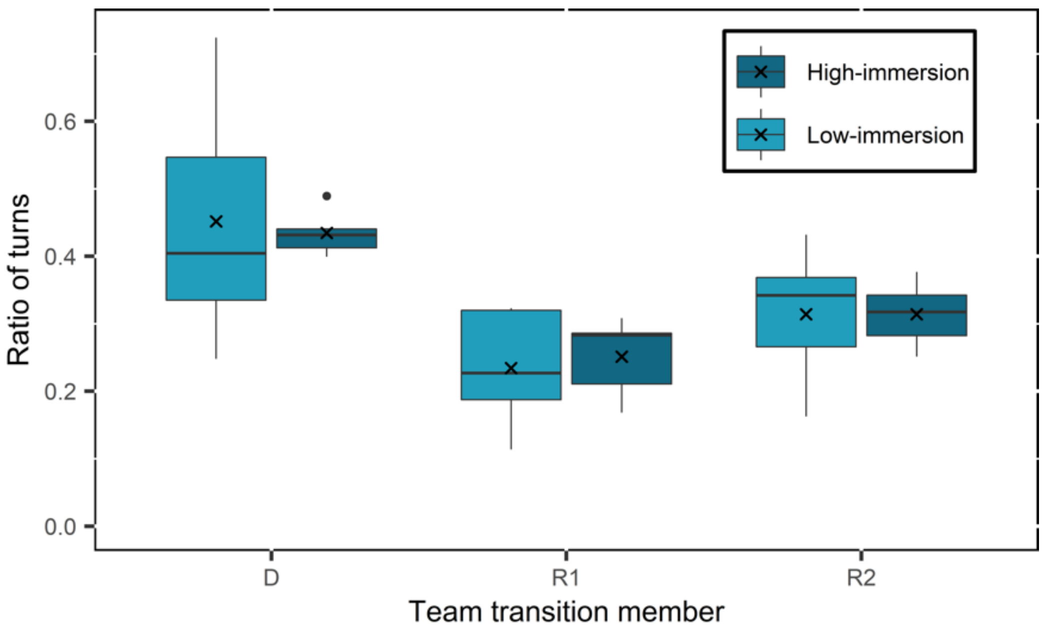

Figure 5.9 Comparing verbal communication in the two environments

The two most first-order turn sequences happened between two members with the highest verbal communication ratio (D and R2 – see Figure 5.10). This finding is true for both directions (D→R2 and R2→D). The lowest ratio of first-order turn sequences was between the two reviewers in both directions (R1→R2 and R2→R1). Furthermore, a comparison between the two conditions shows that the ratios of the first-order turn sequences with designers (D→R1, R1→D, D→R2, and R2→D) had higher means in the low-immersion than in the high-immersion environment. However, these differences were not significant, *p*(D→R1) = 0.63, *p*(R1→D) = 0.78), *p*(D→R2) = 0.47, and *p*(R2→D) = 0.46. In addition, the effect size was small for sequences between D and R1 (Cohen's *d* was 0.24 for D→R1 and 0.14 for R1→D), while the effect sizes of D and R2 sequence differences in the two environments were moderate, i.e., 0.35 for D→R2 and 0.36 for the R2→D type of sequence. Contrary to the turn sequences between a designer and a reviewer, a comparison of sequences amongst reviewers (R1→R2 and R2→R1) shows that they had a higher ratio of the first-order turn sequences in high-immersion than low-immersion conditions. Moreover, these differences were significant for both the R1→R2 sequence ($p = 0.075$) and the R2→R1 sequence ($p = 0.036$). Moreover, the effect sizes were large for both sequence types, i.e., Cohen's *d* is 1.07 for the R1→R2 sequence and 1.38 for the R2→R1 sequence. Finally, the results concerning the sequences with designers suggest that those sequences vary less in the low-immersion than in the high-immersion environment.

These results suggest that immersion affects verbal communication structure, supporting the relationship between the environment input and the teamwork mediator in the team transition model. More specifically, this analysis showed that immersion affects turn sequences that can describe how team members execute the actions (i.e., teamwork).

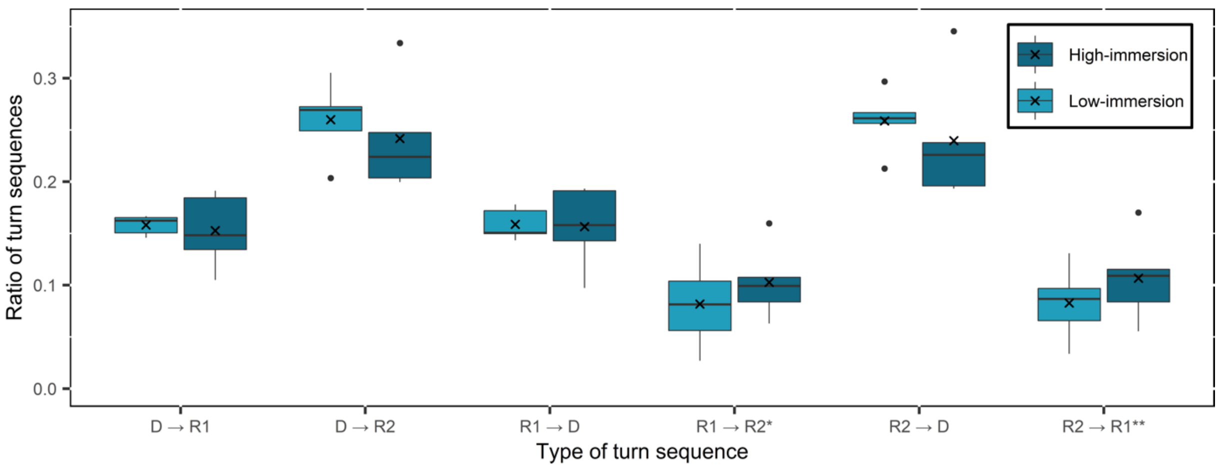

Figure 5.10 Comparing turn sequences in the two environments (* - $p < 0.1$; ** - $p < 0.05$)

5.4. The effect of immersion on the number of feedback items[25]

Based on the team transition model, immersion as input might also affect the outcomes. This relationship has been commonly studied, but there is not yet a consensus about its effect. Hence, to provide evidence for evaluating the team transition model and testing the second part of the hypothesis, the focus of this section is to analyse the effect of immersion (i.e., input) on the design space outcome, as shown in Figure 5.11. More specifically, change in design quality has been operationalised through the number of feedback items – a common indicator of transition performance [28, 32, 33, 75].

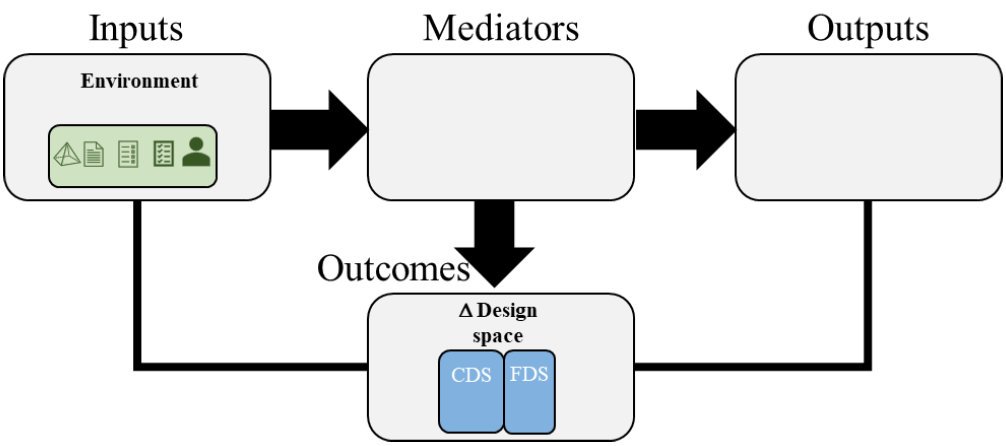

Figure 5.11 Factors considered when analysing the effect of immersion on the number of feedback items

5.4.1. Data analysis of the immersion effect on the number of feedback items

The data for dependent variables were derived from the transition reports. Since transition teams had to agree on the transition report items and there was no duplicate reporting of issues, each row in the transition report was counted as one issue. Based on this dataset, two variables have been used as proxies of the transition efficiency. The first variable is the number of feedback items. The second variable is the proportion of feedback items, described as a ratio between the number of feedback items for each design and the total number of feedback items identified in the corresponding condition. This issue ratio variable showed the issue distribution

[25] This section is based on the paper published and presented at the 32nd CIRP DESIGN Conference 2022 [489].

across the reviewed designs. Before statistical testing for the group differences, the data were tested for normality (the Shapiro-Wilk test) and homogeneity (Levene's test).

5.4.2. Comparing the number of feedback items

Overall, transition teams identified 171 issues in the low-immersion and 109 in the high-immersion environment. Since each condition consisted of five transitions, the average number of feedback items was 34 in the low-immersion and 22 in the high-immersion environment. The breakdown of feedback items for each transition shows a consistently higher number of feedback items in low-immersion than high-immersion environments (Figure 5.12). More specifically, the highest number of feedback items was 45 in the low-immersion and 32 in the high-immersion environment, both during the weightlifting equipment review. The average differences between the feedback items in the two environments were significant on the paired *t*-test (p=0.01). The effect size is also large, as Cohen's d is 2.41.

In the low-immersion environment, reviewers had the highest number of feedback items during the weightlifting equipment transition (22 issues identified by R1 and 23 issues by R2). In the high-immersion environment, reviewers again had the highest number of feedback items during the weightlifting equipment transition (18 issues identified by R1 and 14 issues by R2).

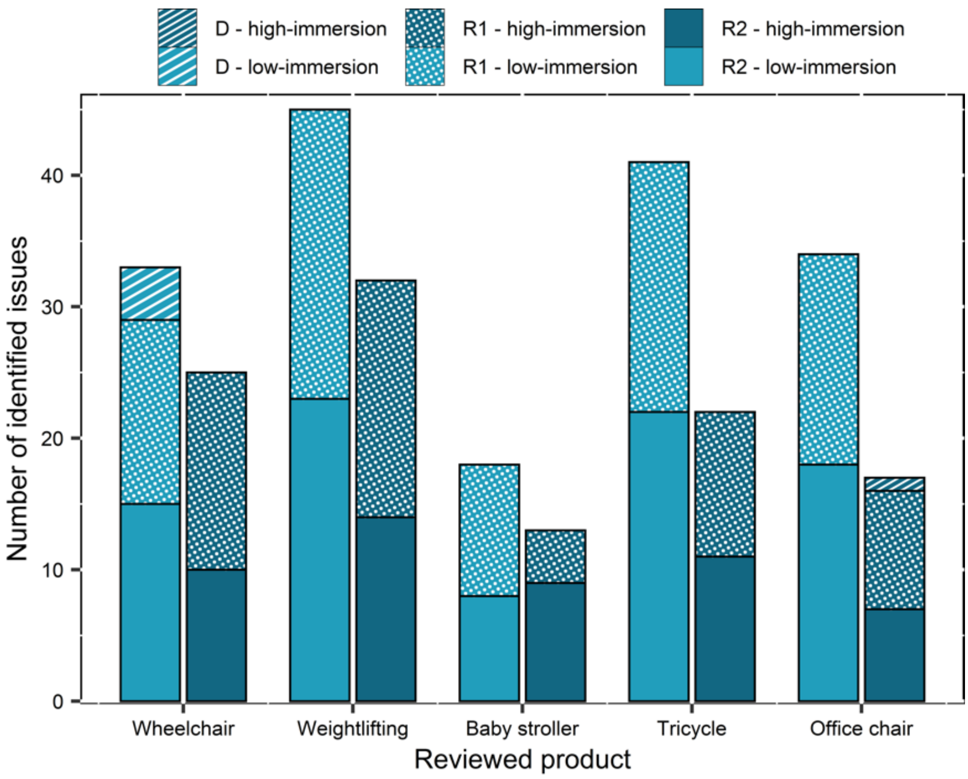

Figure 5.12 The number of feedback items for each environment; D – Designer, R – Reviewer; Note: Baby stroller transition includes only the first session

A detailed comparison of the reviewers suggests that they do not differ significantly in the number of feedback items (Figure 5.13). More specifically, the paired *t*-test shows that *p*-values are insignificant for both environments, i.e., 0.3 and 0.54 for comparing reviewers in low-immersion and high-immersion environments, respectively. However, the comparison of the environments suggests that both reviewers identified fewer issues in the high-immersion than in the low-immersion environment (Figure 5.13). Moreover, the paired *t*-test shows that these differences are significant for both reviewers, i.e., $p(R1) = 0.04$, $p(R2) = 0.04$. The effect sizes are large for both reviewers, with Cohen's *d* being 1.35 for R1 and 1.37 for R2.

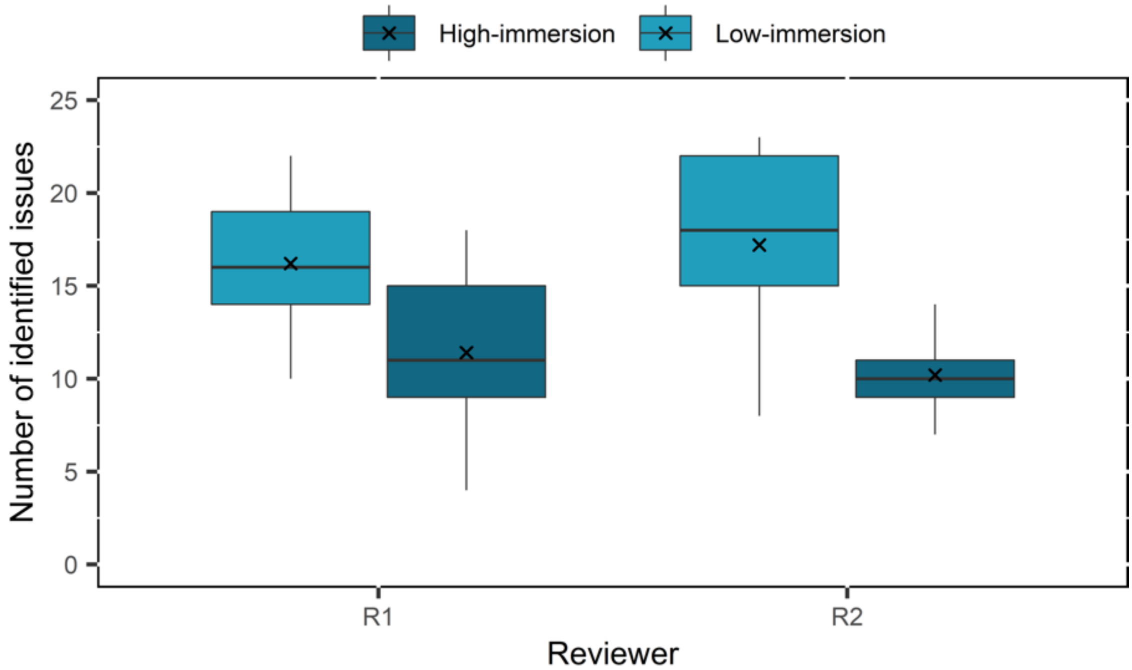

Figure 5.13 The number of feedback items for each reviewer

Since the transition teams consistently identified more issues in the low-immersion environment, normalising the number of feedback items indicated the efficiency of design reviews controlled for this difference. The results show a different distribution of issue ratios across designs for each of the two environments (Figure 5.14), suggesting that issue identification for some designs was better supported in the high-immersion than in the low-immersion environment and vice versa. On the one hand, the ratios of feedback items in the high-immersion environment were higher for the wheelchair, weightlifting equipment, and baby stroller. On the other hand, the ratios of feedback items for the tricycle and office chair were lower in the high-immersion than in the low-immersion environment. This difference might stem from the size of the designs, as weightlifting equipment was the largest in size, while the baby tricycle was the smallest. In addition, both the baby tricycle and the office chair had main mechanisms that were not visible from the outside, while mechanisms in the wheelchair, weightlifting equipment, and baby stroller were all visible. However, future work is needed to better delineate this difference. Nevertheless, the results show that immersion affects transition outcomes, supporting the relationship predicted by the team transition model. More specifically, while immersion was in this sample negatively associated with the design outcome efficiency (i.e., the number of feedback items), the effect of the environment might depend on the design being reviewed.

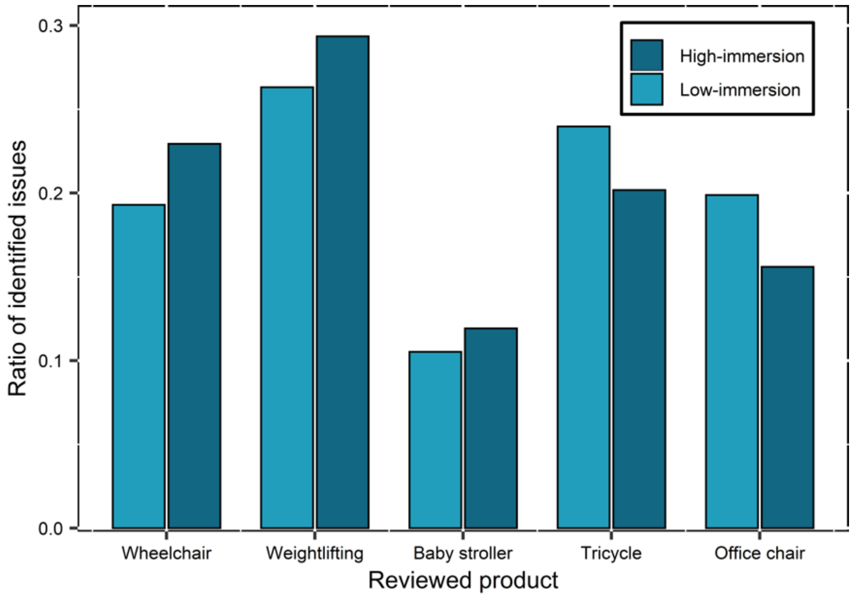

Figure 5.14 The ratio of feedback items in low-immersion and high-immersion environments; Note: Baby stroller transition includes only the first session

5.5. Interplay of uncertainty, affect, working mode, and transition actions in different environments

The third analysis was utilised to evaluate the model of team transition processes. More specifically, as the agents were the ones who executed the actions, their state (i.e., uncertainty and affect) and working mode was assumed to be related to the taskwork of transition actions (i.e., understanding, evaluation, and planning). Therefore, this analysis provides more insights into the relationships between mediator factors. Moreover, due to the already-emphasised immersion effect on the transition mediators, it was assumed that this interplay of factors would differ in low-immersion and high-immersion environments. To provide evidence for evaluating the model of team transition processes and testing the first part of the hypothesis, the focus of this section is to test the effect of emergent characteristics (i.e., uncertainty and affect) and teamwork (i.e., working mode) on taskwork of transition actions for the whole dataset and for each environment separately (low-immersion and high-immersion), as shown in Figure 5.15.

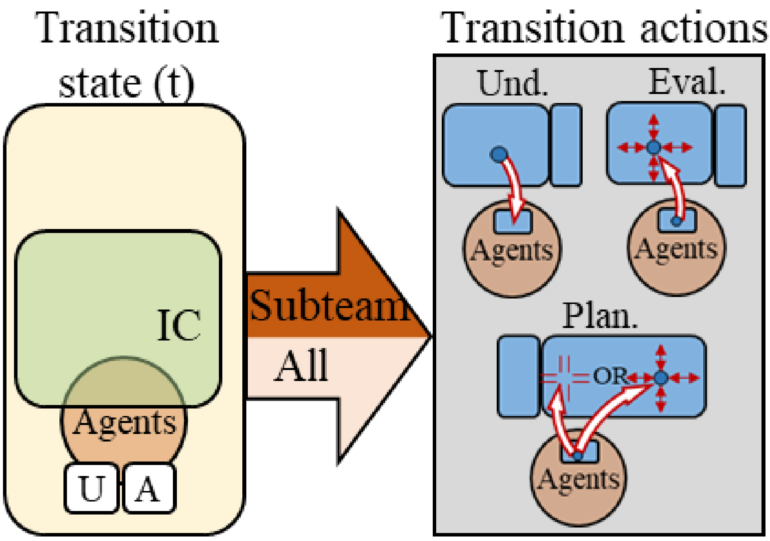

Figure 5.15 Factors considered when analysing the effect of immersion, uncertainty, affect, and working mode on the transition actions

5.5.1. Data analysis

Testing the model is based on the protocol analysis approach [85]. Firstly, the data were segmented using transition actions as a basic unit of analysis. Secondly, each segment was analysed for transition action type, uncertainty, affect, and working mode.

5.5.1.1 Protocol analysis

The data were segmented using a transition action unit of analysis. Following the model of team transition processes (see Section 3.1), each segment could have more than one member executing an action. That way, a transition action segment usually combines a proposal for a transition action and its uptake [73]. Proposals could be utterances or questions, while uptakes could be grounding words (e.g., *uh-huh, yes*) or minimal answers to a question (e.g., *yes, no, I don't know*).

Transition action coding was based on the model of team transition processes and included three types of actions: understanding, evaluation, and planning. Following the nature of design actions [457], the goal of the segments was considered while coding: understanding of the current work [2, 5, 127], evaluation of the current work [2, 5, 50], and planning of future actions [2, 5, 50]. Hence, the *understanding* was operationalised as an action with the goal of comprehending the current design, the *evaluation* as an action with the goal of assessing the current design and the *planning* as an action with the goal of discussing the future design. The rest of the utterances were coded as management since they were related to the discussion of how to proceed during the transition or were directed towards gathering attention. These actions were redacted from the analysis because they are not related to the design space and are thus unnecessary for testing the model of transition processes. As the aim of this study is not related to analysing sequences, this removal does not affect the findings. An example of the coding is shown in Table 5.3. To test the inter-rater reliability for measuring transition actions, a second coder analysed 10% of the data [8] in each condition (about one hour in total). The agreement between the coders on this sample was substantial, as the inter-rater reliability calculated using Cohen's Kappa [413] was 0.63.

Table 5.3 Coded excerpt of the transition discourse (translated from Croatian); Note: Uncertainty hedge words are in italics, and affect hedge words are in bold

Speakers	Discourse	Act.	*Unc.*	**Affect**	WM
R2	Well, now I see this… Can you follow me a bit?	M	-	-	-
D | R2 |R1 | R2 | D	Which screen? | um two | two | two | uh-huh	M	-	-	-
R2 | D | R2	*so* you now have this cylinder | **yes** | and he now has some *kind of* connection and this connection does not work	E	2	0.67	Yes
R2	Because *if* this *would*… *so* this here must from the beginning be some *kind of* compressed air	E	4	0	Yes
R2 | D	Here inside you *mean*? | uh-huh	E	1	0	Yes
R2	Here is compressed air and now you move the lever, that pin downwards	E	0	0	Yes
R2	I don't see what *could* happen to lower down the chair	E	1	0	Yes
R1 | D | R1	Did you take a standard cylinder or made it on your own? | the **colleague** worked on its own | uh-huh	U	0	1x0.25	Yes
R1 | D | R1 | D	Because *then* it is missing here inside, isn't it…it is missing the part where it shows…that whole through which | uh-huh | *can* air enter or exit is it? | uh-huh **yes yes yes**	P	2	3x0.67	Yes
R2 | D	**Yes yes** because you practically don't have a tank of that compressed air | **yes yes yes yes** *clear*	P	-1	6x0.67	Yes
R2	Which *would* make the pneumatic cylinder to function…	P	1	0	Yes
R2 | R1 | R2	[NAME], will you take that | yes yes I will I will | Just take it	M	-	-	-
R2	Okay, I *think* because *then*, you practically have here...at at at the connection...of this cylinder	U	2	0	No

R – Reviewer, D – Designer, Act. – Action, Unc. – Uncertainty, Aff. – Affect, WM – Working mode, U – Understanding, E – Evaluation, P – Planning, M – Management

Uncertainty and affect emergent characteristics were measured with a lexicon-based analysis that included the identification of 'hedge words' in the discourse. This approach is unobtrusive, provides objective measurements, and is already utilised in the design discipline to study uncertainty [143, 144, 175] and affect [148, 458]. The lexicon for uncertainty was based on previous design studies [143]. This lexicon was translated into the Croatian language by translating each term into various forms of its meaning (one-to-many). The final lexicon consisted of 444 terms associated with certainty (value 1) or uncertainty (value -1). Furthermore, the lexicon for the affect was based on the NRC Word-Emotion Association Lexicon [459]. This lexicon was created manually by crowdsourcing and consists of 14 182 words associated with positive (value 1) or negative (value -1) affect. As the data were in Croatian, the Croatian version [460] of the NRC Word-Emotion Association Lexicon [459] was utilised. As some terms were duplicates in the lexicon due to translation (e.g., synonyms), the affect value for these words was averaged, resulting in 13332 terms.

Given the extent of the dataset and lexicons, a natural language processing (NLP) approach was utilised to identify hedge words from the dataset. The NLP approach consisted of tokenisation and lemmatisation that enabled the comparison of inflected word forms to the lexicon terms. This step was conducted using a CLASSLA [461] Python[26] library based on the Stanza NLP toolkit [462]. To tackle negation and issues with translation (e.g., synonyms), a human coder checked the identified words and, where needed, corrected the values by reversing the negation and removing the false positive words. An example of uncertainty and affect coding is shown in Table 5.3. To test the reliability of uncertainty and affect measurements, a second coder also checked 10% of the identified words in each condition (about one hour in total). The agreement between the coders on this sample was high, as Pearson's correlation coefficient was 0.95 for uncertainty and 0.9 for affect.

The working mode was coded by analysing whether all three members participated in the executed actions (i.e., all-together) or not (i.e., sub-team). Although the coding was on the team level (i.e., all-together or sub-team), the decision was based on observing individual team members for participation in the executed action. More specifically, grounding cues [73, 74] were analysed to determine which members participated in the transition action. The positive grounding cues included acknowledgements (e.g., *uh-huh, yeah*), relevant next turns (e.g., answering a question, repeating the content), and continued attention (e.g., looking at each other, looking at the same object). Furthermore, the sub-team cue was related to the one team member doing something else [73, 74], i.e., engaged in a perception-action (e.g., sectioning,

[26] *Python* – a general-purpose programming language. Available at: https://www.python.org/

moving around with a fixed point of view) cycle on the artefact that was not relevant to the conversation. An example of working mode coding is shown in Table 5.3. To test the reliability of working mode identification, a second coder analysed 10% of the data in each condition (about one hour in total). The agreement between the coders on this sample was substantial, as the inter-rater reliability calculated using Cohen's Kappa [413] was 0.69.

5.5.1.2 Analysis procedure

The coded dataset was used to test the relationships in the model of team transition processes. Firstly, each independent variable (i.e., uncertainty, affect, and working mode) was tested for differences between transition actions (regardless of the environment). Secondly, the independent variables were then considered together with the aim of predicting transition actions (also regardless of the environment). Thirdly, the independent variables were then tested for differences between the two environments. Finally, independent variables were considered together in order to predict transition actions in each of the two environments.

The analysis of each independent variable for differences between transition actions depended on the type of variable. Interval-level variables (uncertainty and affect) were tested for homogeneity using Levene's test. Depending on this test, a one-way or Welch ANOVA was used to test the overall differences between variables in different actions. A corresponding pairwise comparison test (*t*-test or Welch *t*-test) with Bonferroni correction was utilised in cases of significance. For the frequency data (working mode), a Chi-square test of independence was used to test the association between transition actions and working mode.

After testing the variables independently, their integration was tested via hierarchical multinomial logistic regression. These regression models predicted the transition action using uncertainty, affect, and working mode as predictors. As these actions (understanding, evaluation, and planning) were not ordered, a baseline-category regression model was developed. The understanding action was chosen as a baseline for all the regression models. This action is usually the starting point for transition teams [2, 5] and serves as a prerequisite for other actions, such as evaluation [127]. As there were three main predictors (uncertainty, affect, and working mode), three regression models were developed for the whole dataset. The first regression model utilised only uncertainty as the main variable that predicted the transition actions [143, 144, 175]. The second regression model included affect as another predictor, as this emergent characteristic was commonly linked to cognition [184] and might influence the decision about which action to pursue next [336–339]. Finally, the third regression model added the working mode as the third predictor, acting as the extent to which uncertainty and affect were transferred across the team. In order to verify the inclusion of predictors in the regression models, multicollinearity between predictor variables was assessed by calculating variance inflation factors (VIF). In all the calculated regression models, the maximum VIF was 1.09, which suggests that the regression models did not suffer from multicollinearity. The three regression models were compared using one-way ANOVA to see whether the inclusion of a new variable provided significantly higher regression model power. While developing each regression model, the collected dataset was randomly down-sampled to the smallest group in order to deal with the imbalanced data. This dataset was used to calculate the regression models using ten-fold cross-validation, thus providing an unbiased measure of regression model performance. The performance measurement included calculating the area under the curve (AUC) based on the receiver operating characteristic (ROC) curve.

After assessing the variables in the model of team transition processes for the whole dataset, the same procedure was repeated for the low-immersion and high-immersion environments. Each independent variable (uncertainty, affect, and working mode) was evaluated for the differences between the low-immersion and high-immersion environments utilising the same procedure as described above. This comparison provided evidence to test if any of the variables differed in the two environments. After testing the differences between the two environments, hierarchical multinomial logistic regression was conducted for both low-immersion and high-immersion environments in order to assess the integration of variables. Finally, the significance and direction of the predictors in three chosen regression models (one for the general dataset, one for the low-immersion condition, and one for the high-immersion condition) were compared to provide additional insights into the predictive power of the model of team transition processes. All calculations were conducted using the *R* language.

5.5.2. Testing the model of team transition processes for the whole dataset

As a first step in testing the model, this section evaluates the explanatory power by comparing transition actions in each independent variable (Subsection 5.5.2.1) and measures the predictive power of the model of team transition processes on the whole dataset (Subsection 5.5.2.2).

5.5.2.1 Comparing transition actions in each independent variable

The Welch ANOVA revealed that there was a statistically significant difference in uncertainty between at least two groups; $F(2, 1879.2) = 104.5$, $p < 2 \times 10^{-16}$. Pairwise comparisons using the Welch *t*-test with Bonferroni correction revealed that evaluation ($t(2928.6) = -6.34$, $p = 2.7 \times 10^{-10}$, $p_{adj} = 8.2 \times 10^{-10}$) and planning ($t(1117.9) = -14.19$, $p < 2 \times 10^{-16}$, $p_{adj} < 2 \times 10^{-16}$) transition actions had significantly higher uncertainty than understanding. Moreover, planning actions had significantly higher uncertainty levels than evaluation actions; $t(1422.5) = -8.76$, $p < 2 \times 10^{-16}$, $p_{adj} < 2 \times 10^{-16}$. The statistically significant differences were found in affect between at least two groups; $F(2, 1915.4) = 15$, $p = 3.5 \times 10^{-7}$. Pairwise comparisons revealed that evaluation action had the lowest affect level, while understanding ($t(2615.6) = 2.35$, $p = 0.019$, $p_{adj} = 0.056$) and planning action ($t(1761.8) = -5.42$, $p = 6.6 \times 10^{-8}$, $p_{adj} = 2 \times 10^{-7}$) had significantly higher affect. Moreover, planning action had a significantly higher affect level than understanding action; $t(1193.8) = -4.21$, $p = 2.7 \times 10^{-5}$, $p_{adj} = 8.2 \times 10^{-5}$. Finally, the Chi-square test of independence did not provide evidence that working mode and action are associated in this dataset ($\chi^2(2, N=4413) = 3.74$, $p = 0.15$). These results suggest that uncertainty and affect interact with the transition actions while working mode does not.

5.5.2.2 Combining independent variables to test the predictive power

Following the hierarchical multinomial logistic regression, three models were developed: uncertainty as a predictor, uncertainty and affect as predictors, and uncertainty, affect, and working mode as predictors (Table 5.4). The first model had low predictive power (AUC = 0.59), while the second and third models had sufficient predictive power (AUC > 0.6) [463–465]. Furthermore, the ANOVA suggested that having uncertainty and affect as predictors performs significantly better than uncertainty alone ($p = 1 \times 10^{-9}$). However, the model with all three predictors did not perform significantly better than the model with uncertainty and affect. These results suggest that adding the affect improves the model's performance while adding the working mode does not. Hence, the second regression model was used for further analysis. In this model, uncertainty was a significant predictor for both evaluation and planning actions. With all other predictors held constant, an uncertainty change from 0 to 1 would increase the odds of evaluation action by 395% ($e^{1.6}$-1) and also the odds of planning by 18027% ($e^{5.2}$-1). An affect change from 0 to 1 would decrease the odds of evaluation by 67% ($e^{-1.1}$-1) but increase the odds of planning by 1246% ($e^{2.6}$-1). As these results partially confirmed the model of team transition processes, the next subsection tests the model of team transition processes in different environments.

Table 5.4 Hierarchical multinomial logistic regression for predicting transition actions

Model	Uncertainty				Affect				Working mode				AUC	ANOVA *p*
	Evaluation		Planning		Evaluation		Planning		Evaluation		Planning			
	Coef.	*p*	Coef.	*p*	Coef.	*p*	Coef.	*p*	Coef.	p	Coef.	*p*		
Unc.	1.7	$2x10^{-4}$	4.6	$< 2x10^{-16}$	-	-	-	-	-	-	-	-	0.59	-
Unc.+Aff.	1.6	$6x10^{-4}$	5.2	$< 2x10^{-16}$	-1.1	0.05	2.6	$5x10^{-6}$	-	-	-	-	0.62	$4x10^{-13}$
Unc.+Aff.+WM	1.4	$2x10^{-3}$	4.9	$< 2x10^{-16}$	-1.2	0.04	2.5	$1x10^{-5}$	0.04	0.72	-0.18	0.1	0.61	1

Unc. – Uncertainty, Aff. – Affect, WM – Working mode, Coef. – Coefficient, AUC – Area under the curve

5.5.3. Testing the model of team transition processes in low-immersion and high-immersion environments

As a next step in testing the model, uncertainty, affect, and working mode were compared between the two environments (Subsection 5.5.3.1), and the integration of these variables in low-immersion and high-immersion environments (Subsection 5.5.3.2) was evaluated.

5.5.3.1 Comparing low-immersion and high-immersion groups in uncertainty, affect and working mode

The usage of the Welch *t*-test to compare uncertainty between the two environments did not yield significant differences, $t(4362.3) = -0.348$, $p = 0.73$. On the contrary, the same test revealed differences in affect levels between the two environments, $t(4105.5) = -2.58$, $p = 0.01$. Similarly, the Chi-square test of independence suggested that working mode and environment are related; $\chi^2(1, N=4413) = 14.04$, $p = 1.8 \times 10^{-4}$. Conditional dependence by controlling each environment was tested to reveal environment-dependent associations between working mode and transition action. Hence, for each environment, a 3x2 contingency table with the working mode (all-together and sub-team) and action (understanding, evaluation, and planning) was analysed using the Chi-square test of independence. The test revealed that working mode and action were associated in both low-immersion ($\chi^2(2, N=2246) = 11.36$, $p = 0.003$) and high-immersion ($\chi^2(2, N=2167) = 4.44$, $p = 0.1$) environment. These results suggest that the affect and working mode were environment-dependent, but the uncertainty was not.

5.5.3.2 Predicting transition actions in low-immersion and high-immersion environments

Following the hierarchical multinomial logistic regression, three regression models to predict transition actions in low-immersion were developed: *uncertainty*, *uncertainty and affect*, and *uncertainty, affect, and working mode* (Table 5.5). All the models in the low-immersion environment had satisfactory predictive power (AUC > 0.6) [463–465]. The ANOVA suggested that having uncertainty and affect as predictors in a low-immersion environment performed significantly better than uncertainty alone ($p = 3 \times 10^{-10}$). The same test revealed that uncertainty, affect and working mode in a low-immersion environment performed significantly better than the model with uncertainty and affect as predictors ($p = 2 \times 10^{-3}$). These results suggest that adding the affect and working mode improved the model performance in a low-immersion environment. Hence, the third low-immersion model was used for further analysis. In this model, uncertainty was a significant predictor for both evaluation and planning actions. With all other predictors kept constant, an uncertainty change from 0 to 1 would, in a low-immersion environment, increase the odds of evaluation by 1544% ($e^{2.8}$-1) and the odds of planning by 109563% (e^{7}-1). An affect change from 0 to 1 would, in a low-immersion environment, decrease the odds of evaluation by 889% ($e^{-2.2}$-1) but increase the odds of planning by 2896% ($e^{3.4}$-1). Finally, a shift from sub-team to all-together work would, in a low-immersion environment, increase the odds of evaluation by 27% ($e^{0.24}$-1) but decrease the odds of planning by 24% ($e^{-0.28}$-1).

Table 5.5 Hierarchical multinomial logistic regression for predicting transition actions in the low-immersion environment

Model	Uncertainty				Affect				Working mode				AUC	ANOVA *p*
	Evaluation		Planning		Evaluation		Planning		Evaluation		Planning			
	Coef.	*p*	Coef.	*p*	Coef.	*p*	Coef.	*p*	Coef.	p	Coef.	*p*		
Unc.	2.3	6×10^{-4}	6	$< 2 \times 10^{-16}$	-	-	-	-	-	-	-	-	0.61	-
Unc.+Aff.	2.8	8×10^{-5}	7	$< 2 \times 10^{-16}$	-2.1	0.028	3.3	3×10^{-4}	-	-	-	-	0.63	3×10^{-10}
Unc.+Aff.+WM	2.8	7×10^{-5}	7	$< 2 \times 10^{-16}$	-2.2	0.022	3.4	2×10^{-4}	0.24	0.1	-0.28	0.06	0.64	2×10^{-3}

Unc. – Uncertainty, Aff. – Affect, WM – Working mode, Coef. – Coefficient, AUC – Area under the curve

The same procedure with three models (each having one predictor more) was used to develop a model for the high-immersion environment (Table 5.6). The first model had low predictive power (AUC = 0.59), while the second and third models had sufficient predictive power (AUC > 0.6) [463–465]. The ANOVA suggested that the model with uncertainty and affect as predictors in a high-immersion environment performed significantly better than the model with uncertainty alone ($p = 2 \times 10^{-7}$). Moreover, having all three variables (uncertainty, affect and working mode) as predictors in a high-immersion environment performed significantly better than the model with uncertainty and affect as predictors ($p = 5 \times 10^{-3}$). These results show that adding more variables improved the model performance in the high-immersion environment. Hence, the third high-immersion model was used for further analysis. In this model, uncertainty was a significant predictor for both evaluation and planning actions. With all other predictors being constant, an uncertainty change from 0 to 1 would, in a high-immersion environment, increase the odds of evaluation by 172% (e^{1}-1) and also the odds of planning by 8902% ($e^{4.5}$-1). An affect change from 0 to 1 would, in a high-immersion environment, decrease the odds of evaluation by 52% ($e^{-0.74}$-1) but increase the odds of planning by 1849% ($e^{2.97}$-1). Finally, a shift from sub-team to all-together work would, in a high-immersion environment, increase the odds of evaluation by 21% ($e^{0.19}$-1) and the odds of planning by 46% ($e^{0.38}$-1).

While working mode was a significant predictor for both low- and high-immersion models, it did not predict the transition actions in the whole dataset (see Subsection 5.5.2). Therefore, the coefficients of the models were qualitatively compared to understand this difference better.

Table 5.6 Hierarchical multinomial logistic regression for predicting transition actions in the high-immersion environment

Model	Uncertainty				Affect				Working mode				AUC	ANOVA *p*
	Evaluation		Planning		Evaluation		Planning		Evaluation		Planning			
	Coef.	*p*	Coef.	*p*	Coef.	*p*	Coef.	*p*	Coef.	p	Coef.	*p*		
Unc.	1.08	0.086	3.5	1.2×10^{-8}	-	-	-	-	-	-	-	-	0.59	-
Unc.+Aff.	0.78	0.2	4	1×10^{-10}	-0.84	0.27	2.6	6×10^{-4}	-	-	-	-	0.61	8×10^{-7}
Unc.+Aff.+WM	1	0.1	4.5	2×10^{-12}	-0.74	0.34	2.97	1×10^{-4}	0.19	0.2	0.38	0.02	0.61	4×10^{-3}

Unc. – Uncertainty, Aff. – Affect, WM – Working mode, Coef. – Coefficient, AUC – Area under the curve

5.5.4. Comparison of the regression models

In order to compare the selected regression models from each hierarchical multinomial logistic regression, the sign and significance of each predictor were compared (Figure 5.16). Uncertainty was the strongest predictor in all the models and was not sensitive to changes in the environment. In all the models, an increase in uncertainty resulted in a significantly higher probability of evaluation and planning. Despite having statistically significant differences between the environments (see Subsection 5.5.3.1), affect as a predictor showed the same coefficient sign across the models. In all the models, higher affect decreased the odds of evaluation and significantly increased the odds of planning. Finally, the working mode shows different coefficient signs in low-immersion and high-immersion environments. More specifically, a change from sub-team to all-together work in the low-immersion environment significantly decreased the odds of planning, while the same change in the high-immersion environment significantly increased the odds of planning. In other words, regression models predict planning in the low-immersion environment to be executed in a sub-team while in the high-immersion all-together. This difference in environments could explain why, in the general dataset, working mode and transition action were not associated (see Subsection 5.5.2.1) and why working mode was not a significant predictor (see Subsection 5.5.2.2). Altogether, these results show that uncertainty and affect might be environment-independent predictors while working mode might provide insights into the differences in the environments.

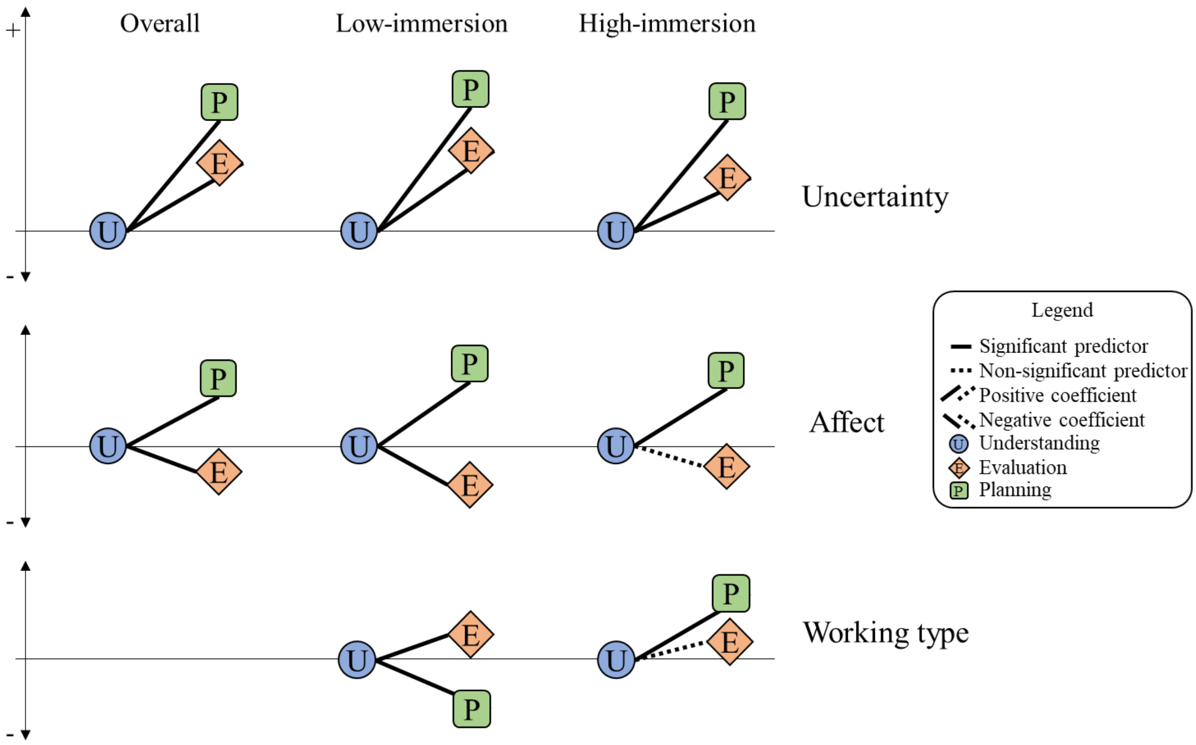

Figure 5.16 Significance and coefficient signs of predictors

5.6. Chapter conclusion

By following the experimental framework, the experiment provided evidence for validating the framework. Furthermore, the study also gathered evidence for evaluating the model of team transition processes, with different behaviours of predictors between the low- and high-immersion environments. Additionally, these results provide evidence for testing the first part of the hypothesis (*VR technologies augment understanding of transition processes*), as the change in the environment enabled a better understanding of the working mode predictor.

The study also provided evidence to support the team transition model. More specifically, the relationship between the environment input (i.e., immersion) and the teamwork behaviour mediator (i.e., verbal communication structure and working mode) was established. This relationship showed that immersion might result in teams working more as a whole, especially for planning actions. These results align with the theoretical suggestions that immersion increases presence in the environment, as well as the subjective evaluations of VR improving teamwork [29].

The study also showed that the same environment characteristic input (i.e., immersion) affects change in the design space (i.e., number of feedback items). However, the established relationship was contrary to theoretical predictions, as the results showed decreased efficiency when teams worked in a high-immersion environment. These results are in line with the contradictory findings related to the effect of immersion on team transition outcomes (see Subsection 2.5.3). Therefore, additional research is necessary to further explore the relationship between immersion and transition outcomes.

In order to establish a relationship between immersion and transition outcomes, a second design review experiment was conducted (Chapter 6). This study provided further evidence to evaluate the team transition model, the experimental framework, and the second part of the hypothesis (*VR technologies improve the execution of evaluation/planning activities*). A discussion of the results, together with the validation and verification of the models and the framework, is provided in Chapter 7.

6. SECOND DESIGN REVIEW EXPERIMENT

This chapter presents the second design review experiment in which fourteen three-member student teams designed a baby stroller as part of the CAD course. After the teams created a CAD model of the baby stroller, a design review (one type of transition) experiment was conducted. In the experiment, four-member transition teams (two industry professionals and two design team representatives) conducted two design reviews (each with a different goal), either in a low- (CAD) or high-immersion (VR) environment. This chapter initially describes the case and experimental study (task, sample, setup, and procedure). Then, experimental results are organised around the effect of immersion and transition goals on the transition outcomes, the transition team performance, and the subsequent development activity.

The aim of the second experiment was to test relationships from the team transition model and to check the usefulness of the experimental framework. With this study, additional evidence has been collected to test if *VR technologies improve the execution of evaluation/planning activities* (the second part of the hypothesis). Similar to the first study, this one also had multiple aims and provided evidence for the causative nature of the hypothesis, thus requiring the collection of various data and high internal validity. Therefore, the experiment was also conducted as part of a larger case.

6.1. Case description

The case study was conducted within the same CAD course as the first study but in the academic year 2021/22. The case study was conducted through project design work as part of the course. Project design work started in the second week of the course. The assignment was to design a baby stroller that satisfies the following characteristics: it is foldable (in one plane only), has a wheel locking mechanism, enables sun protection, offers storage for things, and has a safety handle for a baby. In addition, the strollers were supposed to meet several requirements, such as maximum dimensions and the baby weight they should carry (see Table 6.1). Besides the required characteristics, the design team had to think about production, assembly, ergonomics, and safety.

Table 6.1 Requirements for the baby stroller design assignment (translated from Croatian)

Requirement type	Requirement value
Maximum dimensions (height x width x depth)	110x65x95 cm
Maximum stroller mass	12 kg
Maximum baby mass	15 kg
Maximum storage mass	5 kg
Minimum storage volume	10 L
Angle range of sun protection	0-80° relative to the axis of the upper part of the stroller
Preferred manufacturing technologies	Welding, bending, laser cutting, machining (milling, turning, drilling), polymer processing
Preferred materials	Stainless

As part of the assignment, each team received a patent that meets these characteristics (Figure 6.1). More specifically, a patent from the same Cooperative Patent Classification (CPC) group (i.e., B62B7/06) was provided to each student team. Each patent was available in English and had at least ten images describing the working principles of the stroller. The patent served as a basis for the design, i.e., the teams had to use the same working principles for folding and braking as described in the patent. Overall, 42 third-year undergraduate mechanical engineering students (9 female and 33 male) participated in this case study. The students were randomly divided into 14 three-member teams that worked on designing the strollers.

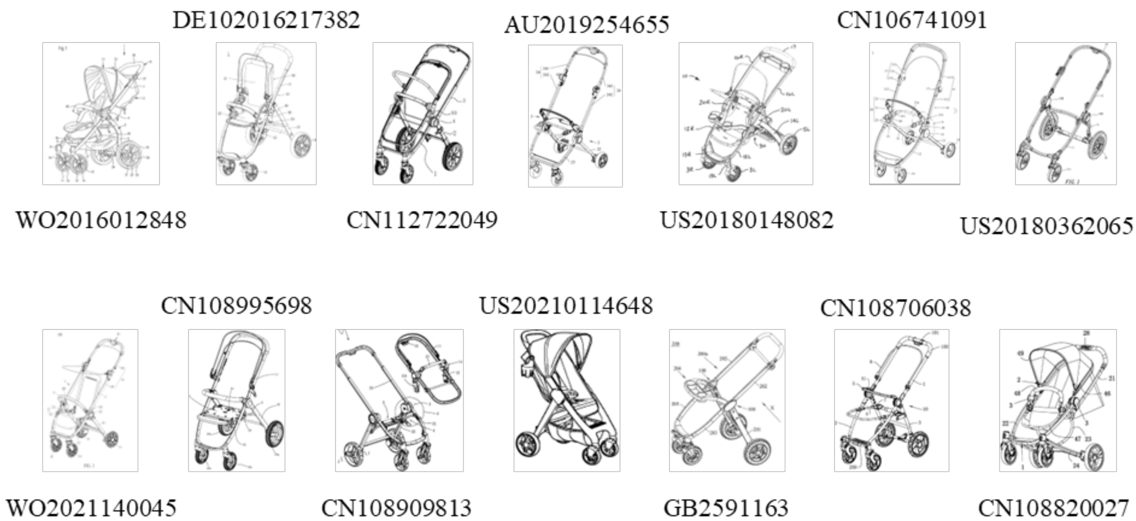

Figure 6.1 Patents that were given to each team as a source of inspiration

The teams worked on the assignment in four phases (Figure 6.2), separated by transitions that served to evaluate the work of the teams and plan the changes to be incorporated until the next transition. During the first phase, teams had to describe working principles and force distribution across the baby stroller. In the first transition, the course instructor reviewed their work and provided them with written feedback. During the second phase, teams addressed the comments from the first transition and delivered a CAD model together with the basic calculations of their design. In the second transition, industry professionals and design team representatives reviewed designs as part of the experiment. The transition was recorded, and designers received a feedback report consisting of issues they needed to resolve in the CAD rework phase. The third phase finished when the course instructor approved the CAD rework report – a document consisting of the design team's response to the issues raised by the reviewers. In the last phase, each team member had to create one assembly and one technical drawing (chosen by the course instructor). At the end of the course, the instructor evaluated the final work of the student design teams and provided a final grade.

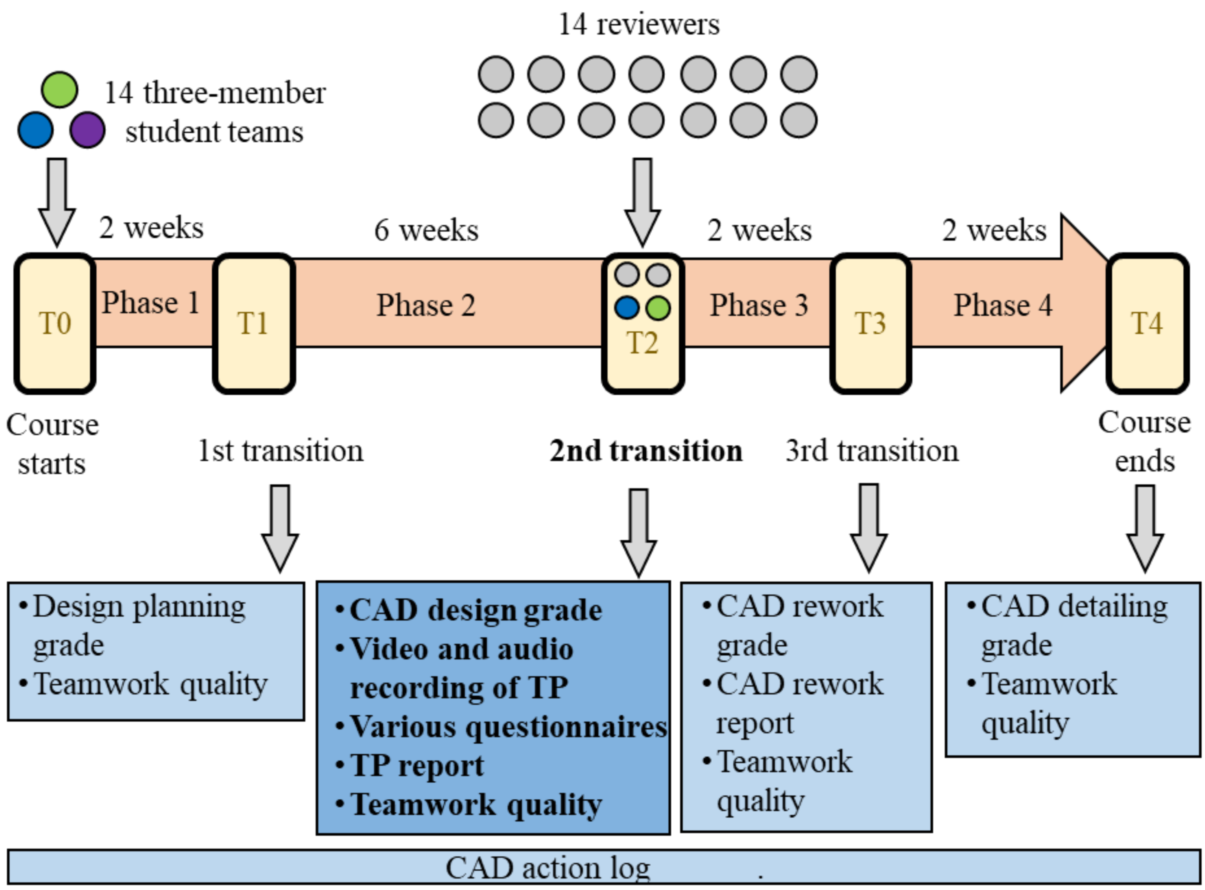

Figure 6.2 Second case study overview

The information and communication technologies students could utilise were the same as in the first case study. More specifically, each team was provided with a private MS Teams channel that enabled distant communication (video conferencing, instant messaging), file sharing, and synchronous document editing. In addition, each team had an Onshape (CAD software practised in the course) project folder that enabled easy collaboration among team members. As in the previous case, Onshape enabled team members to work synchronously on an up-to-date version of the CAD model and also enabled the automatic and unobtrusive collection of CAD action data throughout the course. While various data were collected throughout the course, the second transition was used to provide evidence for evaluating the team transition model and experimental framework. Therefore, the following sections provide more detailed information about the experiment and the obtained results.

6.2. Second transition: Design review experiment

Similar to the first case study, an experimental framework was utilised to design an experiment, taking into account experimental, theoretical, methodological, and implementational considerations.

As the experiment aims to provide evidence for testing the second part of the hypothesis (*VR technologies improve the execution of evaluation/planning activities throughout PD*), immersion was used as a characteristic that depicts the VR aspect of the environment factor [11, 258]. Immersion was again operationalised as the number of simulated sensory cues [267]. Therefore, this independent variable consists of low-immersion and high-immersion categories. Furthermore, as transitions happen throughout product development [5] and involve various stakeholders [67, 68], they might be distinguished by their goals (e.g., manufacturability, ergonomics, customer values). This distinction among the transition goals might provide evidence for the second part of the hypothesis, as it proposes that VR improves the execution of evaluation/planning activities throughout PD. Therefore, a transition goal was another characteristic used in this study, operationalised as the extent to which the goal depicts evaluation/planning related to existing requirements (verification transition) or evaluation/planning to intended use requirements (validation transition) [466–468]. The transition goal independent variable thus consists of the two categories (verification and validation) used as conditions for experimental treatment.

Following the methodological and experimental considerations, most of the transition inputs (see Subsection 3.2.1) were controlled. This control ensured internal validity related to the immersion and transition goal causing changes in transition mediators and outcomes. As immersion relates to the environment, other characteristics related to this factor were held constant. Similarly, as the transition goal independent variable relates to the transition task context inputs, other characteristics related to this factor (e.g., transition duration and formality) and to other transition elements (PD task context, organisational context, and culture) were kept constant. Furthermore, the team inputs (composition and context) were controlled and randomised in order to neutralise the effect of expertise [21, 318]. Similarly, design space aspects were controlled (e.g., artefact characteristics) and randomised (e.g., design quality). More specifically, randomisation is utilised both to allocate designs to the immersion experimental condition (low-immersion or high-immersion) and to allocate reviewers to the transition teams.

As transition teams worked only in one of the two conditions, the experimental design from this perspective was between-subjects. Moreover, as the two transition goals are complementary [466–468], transition teams executed both of them. This makes the study design, from the transition goal perspective, a matched pair. Therefore, the study had both low- and high-immersion teams working on both verification and validation transition goals, making it a two-way full factorial design with one independent sample and one matched pair variable. The next subsections show how the task, sample, setup, and procedure were designed to take into account experimental, methodological, and implementational considerations from the experimental framework.

6.2.1. Experimental sample and task

In total, 42 participants (28 designers and 14 reviewers) took part in the experiment. These participants were distributed across 14 four-member transition teams, having a sample of seven baby stroller transitions in the low-immersion and seven in the high-immersion environment (Figure 6.3). Each team consisted of two designers and two reviewers (Figure 6.4). The designers (two per transition team) and their designs appeared only in one transition (randomly), while each reviewer participated in two sessions. More specifically, each reviewer participated in one low-immersion and one high-immersion review, but with different designers and reviewers in each condition. In order to neutralise the learning effect of reviewers, half of them had their first review in the low-immersion environment and the other half in the high-immersion environment. Finally, to tackle fatigue, reviewers participated in the two conditions on different days.

Each design team had to choose two representatives (i.e., designers) to participate in the review. Their professional backgrounds were very similar, with all 28 members (23 male and five female) being undergraduate 3rd-year mechanical engineering students enrolled at the same university. The reviewers were working professionals, with all of them having similar backgrounds. All 14 reviewers (11 male and three female) were alumni of the same university and held a master's degree in Mechanical Engineering (major in Engineering Design). They worked as designers in the industry for at least two years and were between 26 and 32 years old.

Figure 6.3 Designs reviewed in low- (up) and high-immersion (down) environments

The same transition team size, interdependence, hierarchy, and leadership enabled the control of the team context inputs. In addition, similar backgrounds among designers and reviewers enabled partial control of the team composition inputs [453]. This partial control of the team composition was neutralised by randomly allocating reviewers into transition teams and by randomly allocating transition teams to the immersion condition.

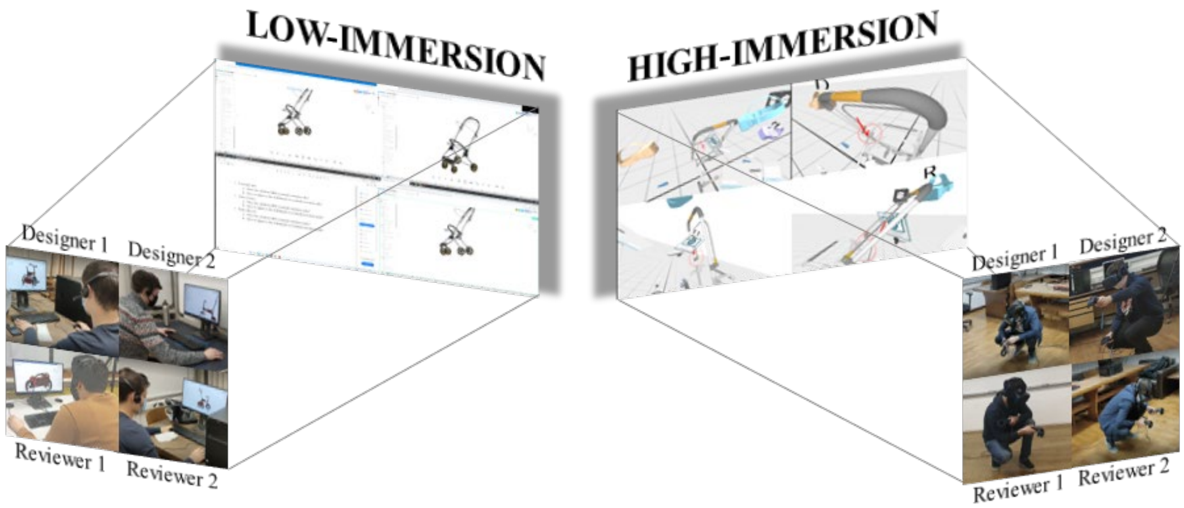

Figure 6.4 Transition in low- and high-immersion environments

The two transition goals were distributed into two experimental sessions (30 minutes each). The first session aimed to review the design regarding the fulfilment of the product (i.e., functional), process (i.e., manufacturing and assembly), and people (i.e., human factors) requirements (see Table 6.2 for the description of these aspects and Table 6.3 for the checklist provided to teams) [147]. The goal of this session was to assess and improve the solution based on the given requirements and constraints. This session is thus referred to as verification [466–468]. The second session involved reviewing the design regarding the fulfilment of the essential customer jobs (what customers are trying to get done), gains (concrete benefits that customers seek), and pains (bad outcomes, risks, and obstacles that customers would like to avoid). These aspects are common considerations in the value proposition design (see Table 6.2 for the description of these aspects and Table 6.3 for the checklist provided to teams) [469]. The goal of this session was to assess and improve the solution based on the values customers have. This session is thus referred to as validation [466–468]. The participants were instructed to capture screenshots that would later be available to the team as a basis for writing the feedback.

Table 6.2 Descriptions of the transition aspects related to verification and validation

Transition goal	Transition aspect	Description
Verification	Product	Describe the product’s features or functions.
	Process	Describe the manufacturing and assembly process.
	People	Describe users’ interaction with a product, ergonomics (e.g., form, dimensions and forces) and appearance.
Validation	Essential jobs	Describe what customers are trying to get done in their work and in their lives, as expressed in their own words.
	Gain creators	Describe the outcomes customers want to achieve or the concrete benefits they are seeking.
	Pain relievers	Describe bad outcomes, risks, and obstacles related to customer jobs.

With the two defined experimental sessions, all other transition situation inputs related to the transition task context could be controlled. Specifically, all the teams received the same description of the transition goal, had the same available review time (2x30 minutes), and were suggested the same approach. Furthermore, focusing on the transitions at the same moment in PD (the second transition of the same course) ensured the control of PD task context aspects (e.g., PD field, PD phase). Finally, as the experiment is part of the same CAD course and as the sample has the same background, the organisational context and culture inputs were also controlled.

Table 6.3 Checklist provided to transition teams

Transition goal	Category	Guiding questions
Verification	Product	Does the solution fulfil all functional requirements? How to improve the fulfilment of the functional requirements?
	Process	Does the solution fulfil manufacturing and assembly requirements? How to improve the fulfilment of manufacturing and assembly requirements?
	People	Does the solution fulfil requirements related to human factors? How to improve the fulfilment of requirements related to human factors?
Validation	Essential jobs	Does the solution fulfil essential customer jobs? How to improve the fulfilment of essential customer jobs?
	Gain creators	Does the solution fulfil essential customer gains? How to improve the fulfilment of essential customer gains?
	Pain relievers	Does the solution fulfil essential customer pains? How to improve the fulfilment of essential customer pains?

6.2.2. Experimental setup

For the low-immersion environment, four rooms were equipped with a working station, monitor (22'', 1920x1080 pixels), headphones, keyboard, mouse, and office chair. Using a traditional computer has been a common comparison condition for VR in transitions [22, 25, 28, 75], as it supports only a few depth cues (e.g., perspective and occultation). This setup does not support cues related to natural sensorimotor contingencies, such as binocular (e.g., stereopsis) or motion-based cues (e.g., motion parallax) [266], and it is thus considered low-immersion.

The software for verbal communication was Microsoft Teams, while the software for low-immersion visualisation of the design was Onshape. Onshape is a cloud-based CAD that enables synchronous work on the same CAD model, providing new ways of creating designs [449]. Besides interacting with the same CAD model in real-time, participants could follow each other and share their views (see top left (designer 2) and bottom right (reviewer 1) views in Figure 6.5). Like other CAD tools, Onshape enabled orbital navigation (i.e., pan, rotate, and zoom) within an environment. In addition, its viewing mode provided basic functionalities, such as a screenshot, measure, marker, section, move parts, and hide parts. In addition to the CAD model, transition teams had access to a transition checklist in PDF format (Figure 6.5 bottom left).

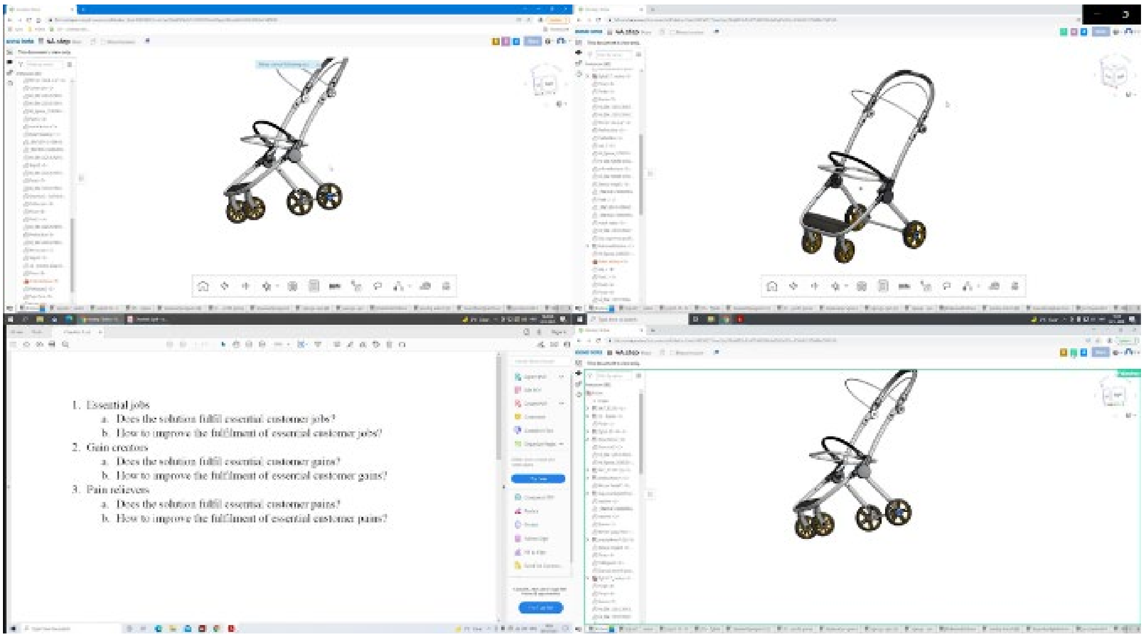

Figure 6.5 Transition in a low-immersion environment

For the high-immersion environment, four rooms were equipped with a VR-ready working station, a VR headset (3 x HTC VIVE Pro, 1 x HTC VIVE Cosmos Elite), and VR controllers (HTC VIVE). These HMDs are comparable as they have similar characteristics and use identical controllers (Table 6.4). Moreover, they track the user's head and position while rendering separate images to each eye of the user, thus supporting both binocular cues (e.g., stereopsis) and motion-based cues (e.g., motion parallax) [266]. Therefore, HMD VR equipment was chosen for the high-immersion hardware.

Table 6.4 Comparison of the HMD devices used in the second experiment

HMD model	HTC VIVE Pro 	HTC VIVE Pro Eye 	HTC VIVE Cosmos Elite 
Resolution	1440 x 1600 pixels per eye	1440 x 1600 pixels per eye	1440 x 1700 pixels per eye
Field of view	Up to 110 degrees	Up to 110 degrees	Up to 110 degrees
Refresh rate	90 Hz	90 Hz	90 Hz
Controller input	Trackpad, Grip buttons, Dual-stage trigger	Trackpad, Grip buttons, Dual-stage trigger	Trackpad, Grip buttons, Dual-stage trigger

The software for the high-immersion environment included Microsoft Teams for verbal communication, SteamVR for setting up a HMD device, and Siemens NX VR for visualising the design. Using SteamVR enabled the visualisation of PDFs in the high-immersion environment, which allowed participants to see the transition checklist during the session. Siemens NX VR enabled synchronous work on the same model using the same functionalities as in the low-immersion environment: screenshot, measure, marker, section, move parts, and hide parts. Having the same functionalities in both environments eliminated a possible confounding variable [34, 271]. Besides manipulating the model using these functions, participants could move around the virtual room (3x3 meters) and see each other's avatars (HMD devices), controllers, and laser pointers. Figure 6.6 shows the viewpoints of the four members during the review session.

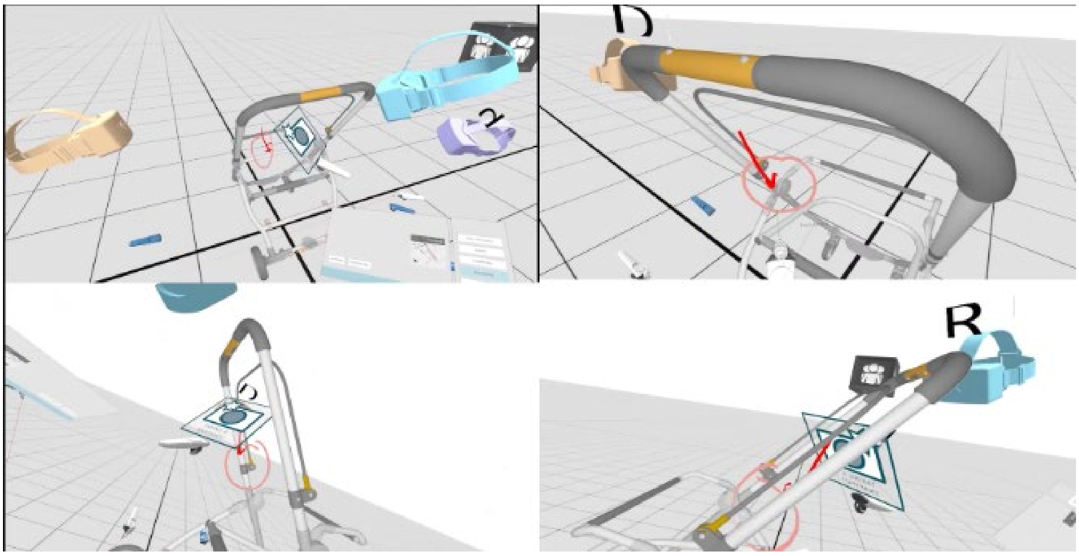

Figure 6.6 Review in high-immersion environment

Having the same artefacts (i.e., CAD model, transition checklist, list of requirements) in low-immersion and high-immersion conditions controlled the artefact characteristics (e.g., fidelity, scale, and dimensionality). Moreover, as all designs were baby strollers, the design context aspects (e.g., design size, complexity, and goal) were controlled. Although the design quality was not constant because having the same solutions would affect the external validity, its effect was neutralised by randomly assigning the designs to conditions. Software functionalities were also similar in both conditions, eliminating another possible confounding variable.

6.2.3. Experimental procedure

The experimental procedure consisted of nine steps (Figure 6.7): 1) Sending the information package to study participants; 2) Preparation and introduction to the equipment for the designers; 3) Preparation and introduction to the equipment for the whole team; 4) First transition session; 5) Reporting the first transition session; 6) Break; 7) Second transition session; 8) Reporting the second transition session; 9) Post-experimental questionnaires.

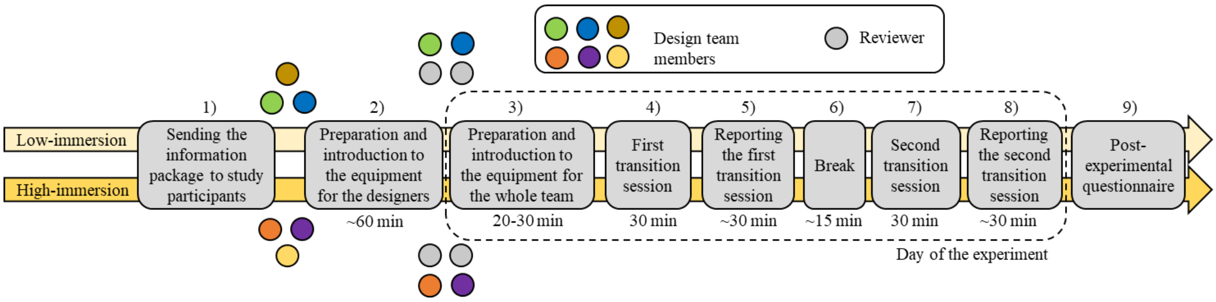

Figure 6.7 Experimental procedure for the second experiment

The information package was sent two weeks in advance and included: the design brief, transition goal (Table 6.2 and Table 6.3), consent form, and equipment tutorials (presentation and video). The goal of the information package was to make participants familiar with the design problem, transition goals, transition procedure, and environment used during the experiment. The presentation was similar for both environments and described navigating in the environment, selecting components, hiding and isolating components, moving components, sectioning, measuring, drawing, taking screenshots, and the collaboration cues. Each functionality was described with text, an image showing buttons that must be pressed, and a screenshot from the software used. The equipment tutorial video demonstrated the use of each software functionality.

In the second step, the design teams (i.e., three student team members) were invited to test the setup at least one day before the transition in order to become familiar with the procedure and equipment. More specifically, all three designers simulated a transition session, which served as a pilot study and as a way to teach designers an environment they used during the transition.

In preparation for the transition (i.e., Step 3), designers and reviewers met briefly in person and were instructed to go into separate rooms. The four physical rooms were technically supported by three researchers (two rooms were close to each other), whose task was to help participants with the equipment, functionalities (only during the tutorial), and experimental procedure and to ensure that all the data were being captured. Moreover, one researcher navigated the participants during the experiment. In order to not interrupt the execution of the transition, the researcher left the call during the data collection period and rejoined after the session. When participants joined the Microsoft Teams call, they were instructed to follow the environment tutorial presentation. The presentations were the same as those sent two weeks before the experiment, but this time participants could test all the software functionalities until they felt ready to start. Since designers had already learned functionalities in Step 2, they were instructed to help reviewers get familiar with the equipment. Once the team reported that they had finished testing, a researcher on the call asked them to confirm that all of them knew the required functionalities (sectioning, measuring, etc.). This environment tutorial step usually lasted about 45 minutes. Since participants only had to grasp a few functionalities, this timing was considered sufficient to tackle the issues related to lower experience in the environment [21, 389].

After the participants became familiar with the environment, researchers started the screen recording, and the team proceeded to the first transition session. This session lasted for 30 minutes and focused on verifying whether the solution met the requirements. The participants were instructed to take screenshots that would later be available to the transition team as a basis for writing the feedback. The first session was followed by a reporting period, during which all participants wrote textual feedback for each screenshot taken during the first transition session. After the verification part of the transition had been finished, a 15-minute break was given to the participants. The second transition session (validation) focused on assessing and suggesting improvements to the solution based on customer values. This session also lasted 30 minutes and was followed by another reporting period. The procedure lasted around three hours per experiment.

A few days after the experiment, a general questionnaire was sent to participants in order to gather qualitative feedback on the effect of immersion on the transition. The questionnaire included open-ended items related to positive and negative aspects of each environment and served to contextualise the quantitative results.

The following sections present the results of the experiment. Section 6.3 analyses the effect of immersion and a transition goal on the context of team outcomes. Furthermore, Section 6.4 reports the effect of immersion and a transition goal on the transition team's performance. Finally, Section 6.5 analyses the effect of immersion on the subsequent design activities. These analyses provide evidence for validating the team transition model and testing the second part of the hypothesis.

6.3. The effect of immersion and transition goal on the number and context of feedback items[27]

In order to provide evidence for evaluating the team transition model and testing the second part of the hypothesis, the focus of this section is to analyse the effect of immersion and

[27] This section has been submitted to the Advanced Engineering Informatics journal.

transition goal (i.e., inputs) on the transition design space outcome (Figure 6.8). The transition design space outcome was operationalised through the number of feedback items [28, 32, 33, 75]. However, focusing solely on the number of feedback items may be insufficient, as several studies found a positive relationship between immersion and this metric [28, 32], while others found a negative relationship [25, 33].

Even if the immersion level does not affect the number of feedback items, contextual aspects of outcomes might be affected. More specifically, utilising different spatial mechanisms suggests that immersion might influence spatial aspects of transitions, such as focusing on user-design interaction rather than relations between different design solution entities [470, 471]. Therefore, the first variable investigated is the spatial relation [470, 471] of the feedback item, which can be either intrinsic or extrinsic (see Table 6.5 for descriptions). This variable is derived from the spatial cognition literature [470, 471], with intrinsic (within an object) and extrinsic (between objects) categories as a common typology of spatial tasks. As the high-immersion level utilises natural sensorimotor contingencies and thus makes the user more aware of the surrounding environment [33], it is suggested that this environment supports extrinsic feedback items. Moreover, as understanding the stances of various stakeholders is crucial to validation [472], this transition goal might also support the identification of extrinsic issues.

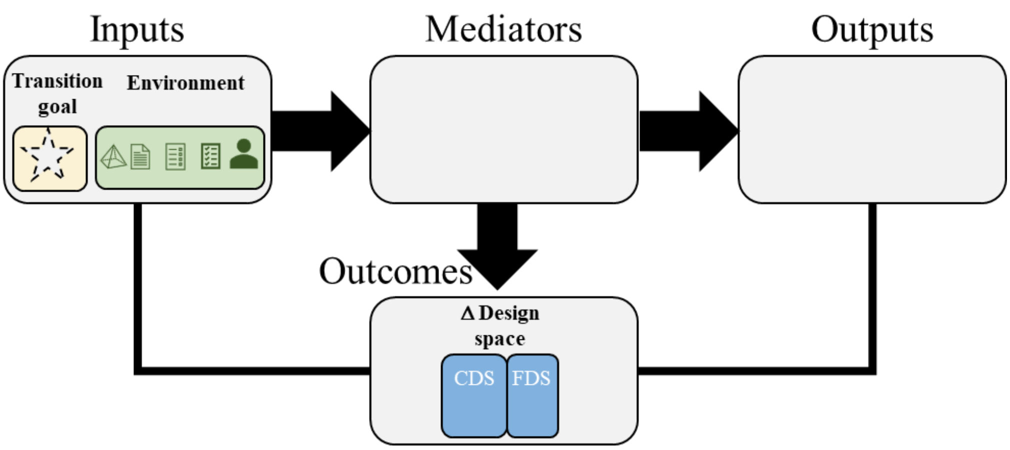

Figure 6.8 Factors considered when analysing the effect of immersion on the number and context of feedback items

The notion that immersion supports user-design interaction [470, 471] because of the natural perception and interaction with the environment suggests that immersion can also affect the focus on the design aspect. More specifically, exploring the use-case scenarios [33] could help transition teams understand the stances of various stakeholders. This support is important in the early design [472], suggesting the potential of immersion for these phases. Early design phases are characterised as more focused on the problem than the later ones [107, 131, 473] and can be depicted by the problem-solution (see Table 6.5 for descriptions) dichotomisation [35–37, 136]. Given the stronger feeling of presence [16, 474] in high-immersion environments, together with a partially better spatial [22, 24], contextual [21, 316], and surrounding [33] understanding, these environments might encourage users to focus more on the problem-related aspects of design. Furthermore, as the validation transition emphasises the connection with various stakeholders [468], this transition might also be focused more on the problem-related aspects.

Table 6.5 Definition of categorical variables

Variable	Category	Description
Spatial relation	Intrinsic	Feedback items that focus on the relations within the design (between parts, within parts)
	Extrinsic	Feedback items that focus on the relationship between the design and a user or environment.
Design space	Problem	Feedback items based on the requirement that was previously unknown to the designers or the requirement that changed from the initial.
	Solution	Feedback items based on the requirement that was previously known to the designers.

6.3.1. Analysis procedure

The results of the analysis were collected from the reviewers' feedback regarding the changes to be made. The feedback was captured using a report template. A segmentation step was conducted to divide the report into feedback items and delete duplicates. For this purpose, a feedback item was defined as the reviewers' written comment from the session that incorporates only one instance from the problem space and/or only one instance from the solution space. This definition enabled the segmentation of the written feedback if reviewers had more than one feedback item in a written comment and enabled the deletion of duplicate feedback items (items that focus on the same instances of problem and solution space).

The feedback items were analysed using thematic coding – an approach of labelling data with codes [85], such as those in Table 6.6. More specifically, each feedback item was coded with a spatial relation (intrinsic or extrinsic) and design space (problem or solution) code based on the description from Table 6.5. The examples of the feedback items and their spatial relations and design space categories are shown in Table 6.6. All the feedback items were coded by the primary researcher, while a portion of the feedback items were also coded by another coder. The second coder rated two sessions (one in each condition), approximately 14% of the data.

This percentage is considered sufficient to calculate inter-rater reliability [4, 8]. The inter-rater agreement for the spatial relation variable was 0.85, with Cohen's Kappa [413] being 0.7, which is considered a substantial agreement. The inter-rater agreement for the design space variable was 0.92, with Cohen's Kappa being 0.84, which is considered near perfect agreement.

Before statistical testing for the differences between the variables, the normality of the data was tested using the *Shapiro-Wilk* test, while the homogeneity of variances was tested using *Levene's* test. Due to the full-factorial mixed research design, statistical testing for the group differences included a mixed ANOVA analysis with immersion as an independent sample and transition goal as a repeated measure variable. The potential deviation from the sphericity assumption has been corrected using the Greenhouse-Geisser procedure. Finally, the homogeneity of covariance of the immersion variable was evaluated using Box's M-test. All analyses were conducted in *R*.

The next three subsections present the results organised around the three studied variables (number of feedback items, spatial relation and design space). Each subsection consists of hypothesis testing related to the number of items, followed by hypothesis testing related to the proportion of items. Finally, the last subsection provides thematically grouped [85] answers from the questionnaire to give context to the quantitative analysis.

Table 6.6 Examples of feedback items with coded spatial relation and design space (translated from Croatian)

Feedback item	Spatial relation	Design space
Handle material (rubber) susceptible to atmospheric influences.	Extrinsic	Problem
The handle does not have a height adjustment feature.	Extrinsic	Problem
The seat is not standardised.	Intrinsic	Problem
The rubber handle is too far from the baby.	Extrinsic	Solution
The diameter of the folding mechanism housing is unnecessarily bulky.	Intrinsic	Solution

6.3.2. Comparing the number of feedback items

In the verification transition, transition teams provided 70 feedback items in the low-immersion and 75 in the high-immersion environment. The number of items per transition session ranged from seven to 15 in the low-immersion and from six to 30 in the high-immersion environment. The average number of feedback items was 10 in the low-immersion and 10.7 in the high-immersion environment.

In the validation transition, transition teams provided 85 feedback items in the low-immersion and 100 in the high-immersion environment. The number of feedback items per transition session ranged from four to 20 in the low-immersion and six to 28 in the high-immersion environment. Finally, the average number of feedback items was 12.1 in the low-immersion and 14.3 in the high-immersion environment. Although averages in the validation session and the high-immersion environment are slightly higher (Figure 6.9), a mixed two-way ANOVA did not reveal significant differences either between the immersion levels ($F(1, 12) = 0.44$, $p = 0.52$) or between the transition goals ($F(1, 12) = 1.91$, $p = 0.19$). The effect size was medium for the transition goal variable ($\eta^2 = 0.07$) and small for the immersion variable ($\eta^2 = 0.02$) [475].

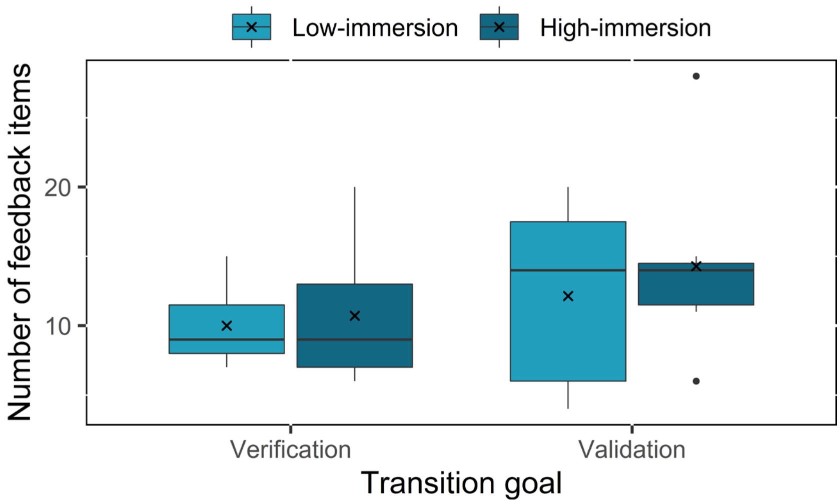

Figure 6.9 Distribution of the number of feedback items by transition goal and immersion level

6.3.3. Comparing the spatial relation of feedback items

In total, transition teams identified 184 intrinsic and 146 extrinsic feedback items. Out of the intrinsic feedback items, 108 were reported in the verification transition and 76 in the validation transition. In the verification transition, teams provided, on average, eight intrinsic feedback items in the low-immersion and 7.43 in the high-immersion environment (Figure 6.10). Furthermore, the average number of intrinsic feedback items in the validation transition was lower, with 5.71 intrinsic feedback items in the low-immersion and 5.14 in the high-immersion environment (Figure 6.10). A mixed two-way ANOVA showed that this difference in the number of intrinsic feedback items was significant between the transition goals ($F(1, 12) = 5.67$, $p = 0.035$) but not between the immersion levels ($F(1, 12) = 0.1$, $p = 0.76$). The effect size was medium to large for the transition goal variable ($\eta^2 = 0.1$) and small for the immersion variable ($\eta^2 = 0.01$) [475].

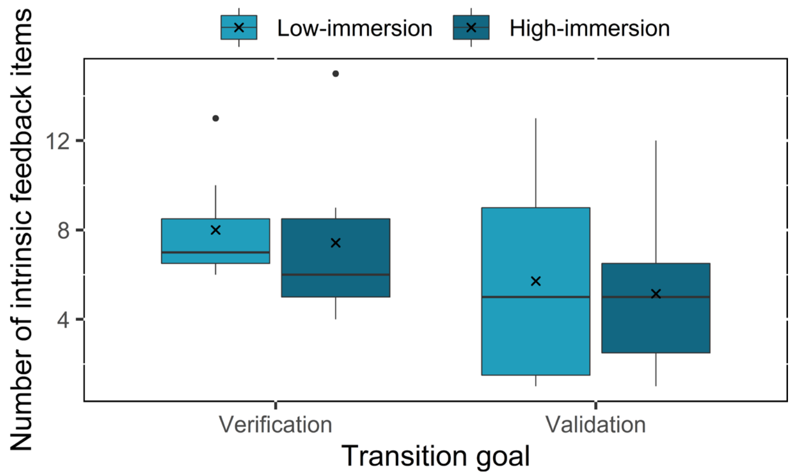

Figure 6.10 Distribution of the number of intrinsic feedback items by transition goal and immersion level

Out of 146 extrinsic feedback items, 37 were reported in the verification transition and 109 in the validation transition. In the verification transition, the average number of extrinsic feedback items was 2 in the low-immersion and 3.29 in the high-immersion environment (Figure 6.11). In the validation transition, the average number of extrinsic feedback items was higher, with 6.43 feedback items in the low-immersion and 9.14 in the high-immersion environment (Figure 6.11). A mixed two-way ANOVA showed that this difference in the number of extrinsic feedback items was significant between the transition goals ($F(1, 12) = 11.55$, $p = 0.05$) but not between the immersion levels ($F(1, 12) = 2.13$, $p = 0.17$). The effect size for the transition goal was large ($\eta^2 = 0.35$). Moreover, despite having a non-significant effect, the effect size of the immersion was medium ($\eta^2 = 0.07$) [475].

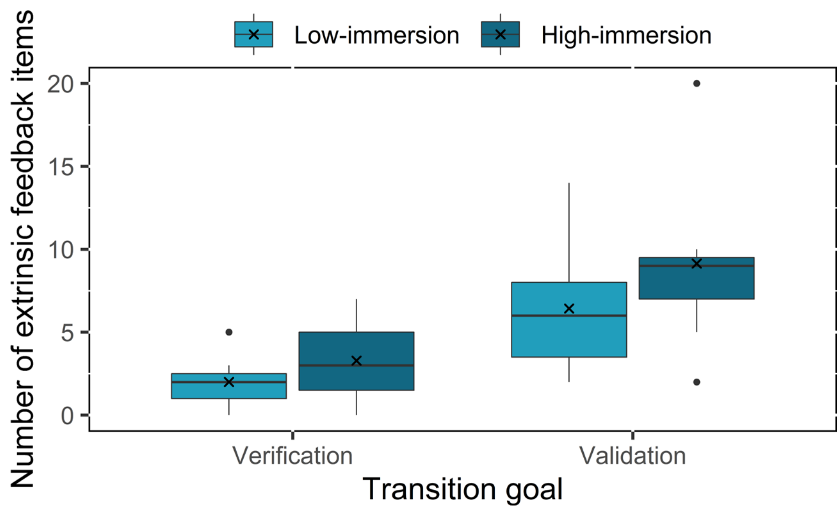

Figure 6.11 Distribution of the number of extrinsic feedback items by transition goal and immersion level

To better understand the distribution between the intrinsic and extrinsic feedback items, a proportion of extrinsic feedback items was calculated for each transition (Figure 6.12). In the verification transition, the average proportion of extrinsic feedback items was 0.19 in the low-immersion environment and 0.29 in the high-immersion environment. In the validation transition, the average proportion of extrinsic feedback items was higher, with an average of 0.57 in the low-immersion and 0.65 in the high-immersion environment. A mixed two-way ANOVA showed that this difference in the proportion of extrinsic feedback items was significant between the transition goals ($F(1, 12) = 30.29$, $p = 1.4 \times 10^{-4}$), but not between the immersion levels ($F(1, 12) = 1.07$, $p = 0.32$). The effect size for the transition goal was large ($\eta^2 = 0.47$). Moreover, despite not having a significant effect, the effect size of the immersion was medium ($\eta^2 = 0.06$) [475].

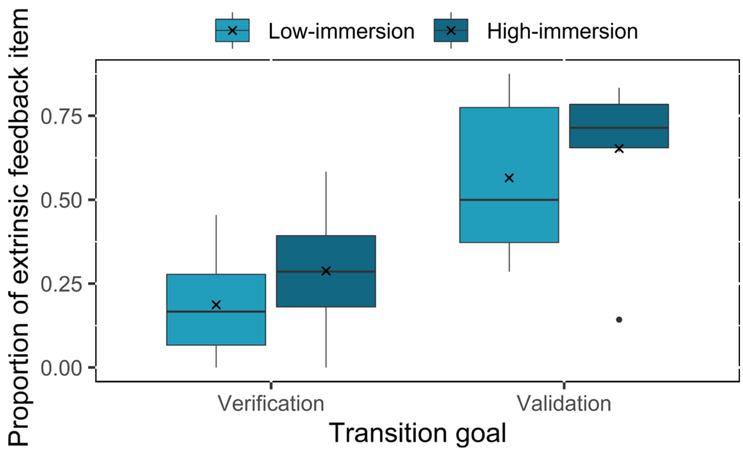

Figure 6.12 Distribution of the proportion of extrinsic feedback items by transition goal and immersion level

6.3.4. Comparing the design space of feedback items

In total, transition teams identified 83 problem-related and 247 solution-related feedback items. Out of the problem feedback items, 24 were reported in the verification transition and 59 in the validation transition. In the verification transition, teams provided, on average, one problem feedback item in the low-immersion and 2.43 in the high-immersion environment (Figure 6.13). Furthermore, the average number of problem feedback items in the validation transition was higher, with 2.86 problem feedback items in the low-immersion and 5.57 in the high-immersion environment (Figure 6.13). A mixed two-way ANOVA showed that this difference in the number of problem feedback items was significant between the transition goals ($F(1, 12) = 7.4$, $p = 0.019$) and between the immersion levels ($F(1, 12) = 8.7$, $p = 0.012$). The effect size was large for the transition goal variable ($\eta^2 = 0.28$) and the immersion variable ($\eta^2 = 0.21$) [475].

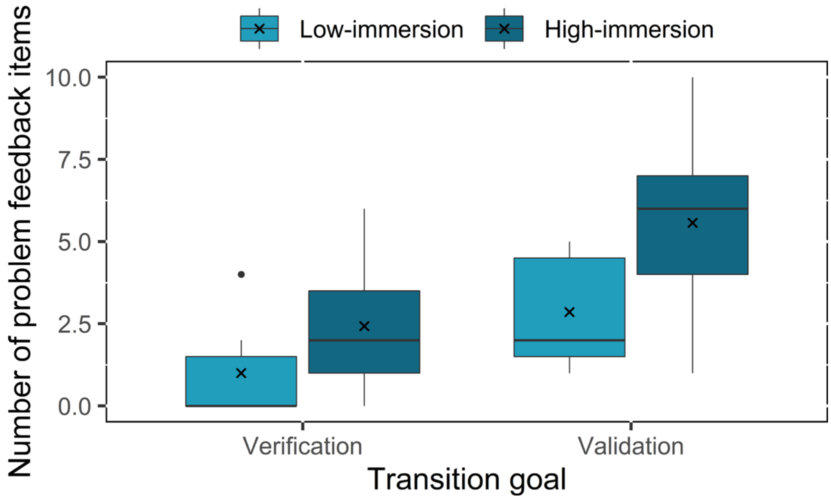

Figure 6.13 Distribution of the number of problem feedback items by transition goal and immersion level

Out of 247 solution feedback items, 121 were reported in the verification transition and 126 in the validation transition. In the verification transition, the average number of solution feedback items was 9 in the low-immersion and 8.29 in the high-immersion environment. In the validation transition, the average number of solution feedback items was slightly higher, with 9.29 items in the low-immersion and 8.71 in the high-immersion environment. Although averages in the validation session and the low-immersion environment are slightly higher (Figure 6.14), a mixed two-way ANOVA did not reveal significant differences either between the transition goal ($F(1, 12) = 0.07$, $p = 0.8$) or between the immersion levels ($F(1, 12) = 0.1$, $p = 0.76$). The effect sizes were also small, i.e., $\eta^2 = 2 \times 10^{-3}$ for the transition goal variable and $\eta^2 = 6 \times 10^{-3}$ for the immersion variable ($\eta^2 = 0.02$) [475].

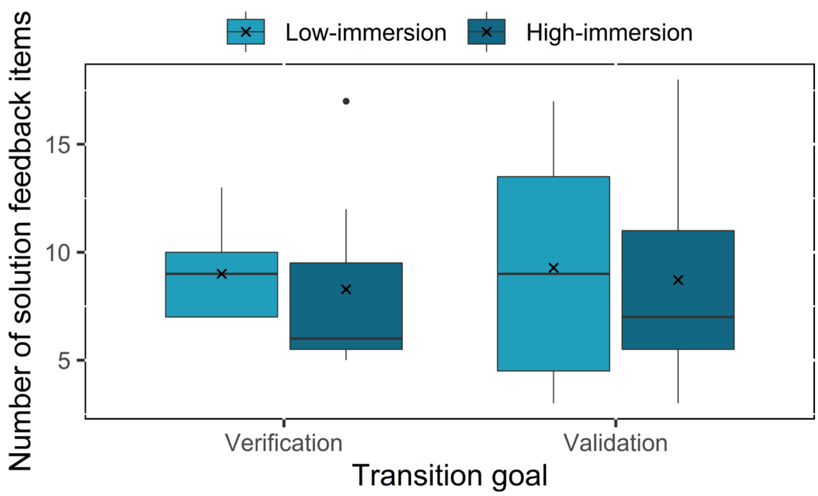

Figure 6.14 Distribution of the number of solution feedback items by transition goal and immersion level

To better understand the distribution between the problem and solution feedback items, a proportion of problem feedback items was calculated for each transition (Figure 6.15). In the verification transition, the average proportion of problem feedback items was 0.08 in the low-immersion environment and 0.22 in the high-immersion environment. In the validation transition, the average proportion of problem feedback items was higher, with an average of 0.25 in the low-immersion and 0.41 in the high-immersion environment. A mixed two-way ANOVA showed that this difference in the proportion of problem feedback items was significant between the transition goals ($F(1, 12) = 12.72$, $p = 0.004$) and between the immersion levels ($F(1, 12) = 4.77$, $p = 0.05$). The effect size for the transition goal was large ($\eta^2 = 0.35$). The effect size was large for the transition goal variable ($\eta^2 = 0.28$) and the immersion variable ($\eta^2 = 0.2$) [475].

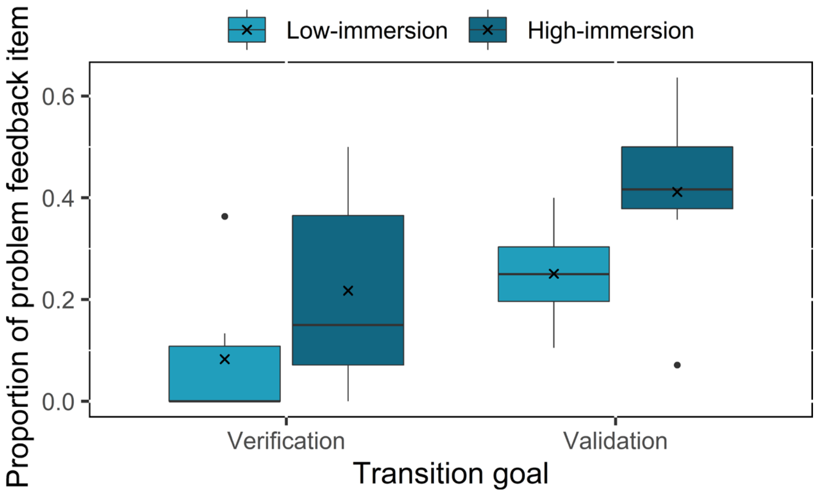

Figure 6.15 Distribution of the proportion of problem feedback items by transition goal and immersion level

6.3.5. Results from the questionnaire

The post-experiment questionnaire suggests that the design was easy to perceive in both conditions (Table 6.7). For the high-immersion environment, participants often reported that it was easy to imagine the size of the baby stroller. Furthermore, they also noted that the high-immersion environment enabled natural interaction and movement around the design and suggested that it was easy to understand the object of communication.

For the low-immersion environment, participants reported that it was easy to review details of the design components (e.g., check for misalignments). They also pointed out the possibility of working synchronously and following each other's views. Furthermore, participants also reported that the controls were intuitive because of their experience with the technology.

Table 6.7 Aggregated answers from the post-experimental questionnaire (translated from Croatian)

Question	Participants' answers
What are the good things about reviewing in a high-immersion environment?	A better sense of the dimensions Easy interaction with the design and the possibility of moving around Easy to understand what other team members were referring to Possibility to "hold" the baby stroller with my hands and estimate ergonomic aspects
What are the good things about reviewing in a low-immersion environment?	Easy to review detailed stuff around components Checking for misalignments Synchronous work and following other people's views Intuitive controls

These results show that both immersion and transition goals affect transition outcomes, supporting the relationship predicted by the team transition model. While the effect of immersion was not associated with the number of feedback items, it was positively related to extrinsic (issues related to the relationship between the design and a user or environment) and problem space issues. Both of these aspects (extrinsic and problem space issues) were also more common in the validation session. Therefore, these findings suggest that a high-immersion environment (i.e., VR) might be more suitable for transitions that are oriented towards the users and defining a problem, i.e., validation ones. The next section explores the relationship between immersion and transition team performance for the two transition goals.

6.4. The effect of immersion and transition goal on the transition team performance[28]

The main indicators of performance are efficiency and effectiveness [201]. Efficiency corresponds to the outcome produced in the activity (e.g., explored issues) per unit of resource (e.g., people, time), while effectiveness is the extent to which the results (e.g., explored issues) meet the activity goal (e.g., manufacturability, customer values). Focusing on transition outcomes through these indicators might provide insights into the execution of these processes. For instance, the higher number of feedback items [28, 32] suggests that the transition team worked efficiently. Similarly, the better final decision [205] suggests that the transition team

[28] The initial version of this section has been accepted for publication in the International Conference of Engineering Design 2023 [513].

worked effectively. However, these indicators largely depend on the inputs. For example, the initial quality of the design affects the number of feedback items, as it might be easier to identify the issues in a low-quality design than in a high-quality design. Although the randomisation of designs into conditions enables relative comparisons between the treatment and control groups, the actual performance of each transition cannot be measured using the outputs (e.g., transition report). More specifically, as reviewers report only aspects that have to be changed (i.e., they do not report positive evaluations), the outcome-related indicators present the relative change in the design space but not the performance itself (e.g., how well agents reviewed the design). Therefore, performance indicators should not consider only outcomes but also transition mediators [412].

Following the suggestions to consider different performance aspects [201] while focusing on the transition mediators [412], three dependent variables were developed: the number of discussed issues per unit of time (related to efficiency), the ratio between the number of goal-related and overall number of discussed issues (related to effectiveness), and the number of goal-related discussed issues per unit of time (related to goal-related efficiency). This section thus analyses the effect of transition goals and immersion on the design space outcomes in terms of these three variables (Figure 6.16).

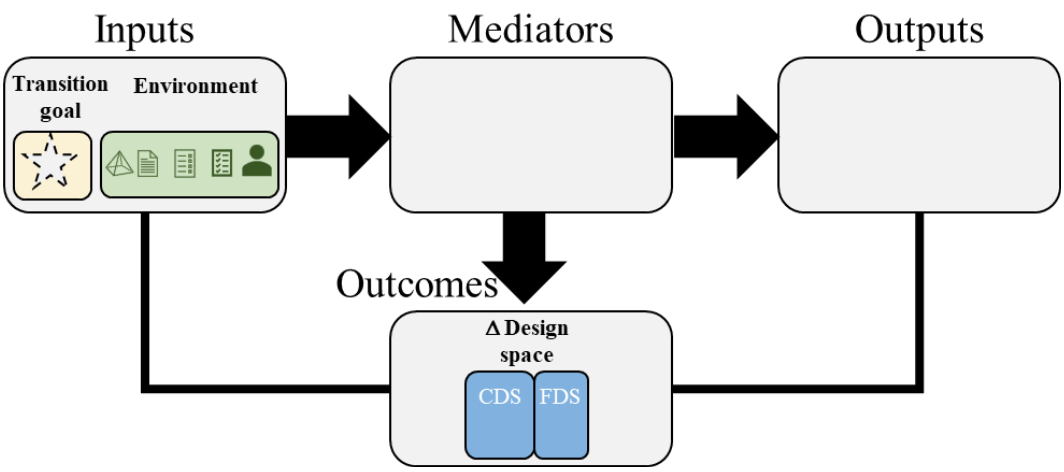

Figure 6.16 Factors considered when analysing the effect of immersion on the transition team performance

6.4.1. Analysis procedure

The data for the analysis were collected following the protocol analysis approach. First, video and audio recordings were transcribed and segmented. The segmentation step was based on actions at the team level, considering the three types of actions (understanding, evaluation, and planning) common for transitions. Second, in order to depict whether each action was related to the goal of the experimental session, a binary variable (i.e., Goal-related) was coded. The goal-relatedness was assessed by considering whether the issue discusses functionality, manufacturability, assembly, or human factor aspects (verification) or whether it is focused on customer values in terms of essential jobs, gains, and pains (validation). Third, the issue variable depicted the discussed issues during the transitions. For this purpose, an issue was defined as the set of reviewers' actions (understanding, evaluation, or planning) focusing on only one instance of the design problem and only one instance of the design solution. The issue variable consists of four codes: New (action deals with the new issue), Previous (action deals with the same issue as in the previous action), Repeated (action deals with the issue different from the one in the previous action but the one that was already discussed in the session), and Without (action does not deal with any issue). To test the reliability of the goal-related and issue coding, a second coder analysed about 7% of the data (about one hour in total). The agreement between the coders on this sample was substantial, as the inter-rater reliability calculated using Cohen's Kappa [413] was 0.79 for coding goal-relatedness and 0,72 for coding issues. An excerpt with the coded data is shown in Table 6.8.

Data were analysed by comparing discussed and goal-related issues in the two environments and across two goals (verification and validation). More specifically, a mixed ANOVA analysis with immersion as an independent sample and transition goal as a repeated measure variable was used due to the full-factorial mixed research design. All analyses were conducted in *R*.

Table 6.8 Coded excerpt from the validation transition in a high-immersion environment (translated from Croatian)

Speaker(s)	Text	Goal-related	Issue
R1/R2/R1	I took the [screenshot of the] shade, [and] the wheel / I did I did [take a screenshot of the seat]/ …and the handle, and I also took the wheel for the breaking, I would	0	Without
R1/D1/R1/R2/R1	And for that same mechanism, regarding thickening the cylinders, that would make it easier, so to speak, for everything to stay in the breaking position / yeah / I mean it would be more functional / yes / if it was [thicker]	0	Repeated
R2/D2/R2/D2	Another thing, this part on top for folding it, it really seems awkward to use, it looks robust and / yeah / and I don't like that it has right angles / yeah, alright	1	New
D2/R2	So it should be more like / again, in that rod	1	Previous

6.4.2. Comparing efficiency, effectiveness, and goal-related efficiency of transitions

In the verification transition, transition teams discussed 241 issues in the low-immersion and 253 issues in high-immersion environments. The average number of discussed issues per minute (efficiency) was 1.12 in the low-immersion and 1.15 in the high-immersion environments. In the validation session, the number of discussed issues was slightly higher, with 255 issues in the low-immersion and 263 issues in the high-immersion environments. Consequently, the average number of discussed issues per minute (efficiency) was also higher, i.e., 1.19 in the low-immersion and 1.23 in the high-immersion environments. Although averages in the validation session and the high-immersion environment are slightly higher (Figure 6.17), a mixed two-way ANOVA did not reveal significant differences either between the immersion levels ($F(1, 12) = 0.05$, $p = 0.82$) or between the transition goals ($F(1, 12) = 1.4$, $p = 0.26$). The effect size was small in both cases, i.e., $\eta^2 = 0.004$ for the immersion effect and $\eta^2 = 0.02$ for the transition goal effect [475].

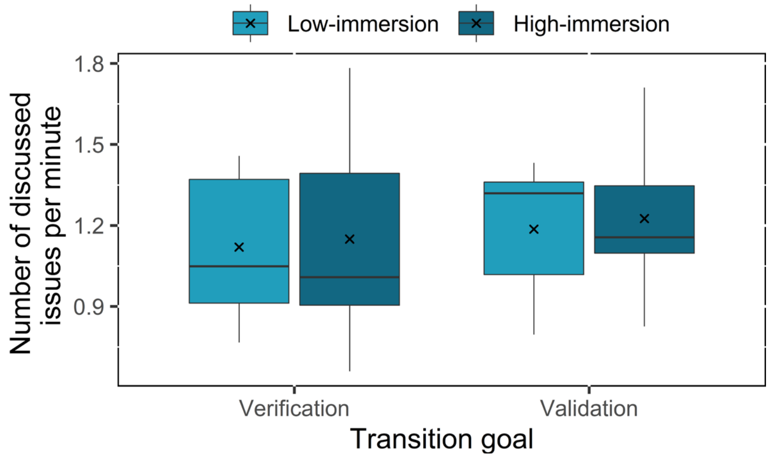

Figure 6.17 Efficiency of transition teams in transition with different goals and environments

The effectiveness was dependent on the transition goal (Figure 6.18). More specifically, while the average effectiveness in the verification session was close to one (i.e., 0.996 in low-immersion and 0.99 in high-immersion environments), the effectiveness in the validation session was 0.75 in the low-immersion and 0.9 in the high-immersion environments. A mixed two-way ANOVA showed that this difference in effectiveness was significant between the transition goals ($F(1, 12) = 49.47$, $p = 1.4 \times 10^{-5}$) but not between the immersion levels ($F(1, 12) = 0.99$, $p = 0.34$). The effect size for the transition goal was large ($\eta^2 = 0.66$). Moreover, despite not having a significant effect, the effect size of the immersion was small to medium ($\eta^2 = 0.04$) [475]. Finally, an interaction effect was also not significant ($F(1, 12) = 1.38$, $p =$

0.26), but its effect size was close to medium ($\eta^2 = 0.05$) [475]. Therefore, a post-hoc *t*-test was used to analyse whether the transition teams working in the high-immersion environment had higher effectiveness in the validation session. However, the effect of the environment on the effectiveness of the validation session was not significant; $t(12) = 1.09$, $p = 0.15$. Despite not being significant, the effect size was medium ($d = 0.58$). These results point out that the validation transition might be less goal-related. This difference between the sessions might be reduced by utilising high-immersion technologies.

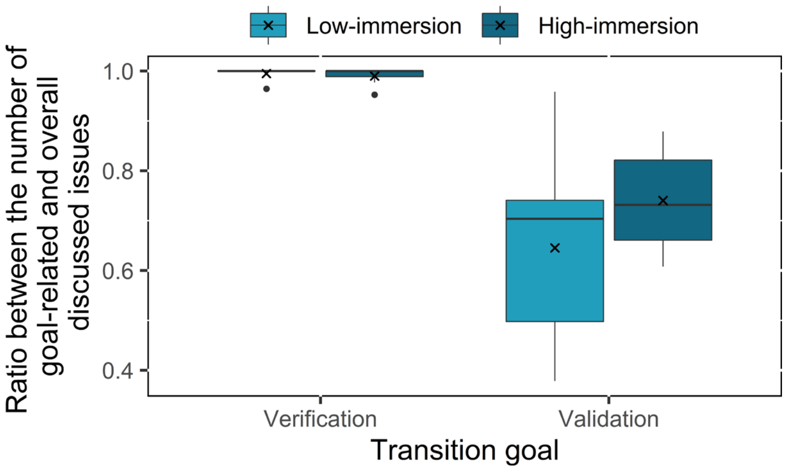

Figure 6.18 Measured effectiveness of transition teams in transition with different goals and environments

As goal-related efficiency is related to both efficiency and effectiveness, it is assumed that its behaviour follows the combination of the two. Therefore, the goal-related efficiency was also dependent on the transition goal (Figure 6.19). In the verification transition, transition teams discussed 240 goal-related issues in the low-immersion and 251 goal-related issues in the high-immersion environments. The average number of discussed goal-related issues per minute (goal-related efficiency) was 1.12 in the low-immersion and 1.14 in the high-immersion environments. In the validation session, the number of discussed goal-related issues was lower, with 160 issues in the low-immersion and 194 issues in the high-immersion environments. Consequently, the average number of discussed goal-related issues per minute (goal-related efficiency) was also lower, i.e., 0.75 in the low-immersion and 0.9 in the high-immersion environments. A mixed two-way ANOVA showed that this difference in the goal-related efficiency was significant between the transition goals ($F(1, 12) = 12.7$, $p = 0.004$) but not between the immersion levels ($F(1, 12) = 0.51$, $p = 0.49$). The effect size was large for the transition goal ($\eta^2 = 0.25$) and small for the effect of the environment ($\eta^2 = 0.03$). Following a post-hoc analysis conducted for effectiveness, a *t*-test was used to examine whether the transition teams working in the high-immersion environment had higher goal-related efficiency in the validation session. The effect of the environment on goal-related efficiency in the validation session was significant; $t(12) = 1.36$, $p = 0.099$. The effect size was medium to large ($d = 0.73$). Overall, these results point out that the validation transition might be more difficult to execute in the analysed sample. However, this difference between the sessions might be reduced by utilising high-immersion technologies.

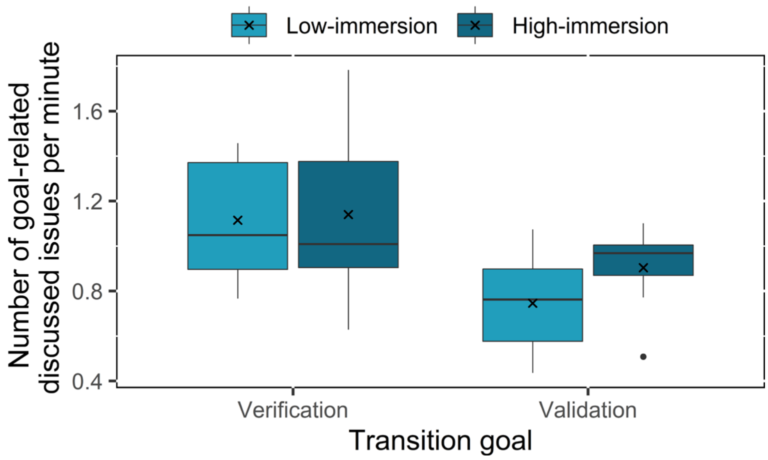

Figure 6.19 Measured goal-related efficiency of transition teams in transition with different goals and environments

These results show that immersion affects transition outcomes through team performance, supporting the relationship predicted by the team transition model. The effect of immersion was mainly related to the effectiveness aspect of the validation session, which then also persisted in goal-related efficiency. Moreover, the validation session consistently had lower effectiveness than the verification one, suggesting that its goal was more difficult for the transition teams. Therefore, these findings suggest that the usage of high-immersion environments (i.e., VR) might result in better addressing the validation goal. Furthermore, high-immersion environments might produce output that is more related to changing the design problem, which might have long-term consequences for subsequent activities. The next section explores the relationship between immersion and taskwork in the subsequent activities.

6.5. The effect of transition on the subsequent activities

The transition outcomes are affected by the environment (see Sections 5.4, 6.3, and 6.4). Therefore, the output of transition activities also depends on the environment, suggesting that this factor might affect subsequent development activities. Therefore, the focus of this section is to analyse the effect of immersion on subsequent development activities (Figure 6.20). This analysis provided additional evidence for evaluating the team transition model and testing the second part of the hypothesis.

The different goal-related efficiency, coupled with the different contexts of the outcomes, suggests that immersion affects the rework phase of the course. More specifically, given that the VR transitions support the focus on problem space aspects, it might be that the final design changed more after the high-immersion transition. It is thus assumed that design teams might require more actions to address reviewers' comments generated during the high-immersion transition. Therefore, the first variable related to work in subsequent activities is the number of actions design teams execute to address the reviewers' comments – a commonly studied metric to assess design work [449, 450]. In addition, given that the problem space aspects change the design goal, the final design might have to satisfy these new requirements. Consequently, design teams might need to create design components (e.g., a cup holder) that did not exist before. In contrast, the focus on the solution space aspects in a low-immersion environment might result in design teams mainly editing the current design entities. Therefore, the second analysed variable was the ratio between the number of creation actions and the overall number of actions. Specifically, following the prior procedure, actions were divided into those related to the creation (e.g., creating a new feature) or revision (e.g., editing, deleting) of the design content [476].

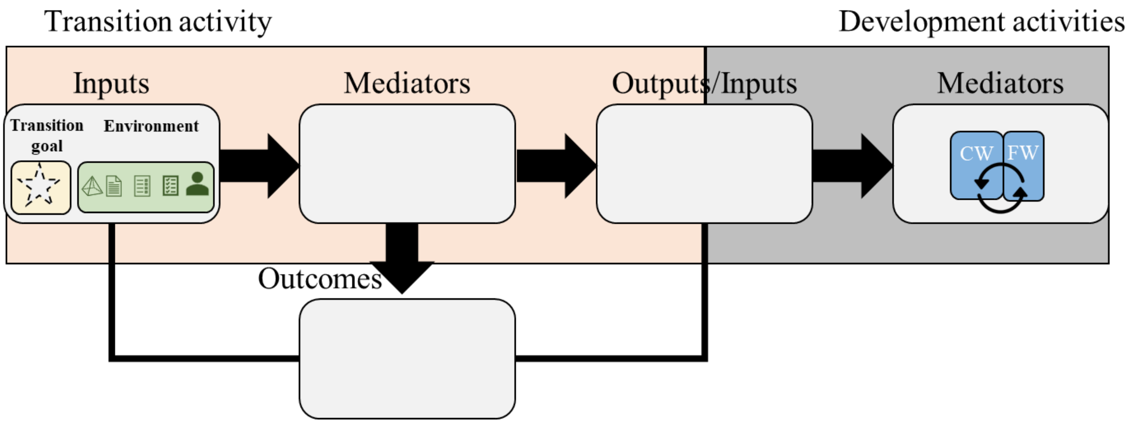

Figure 6.20 Factors considered when analysing the effect of immersion in the transition on the subsequent development activities

6.5.1. Analysis procedure

Being the main boundary object during the transitions, as well as the main outcome of the course, the actions during the rework phase were captured by tracking the CAD changes, i.e., gathering the CAD log data. The process follows a work sampling approach [477], with data being collected in a non-intrusive manner. More specifically, data was collected with *Onshape Analytics*[29] by collecting logs of actions that users executed within the CAD environment. The total number of actions collected this way was 138 995 before the transition and 16 428 after the transition. However, as the focus of this subsection is on analysing the CAD changes, only the actions related to the design changes are included, i.e., actions such as those related to design organisation (e.g., renaming documents, opening parts) were removed from the dataset. Therefore, the sample consisted of 122 213 actions before the transition and 15 270 actions after the transition. These actions were classified into creation or revision classes following the previously developed classifications [449, 450, 478]. Table 6.9 provides an overview of the classification of CAD actions into creation and revision.

Table 6.9 Classification of CAD actions into creation and revision

Creation actions	Revision actions
Add part studio feature, Copy paste sketch, Add assembly instance, Add assembly feature, Linked document insert, Paste: instance	Start edit of part studio feature, Move part, Start edit of assembly feature, Set mate values, Configure suppression state, Start assembly, Move to origin, Load named position, Replace part, Fix part, Unfix part, Suppress part, Assign material, Change part appearance, Delete part studio feature, Delete assembly feature, Delete assembly instance, Cancel operation, Reset mates to initial positions, Restore previous

6.5.2. Comparing the development actions before and after the transition in low- and high-immersion environments

The number of design-related actions was higher before the transition than after (Figure 6.21). More specifically, teams executed an average of 9106 actions before the transition in the low-immersion environment and 8353 before the transition in the high-immersion environment. The number of actions was, on average, 960 after the transition in the low-immersion environment and 1221 after the transition in the high-immersion environment. As expected, a mixed two-way ANOVA showed that this difference in the total number of actions was significant between the design process phases ($F(1, 12) = 72.4$, $p = 2 \times 10-6$) but not between the immersion levels ($F(1, 12) = 0.05$, $p = 0.83$). The effect size was large for the transition goal ($\eta 2 = 0.7$) and small for the effect of the environment ($\eta 2 = 0.002$).

[29] *Onshape Analytics* – an Onshape feature that automatically tracks actions that designers execute during CAD modelling.

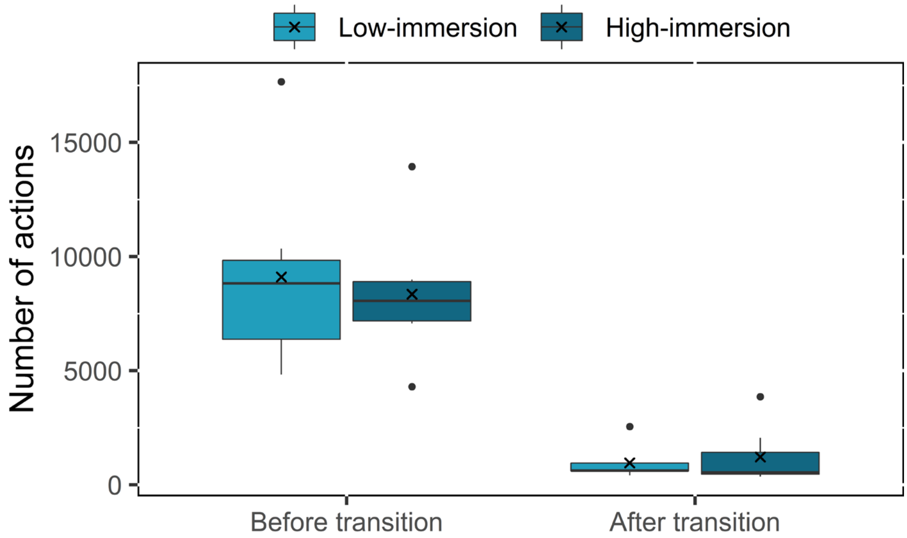

Figure 6.21 The number of conducted actions as a function of the design phase and transition environment

In order to compare the actions before and after transitions, a proportion of creation actions was calculated for each period. In the phases before transition, the average proportion of creation actions was 0.22 for teams that later conducted a transition in the low-immersion environment (this was not known until the transition) and slightly lower (0.21) for teams that later conducted a transition in the high-immersion environment (Figure 6.22). The average proportion of creation actions in the rework phase was 0.21 for teams that would have the transition in low-immersion environment and 0.25 for teams that would have the transition in high-immersion environment. A mixed two-way ANOVA showed that this difference in the proportion of creation actions was not significant between the phases ($F(1, 12) = 1.63$, $p = 0.23$) or the immersion levels ($F(1, 12) = 0.38$, $p = 0.55$). The effect size was small for both effects, i.e., $\eta^2 = 0.02$ for the effect of phase and $\eta^2 = 0.03$ for the effect of immersion [475].

Finally, an interaction effect was significant ($F(1, 12) = 8.24$, $p = 0.014$), and its effect size was large ($\eta^2 = 0.14$) [475]. More specifically, the low-immersion environment reduced the proportion of creation actions after the transition, while the high-immersion environment increased the proportion. Therefore, matched pair post-hoc *t*-tests were used to test whether the proportion of creation actions significantly decreased after the transition in the low-immersion environment and whether the proportion of creation actions significantly increased after the transition in the high-immersion environment. On the one hand, the proportion of creation actions before and after the transition in the low-immersion environment was not significantly different; $t(6) = 0.95$, $p = 0.19$. The effect size was small ($d = 0.38$). On the other hand, the proportion of creation actions after the transition in the high-immersion environment was significantly higher than before the transition; $t(6) = 3.82$, $p = 0.004$. Moreover, the effect size was large ($d = 1.24$). These results point out that the immersion of the transitions might affect the subsequent phases.

The average proportion of creation actions after the transition was 0.21 for teams that had the transition in the low-immersion environment and 0.25 for teams that had the transition in the high-immersion environment (Figure 6.22 right). However, a t-test showed that this difference was not significant; $t(12) = 1.51$, $p = 0.16$. Despite not being significant, the effect size was large ($d = 0.81$). These results suggest that transitions executed in the high-immersion environment might result in more actions related to the creation of new content than revising the existing content. This finding is in line with the higher focus on problems rather than solutions during the transitions in the high-immersion environment.

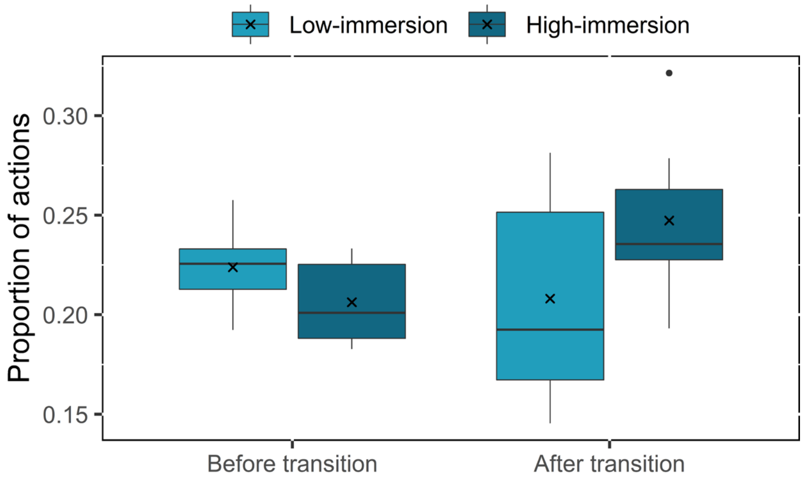

Figure 6.22 Proportion of creation actions before and after transitions

6.6. Chapter conclusion

By following the experimental framework, the experiment provided evidence for its evaluation. Furthermore, the study also gathered evidence that supports the team transition model. Studying the effect of environment (i.e., immersion) and transition context (i.e., transition goal) characteristics on design space outcomes (i.e., change in the design space in terms of performance and context) revealed various relationships that support the team transition model. These relationships suggest that VR might improve the execution of validation transitions. In addition, transitions related to the problem space and extrinsic aspects (i.e., the relationship between the design and users or environment) might also be improved. Therefore, these findings provide evidence to test the second part of the hypothesis (*VR technologies improve the execution of evaluation/planning activities*). These results are discussed in the validation and verification of the models and the framework (Chapter 7).

7. VALIDATION AND DISCUSSION

This chapter first identifies validation criteria and presents validation of the theoretical models and the experimental framework. Then, two parts of the research hypothesis were verified, and the research questions were revisited. Finally, the implications and limitations of the research were discussed, and future work was proposed.

The proposed theoretical models and the experimental framework were tested by validation [479]. The validation implies testing the statements that can be derived from the models and the framework [479]. Testing the statements derived from the models and the framework includes structural and performance validation [87, 480]. Structural validation is focused on validating the model and the framework factors, both individually and integrated. This aspect also includes validating that empirical studies reflect the problems for which the factors are generally accepted. Performance validation is focused on testing the model and framework for the studied problem and accepting that the results refer to the relationships predicted by the model (i.e., internal validity). This aspect also aims at elaborating that the model and the framework can be applied beyond the studied problems. Therefore, these two aspects were used to validate the models and the framework, forming the first two criteria of the validation: structural and performance validity.

Structural and performance validity can be assessed through empirical observation and theoretical discussion [481]. Therefore, testing the statements in the design discipline can be conducted with different levels of empirical support, suggesting that validation is a long-lasting process [482]. Following this principle, contributions are initially tested in the laboratory under controlled conditions. During this process, specific statements derived from the models and the framework can be falsified, but this falsification does not refute the contributions. Rather, this falsification updates the contributions so that they also describe the new findings. After various laboratory experiments, contributions are tested in industrial environment. Therefore, as an initial step in testing the models and the framework, a third validation criterion is that contributions are valid in a laboratory environment.

Following the validation criteria to have structural and performance validity [87, 480] in a laboratory environment [482], the main contributions were validated: the model of the team transition processes (Section 7.1), the team transition model (Section 7.2), and the experimental framework (Section 7.3). Based on the empirical findings and the validation, the research hypothesis was discussed in Section 7.4, while the research questions were revisited in Section 7.5. Finally, implications of the conducted research were discussed (Section 7.6), limitations were acknowledged (Section 7.7), and future work was proposed (Section 7.8).

7.1. Validating the first contribution: model of team transition processes

The model of team transition processes (Section 3.1) is developed as an answer to the first RQ and consists of elements describing the transition state and transition actions. The transition state is modelled with agents that have uncertainty and affect, the information content with a design problem, design solution, transition report, transition goal, and avatars, the design space with current and future design, and the other transition elements (e.g., current design phase). This state advances through teamwork and the taskwork of transition actions. While taskwork of transition actions (e.g., understanding, evaluation, and planning) describes changes in the value of transition state elements, teamwork describes how they change (e.g., all-together, sub-team). This model has been empirically tested in Section 5.5. The following subsections discuss its structural and performance validity (see Figure 7.1 for the validation process).

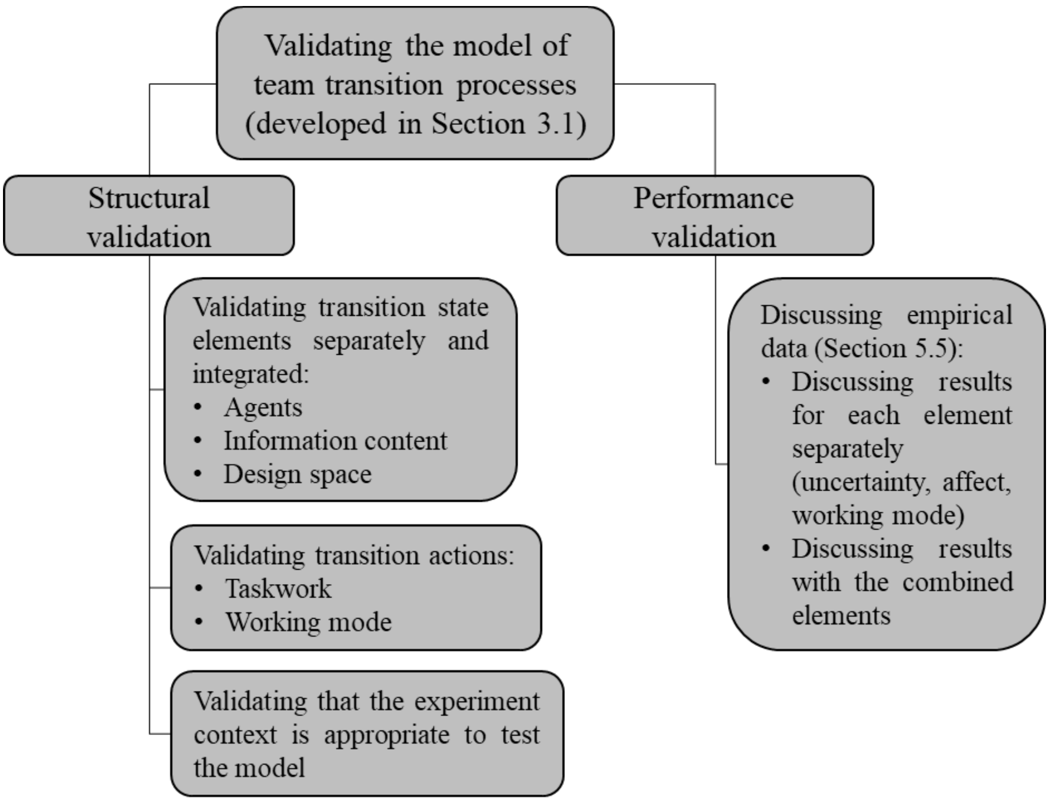

Figure 7.1 Validation process for the model of team transition processes

7.1.1. Structural validity

The structural validity of the model of team transition processes consists of validating transition state elements and transition actions separately, their integration, and the experiments used to empirically test the model. Validating transition state elements includes validation of modelled agents, information content, and design space. Firstly, an agent is modelled with their uncertainty and affect levels (Subsection 3.1.1). These emergent characteristics are accepted, as both of them have been found to influence the design at the micro-scale. More specifically, uncertainty affected the design through the metacognitive lens and was often used to predict actions [60, 143, 146]. Similarly, affect has also been identified as a driver of design work [147]. The affect might be even more emphasised in a team setting, as it is transmittable between agents [335] and has an important role in relating an agent with other agents [335]. Moreover, the well-documented impact of affect on cognition [184] proposes that both affective (i.e., affect) and cognitive (i.e., uncertainty) states should be considered together, thus accepting their integration.

As another element in the transition state, the design space has been separated into current and future designs (Subsection 3.1.1). This distinction is in line with the design space definition, as it describes a set of all possible design solutions for the design problem [41], both the current and possible future ones. Differentiating the current and future designs is also in line with the definition of transitions, as they are used to evaluate the current and plan future work. Therefore, the structural validity of the design space element is accepted.

Furthermore, information content (IC) serves as a medium between the design space, agents, and other transition elements (Section 3.1.1). The design space IC relates to the current state of the design problem and solution (common characterisations of the design space [4, 35, 39, 41]) and to the future state of the design (e.g., report template) [2, 7, 133]. In addition, as transitions are goal-oriented activities, the IC related to the transition goal (e.g., a checklist) is also used to describe the transition state. The IC element thus provides an information layer to the transition state elements (i.e., agents and design space) that were accepted to be structurally valid. Moreover, these IC elements are commonly utilised during the transitions, as agents (represented with avatars) discuss design problems and solutions based on the specific transition goal (i.e., IC of the other transition elements) and report the identified issues [2, 77, 132], thus accepting both separate and integrated structural validity of the IC element.

Validating transition actions includes the validation of the taskwork of transition actions and working mode. Based on the definition of transitions, the elements of the states are transformed with transition actions (Subsection 3.1.2). While the various actions can characterise transitions, three of them are of particular importance for these activities [2, 4, 5]: understanding, evaluation, and planning. The evaluation and planning actions are directly linked to the goal of transitions (i.e., evaluation of current work and planning of future work), thus suggesting their structural validity. In order to execute these goal-oriented actions, understanding is often considered a prerequisite [127]. As these three actions complement each other, their integrated structural validity is accepted. Finally, the working mode depicts how agents execute actions (Subsection 3.1.2), and its division into all-together and sub-team work is of particular importance for decision-oriented activities such as transitions. Therefore, the working mode is structurally valid.

The experiments used to empirically test the model (Chapter 5) have been developed to adhere to the model's intended purpose. Studying transitions as part of the larger case provides ecological validity, making them similar to the transitions for which the model is intended. Furthermore, the IC in the empirical studies included artefacts according to the model, i.e., transition teams were provided with design problem artefacts (i.e., a list of requirements), design solution artefacts (i.e., CAD models), a transition report (i.e., a template to capture the issues), and a transition goal (i.e., a checklist to guide them), while transition team members were represented by avatars (i.e., digital avatars). This information content has been commonly utilised in the studies of transitions [2, 5, 133], thus providing support for structural validity. In addition, teams with external and internal members have been commonly utilised for transitions [68, 76], where more experienced members provide comments to less experienced members. Based on this discussion, the structural validity of the model of team transition processes is accepted. The next subsection discusses the performance validity of the model.

7.1.2. Performance validity

The model of team transition processes showed its usefulness in the first experiment as the three transition actions differed in terms of uncertainty, affect, and working mode. More specifically, the results showed that the transition characteristics depicted in the model of team transition processes (i.e., uncertainty, affect, and working mode) could be used individually but that they perform better when considered together (Section 5.5).

The individual considerations of uncertainty across transition actions (Subsection 5.5.2.1) align with the findings that uncertainty might be a driver of design work [60, 143, 146, 175, 483]. Moreover, the significantly higher uncertainty for the evaluation and planning actions (Subsection 5.5.2.1) aligns with the prior work on mental simulations and analogies as strategies to cope with uncertainty [146] that are mainly employed during these actions [146]. Therefore, the performance validity of uncertainty and transition actions has been accepted.

Results also show that affect was lowest during evaluation action and highest in planning (Subsection 5.5.2.1). These findings resemble Dong et al.'s [147] notion that negative affect causes designers to focus more on technical data and analysis (understanding and evaluation), while positive affect allows them to proceed onward (planning) by relying on prior knowledge. Furthermore, the identified higher affect in high-immersion environments (Subsection 5.5.3.1) is consistent with prior studies on individuals [18]. Therefore, the performance validity of affect and transition actions has been accepted.

Next, although working mode and actions were not associated in the whole dataset (Subsection 5.5.2.1), they were associated in low-immersion and high-immersion environments. These results confirm the prior finding that working mode varies across actions [154] and extend it by proposing that the environment might moderate this association. Furthermore, working mode and environment were associated (Subsection 5.5.3.1), suggesting that a change in the environment would influence working mode. These results align with the social presence theory [454] and empirical findings that the use of high-immersion environments might support teamwork [27–29, 484]. Therefore, the performance validity of working mode, environment, and transition actions has been accepted.

Furthermore, uncertainty, affect, and working mode were considered together with the hierarchical multinomial logistic regression (Subsections 5.5.2.2 and 5.5.3.2). The gathered results provided evidence for the integrated validity of the modelled characteristics for the analysed transition. Moreover, all the integrated regression models showed satisfactory predicting power (AUC > 0.6) for the whole dataset, low-immersion subset, and high-immersion subset. Uncertainty prediction was similar in general, low-immersion, and high-immersion models (Subsection 5.5.4), suggesting its universality and providing evidence of its importance in the design discipline [60, 143, 172]. Similarly, the prediction behaviour (sign and coefficient) of the affect was similar in general, low-immersion, and high-immersion models (Subsection 5.5.4). Finally, the working mode depended on the environment, as planning actions were usually conducted in a sub-team within a low-immersion environment and with all members together within a high-immersion environment (Subsection 5.5.4). As the planning actions were also associated with the agents being most uncertain and positive, the high-immersion environment resulted in all members working together in these uncertain and emotional moments. These results are in line with the notion that designers influence each other's thoughts and rationales [45, 191–194], showing the importance of working mode during transitions.

The usefulness of the developed model in the empirical study, coupled with the internal validity of the experimental study (discussed in Subsection 7.3.2), supports the performance validity of the model. Altogether, the statements derived from the model of team transition processes demonstrated both structural and performance validity in the laboratory experiment. Although broader validity was theoretically discussed, future studies should collect empirical data on the other statements that could be derived from the model. In addition, future studies should also test the model in an industrial environment.

7.2. Validating the second contribution: model of team transitions

The model of team transitions (Section 3.2) is also developed as an answer to the first RQ but on the meso-scale level. Inputs in the model correspond to the initial transition state, while outputs to the final transition state. Similarly, outcomes correspond to differences between outputs and inputs and are also represented by the transition state elements. Mediators consist of team behaviour and emergent factors. Team behaviour can be directly mapped to the transition processes in terms of taskwork and teamwork. Emergent factors represent dynamic changes in cognitive and affective aspects. This model thus embraces complexity and assumes many relationships. The following subsections discuss the structural (Subsection 7.2.1) and performance (Subsection 7.2.2) validity of the model (see Figure 7.2 for the validation process).

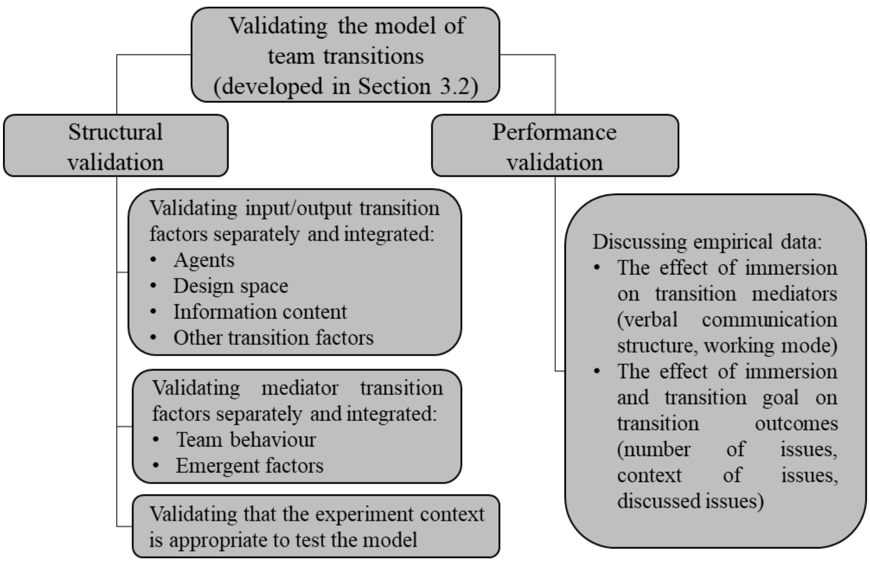

Figure 7.2 Validation process for the model of team transitions

7.2.1. Structural validity

Most of the elements in the team transition model are based on the micro-scale model, whose structural validation has been comprehensively discussed in the previous section. Furthermore, as the model elements were detailed by factors (Section 3.2), this subsection discusses them separately, their integration, and the experiments used to empirically test the model.

Input factors (i.e., those related to design space, team/agents, information content, and other transition elements) were based on the commonly utilised models of team performance (see Subsection 2.4.3 for an overview of the models). This mapping of the model of team transition processes to models in management literature ensured comprehension when detailing the elements. For example, team/agents have been divided into composition and context, thus adhering to a commonly accepted conception of dividing the team factors into agent, their combination (i.e., composition), and structural characteristics of the team (e.g., size, hierarchy) [248–251]. Therefore, the team factors are accepted as structurally valid. Next, design space has been divided into current and future design factors, adhering to the two goals of transitions and design space definition (see 7.1.1 for a more comprehensive discussion).

The conceptualisation of IC into environment and artefact factors contrast prior suggestions of having these two factors coupled. The misconception probably arises from traditional user interfaces, as interaction was determined by the digital or physical constitution of artefacts. Interaction with physical artefacts was like everyday interaction with objects, while interaction with digital artefacts usually includes a mouse, keyboard, and monitor. However, the proliferation of new human-computer interaction technologies (e.g., VR) enabled the use of various interaction techniques with the same artefacts [485, 486]. Therefore, these two factors are structurally valid.

Finally, factors related to other transition elements, such as design process, transition task context, organisation context, and culture, were also derived from the description of team inputs divided into task context (i.e., design process and transition task contexts), organisational context, and culture [248, 249]. The task context has been divided to differentiate between isolated (i.e., transition task contexts such as transition goal and working approach) and integrated (i.e., design process contexts such as design phase and integration level) factors. Therefore, all the input factors show individual structural validity. In addition, as their development is based on the team model, their integrated structural validity is also accepted.

Similarly, mediators are also developed based on the models from the team performance literature, thus accepting their structural validity. More specifically, transition actions are mapped onto team behaviour, while changes in agents' states are mapped onto emergent factors. These two elements are commonly used to describe mediators in the team literature, thus providing evidence to accept their structural validity. In addition, team behaviour has been divided into teamwork and taskwork, while emergent factors are divided into cognition and affect (Subsection 3.2.2), adhering to both the model of team transition processes and the models of team performance. Therefore, the structural validity of mediators is also accepted.

The experiments used to empirically test the model have been developed to adhere to the model's intended purpose, as both experiments were part of the larger case. Accepting the context of the empirical study has been discussed in Subsection 7.1.1. Additionally, the experiments were also designed to adhere to the model's purpose, as they enabled tracking inputs, mediators, and outcomes. More specifically, the experiments were conducted in an ecologically valid environment that enabled the measurement of mediators. Based on this discussion, the structural validity of the team transition model is accepted.

7.2.2. Performance validity

The proposed model was useful in the context of the experiments, as shown by several identified relationships. More specifically, the effect of immersion and transition goals on mediators (Subsection 7.2.2.1) and outcomes (Subsections 7.2.2.2, 7.2.2.3, and 7.2.2.4) has been identified. These relationships could be established due to the internal validity of the experiment (discussed in Subsection 7.3.2), established mainly by having a true experiment design (treatment and control groups with the random assignment) and by controlling all the inputs that were not part of the experiment. This control has been made feasible as the number of input factors has been designed to address humans' information processing limits [487].

7.2.2.1 The effect of immersion on the mediators

The effect of immersion and transition goals on mediators has been visible in terms of the effect on verbal communication structure (Subsection 5.3.2) and working mode (Subsections 5.5.2 and 5.5.3). For example, the lower average proportion of verbal communication (Subsection 5.3.2) suggests that team members communicate less in high-immersion environments. These results might be because of different social cues in the two environments, as the high-immersion one displays the position and orientation of the participant's head and controllers. Hence, it might be that review teams used other communication modes to replace a portion of verbal communication in a low-immersion environment. Another explanation might be that team members in a high-immersion environment were always in a shared space, which might result in higher awareness of members' actions [134, 309], thus requiring less verbal communication.

Furthermore, turn sequences between reviewers and designers were higher than turn sequences among reviewers (Subsection 5.3.2). Hence, transitions had dyadic sequences between one of the reviewers and a designer. These results align with the theoretical assumptions of the mixed review team and the role of understanding action during transitions [2, 5] rather than being conducted in advance [32, 133]. Moreover, the central role of a designer in verbal communication during transitions is in line with the qualitative findings, as designers explain the progress of their work and often try to persuade external members during transitions [68].

As another aspect of the verbal communication structure, the first-order turn sequences were different between the two environments (Subsection 5.3.2). As reviewers also had the lowest portion of turn sequences, these results suggest that high-immersion environments might equalise the engagement of transition team members. The possible explanation is again related to the higher number of social awareness cues and the use of shared space in immersive conditions, as team members might be more aware of each other. Consequently, reviewers might have collaborated more in a high-immersion than in a low-immersion environment, suggesting that the decisions in a high-immersion environment are made with all members together (i.e., agreed upon on a team level – see Subsection 5.5.4). Indeed, these results are aligned with the perception of transition team members that a high-immersion environment provides better communication [28], fuller participation [29], and improved collaboration [27, 32]. Based on these findings, the performance of the team transition model related to the relationship between inputs and mediators is accepted as valid. The next subsection discusses the relationships between inputs and the number of feedback items (Subsections 7.2.2.2), the context of feedback items (Subsections 7.2.2.3), and the discussed issues (Subsection 7.2.2.4).

7.2.2.2 The effect of immersion and transition goal on the number of issues

The effect of immersion on the number of feedback items has provided contradictory evidence. On the one hand, the results in Section 5.4 showed a decreased number of feedback items in the high-immersion environment. On the other hand, Subsection 6.3.2 showed that the number of feedback items was not significantly different. This misalignment might be due to several reasons, such as the tools used [34, 234], the transition goal [5], and the design context [33, 273, 488]. Regarding the tool used, previous results suggest that the same environment with different functionalities might result in different transition outcomes [34, 234]. For example, as high-immersion environments usually support more social cues, the transition team members might have worked all-together [134, 309]. As a result, teams might have a lower amount of independent individual work and fewer feedback items. However, different high-immersion environments might support different social cues (e.g., different avatars), which might have affected this working mode and, consequently, the number of feedback items. Moreover, high-immersion environments might also support different functionalities that might support teams more or less. Therefore, in order to better understand the effect of immersion on the number of feedback items, future studies should consider other characteristics of the environment as well (see Table 3.3).

Next, the transition goal might moderate the effect of immersion, as previous studies that found a reduced number of feedback items in a high-immersion environment focused on transitions related to verification (e.g., manufacturing and assembly) [28, 29]. Hence, it might be that the low-immersion environment was more suitable for these transition goals. This was partially supported by the post-experimental questionnaire (see Subsection 6.3.5), in which participants suggested that a low-immersion environment was more suitable for detailed review (e.g., checking the collision). Therefore, the transition goal might moderate the effect of immersion on the number of proposed feedback items.

Finally, the size and complexity of the design solution might also play a role, as researchers previously argued that high-immersion environments might be more suitable for larger and more complex artefacts than for smaller and less complex ones [33, 273, 488, 489]. For example, although the studied designs have a similar level of complexity, the largest design in size (weightlifting equipment) had a higher ratio of feedback items in a high-immersion than in a low-immersion environment. In contrast, the smallest design in size (tricycle) had a higher issue ratio in low-immersion compared to the high-immersion environment. These results align with the theoretical assumptions that users perceive objects of different sizes differently [490] and that high-immersion environments might help in reviewing larger designs [33].

Although the effect of the environment on the number of identified issues remains unclear, possible confounding factors for the contradictory results are captured by the team transition model. These alternative explanations derived from the model provide evidence for the performance validity of the relationship between immersion and the number of feedback items.

7.2.2.3 The effect of immersion and transition goal on the context of issues

Immersion and the transition goal also affect the context of feedback items. In the high-immersion environments, the transition teams focused more on the interaction between the design solution and environment (e.g., users, physical environment) when compared to the low-immersion environment (Subsections 6.3.3 and 6.3.4). These kinds of issues were also more common for the validation transition goal. Focusing on different contextual aspects of a design solution might be rooted in the effects that high-immersion environments have on the sense of presence. The first effect of the high-immersion environment on the presence is related to the higher number of simulated sensory cues [15, 491] and, consequently, the better spatial perception of the design solution, as indicated by various researchers [17, 22, 24, 488] and confirmed by the post-experiment questionnaire. The increased spatial perception makes it easier to perceive the object in relation to the user [492], which is important for analysis tasks such as ergonomic assessments [493]. Another effect of presence that might be relevant to the relationship between immersion and spatial relations is a better perception of what others are doing (see Table 6.7). Seeing others interact with the product might help participants see how the design solution might be used and hence support the identification of issues focused on the interaction between the solution and environment (i.e., extrinsic issues). Therefore, the identified relationship between immersion and the spatial context of feedback items provides evidence to accept the performance validity of the team transition model.

Another contextual aspect of issues affected by immersion and the transition goal is the design space of feedback items. The significantly higher number and proportion of problem-related feedback items in the high-immersion environments (Subsection 6.3.4) indicate their better suitability for the early phases since these phases rely heavily on the co-evolution of problem and solution spaces [131]. Similarly, the significantly higher number of problem-related issues in the validation transition (Subsection 6.3.4) suggests that this goal might be better suited in the early phases. Several mechanisms through which immersion affects users might play a role in this finding. First, improved spatial understanding [22, 24, 488] and partially improved contextual understanding [315, 316, 494] of design artefacts in high-immersion environments might affect the problem and solution space exploration. More specifically, the improved understanding might result in lower cognitive load in high-immersion environments [436], thus leaving more mental capacity for other actions that support problem and solution space exploration, such as generative sensing [157] and mental simulations [483]. Another reason might be due to the support of different spatial mechanisms in high-immersion than in low-immersion environments [490, 495], resulting in more natural interaction and navigation (see Table 6.7). Indeed, users in high-immersion environments feel a stronger sense of presence [15], which might thus make them more aware of the context in which the product is used and make it easier for them to perceive the problem space. Finally, priming might also partially explain these results [18, 496]. For example, while exploring the design solution in a high-immersion environment, transition teams might take advantage of previous experience in the real world [33]. In this context, transition teams might focus more on real-world scenarios, such as use cases and assessments of the problem space. As CAD tools are most often utilised in later design phases [497], working in a low-immersion environment might prime transition teams to think more about the aspects they often do in CAD tools, i.e., detailing (e.g., checking for misalignments and collisions). Therefore, the identified relationships between immersion and the context of feedback items (spatial and design space) provide evidence to accept the performance validity of the team transition model.

7.2.2.4 The effect of immersion and transition goal on the discussed issues

Another relationship that has been established relates to the issues discussed during the session in terms of effectiveness and goal-related efficiency. The lower effectiveness and performance of the validation transition as compared to the verification one (Subsection 6.4.2) suggests that the validation might be more difficult for mechanical designers. Specifically, a transition is affected by team expertise [67], and mechanical designers might be more suitable for verification problems [63]. Therefore, it is not just the goal that affects transition but the fit between the goal and the background of the transition team. For example, mechanical designers often work with more defined problems than industrial designers, suggesting that they might be better suited for verification transitions. This difference confirms findings that transitions are conducted with stakeholders that have various backgrounds [68].

The results also show that the high-immersion environment is more suitable for validation transitions, as teams in this environment had higher performance than in low-immersion validations (Subsection 6.4.2). These results are in line with the finding that high-immersion environments might support divergent thinking [46]. Divergent thinking is an important aspect of validation, as these transitions require the interpretation of customer values before evaluating and planning the design. Furthermore, the results also support the finding that this environment might help people with less expertise [21], as the mechanical design background of the team might be more suitable for the verification transition [63]. Finally, these results suggest that the analysis of design artefacts does not only depend on the goal of transition [67, 68] but also on the environment in which this artefact is represented.

These findings might be explained by more natural interaction and navigation in high-immersion environments than in low-immersion ones, resulting in users feeling a stronger sense of presence in high-immersion environments [15]. These characteristics of high-immersion environments might improve spatial [24] and contextual [21] understanding of designs under transition - a prerequisite for evaluation [127]. Consequently, users in high-immersion environments might become more aware of the context in which the design is used. This easier interpretation might leave more mental capacity for evaluation and planning actions. Furthermore, natural interaction and navigation in high-immersion environments might, through priming, trigger previous experiences in the real world [33]. In this context, transition teams in high-immersion environments might focus more on real-world scenarios, such as use cases and assessments of the design problem. Through the same priming effect, low-immersion environments might trigger previous experience regarding work in CAD, which is common for mechanical designers. More specifically, mechanical designers usually utilise CAD tools in later design phases, suggesting that working in this environment might prime transition teams to think more about the later phase aspects, thus supporting convergent thinking [63]. Altogether, the results shed new light on the conflicting findings related to the effect of the environment on the transitions [26, 28, 30, 32, 33].

Based on the theoretical argumentation for the relationships, coupled with the internal, external, and measurement validity of the experiment (discussed in Subsection 7.3.2), the established relationships are accepted as valid. Therefore, the model showed the possibility of establishing relationships, thus accepting its performance validity. Altogether, the model of team transitions demonstrated both structural and performance validity in the laboratory experiment, thus adhering to the validation criteria. Although validity beyond the experiments was theoretically discussed, future studies should collect empirical data related to the other statements that could be derived from the model and test the model in an industrial environment.

7.3. Validating the third contribution: the experimental framework

The experimental framework (Section 4) is developed as an answer to the second RQ and consists of experimental, theoretical, methodological, and implementational considerations. The experimental considerations are divided into research ethics, resources, reliability and replicability, and validity. Theoretical considerations include research questions and transition factors. Methodological considerations include factor measurements, sample definition, experimental setting, and data analysis. Implementational considerations consist of the experimental setup and procedure. Finally, pilot studies are suggested to test the experiment and fine-tune the experimental parameters. The following subsections discuss the validity of the framework in terms of structure and performance (see Figure 7.3 for the validation process).

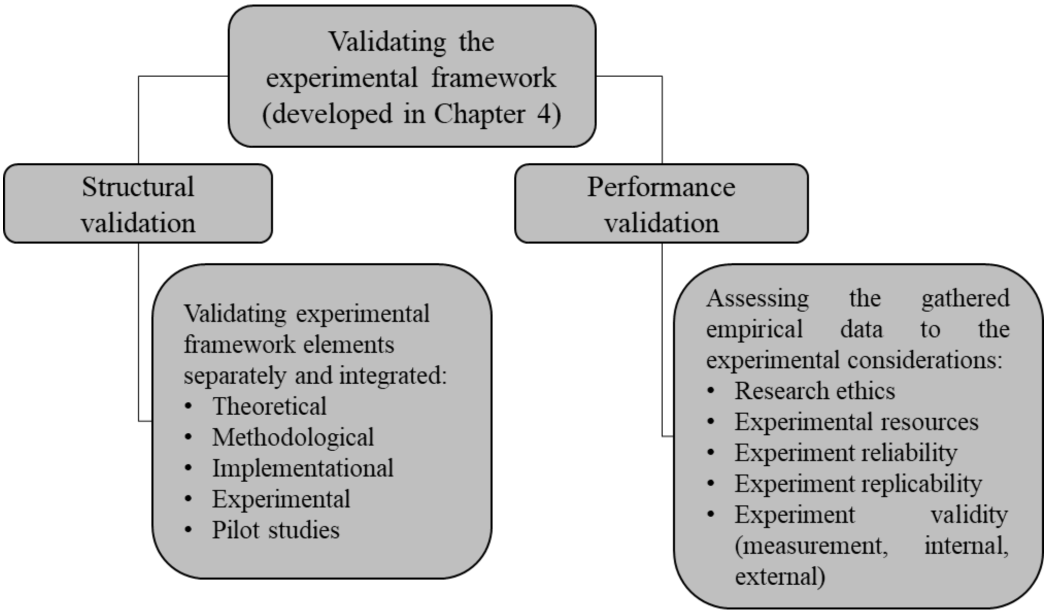

Figure 7.3 Validation process of the experimental framework

7.3.1. Structural validity

A separate and integrated structural validity of the experimental framework elements is tested by comparing them with the experimental research suggestions [84, 85, 375, 377, 398, 408]. For example, Coleman and Montgomery [498] suggest seven steps to design an experiment: 1) recognition of and statement of the problem; 2) choice of factors, levels, and range; 3) selection of the response variable; 4) choice of experimental design; 5) performing the experiment; 6) statistical analysis of the data; 7) conclusions and recommendations. Researchers suggest first defining the problem that the experiment aims to solve, which corresponds to the research objective in the experimental framework (Subsection 4.2.1). Next, researchers suggest selecting factors and their levels. The selection of factors corresponds to the transition factors (theoretical considerations) in the framework (Subsection 4.2.2), for which researchers can use the developed team transition models. The levels of factors and response variables are depicted in the factor measurements (Subsection 4.3.1). Furthermore, the choice of experimental design involves sample definition (Subsection 4.3.2) and experimental setting (Subsection 4.3.3). Conducting the experiment requires describing the experimental setup (Subsection 4.4.1) and procedure (Subsection 4.4.2) (implementational considerations). After the experiment is conducted, the data are to be analysed, which is also depicted in the framework as part of methodological considerations (Subsection 4.3.4). This is in line with the suggestions of many scholars to consider data analysis early in the experimental design process. Finally, researchers also suggest that ethical and research rigour principles should be followed from the beginning and in every step (Section 4.1). These are grouped under the experimental considerations that researchers have to take into account at every step of developing an experiment. As many considerations need to be taken into account, pilot studies are suggested as the main procedure to gather feedback on the current state of the experimental design (Section 4.5). Based on this mapping of experimental steps to the framework for VR-supported team transitions, the elements are considered to be structurally valid both individually and integrated.

7.3.2. Performance validity

The performance validity of the framework can be tested by evaluating the conducted experiments against the following experimental considerations: research ethics, experimental resources, experiment reliability, experiment replicability, and experiment validity. Firstly, ethics approval has been granted for the conducted research (see Appendix A). Secondly, the experimental resources needed to conduct the experiments were within the time and budget of the research. Thirdly, the experiment reliability in terms of the inter-rater agreement has been calculated for various measures used in the analysis: transition action (Subsection 5.5.1.1), uncertainty (Subsection 5.5.1.1), affect (Subsection 5.5.1.1), working mode (Subsection 5.5.1.1), the design space and spatial context of issues (Subsection 6.3.1), discussed issues (Subsection 6.4.1), and goal-relatedness of discussed issues (Subsection 6.4.1). The reliability was not calculated for the verbal communication structure, as this analysis is content-independent and thus usually results in high reliability. As all agreements were substantial or perfect, the experiments were considered reliable. This reliability was a prerequisite for replicability, which was also supported by the detailed description of the experimental study.

The validity of the experiments (measurement, internal, and external) as another aspect of research rigour has also been addressed by the conducted experiments. Firstly, measurement validity has been accepted for all the measures. More specifically, lexicon-based approaches for measuring uncertainty and affect measures have been commonly utilised in the design discipline [143, 146, 148, 175, 458], thus showing face validation [399]. Next, transition actions and verbal communication have often been measured through protocol analysis [109, 236, 443, 444, 499], thus also showing face validity [399]. Furthermore, the context of issues has been measured by the theoretical development of the measure. More specifically, design space has been commonly depicted by the problem-solution dichotomisation, while spatial aspects have been dichotomised between intrinsic and extrinsic. The discussed issues and the number of feedback items were used as measures while considering the larger context (i.e., working mode, transition actions, and context of feedback items), and they were accepted through concurrent validation [399]. In addition, the number of feedback items has been augmented with the qualitative findings, thus utilising convergent validity [400]. These measures were also theoretically derived from the lenses of efficiency, effectiveness, and goal-related efficiency [201], thus providing further evidence of their purpose. Therefore, the measurement validity of the conducted experiments is accepted.

Internal validity has been accomplished by having experimental and control groups with randomly assigned participants [86]. In addition, the random assignment of the order in the first experiment enabled the neutralisation of the learning effect. Furthermore, equalising the treatment with the same experimental tutorial regardless of the group also contributed to the internal validity [402]. Furthermore, having a fixed experimental design with a fixed number of participants also contributed to internal validity [85]. Finally, controlling the other factors in the team transition model also provided evidence for internal validity. Therefore, the internal validity of the experiments is accepted.

Considering external validity early in the design of experiments resulted in designing the experiments as part of larger cases. In that case, the outputs produced during the transitions were used by the real teams, providing support for ecological validity [403]. Moreover, the experiments utilised participants from the industry, overcoming the issues that might result from the lower expertise of reviewers. In order to minimise their change in behaviour due to participation in the study (i.e., the Hawthorne effect [404]), transition teams were video recorded rather than directly observed [500]. Furthermore, as the main elements of the experiments (i.e., agents, IC, design space, and other transition elements) were the same as they would be in the real environment, the research can be generalised based on theory. However, the generalisation is limited as factors such as design discipline, size, and complexity were kept constant for experiment validity purposes. Nevertheless, this type of study aligns with the aim of identifying new relationships [408]. Therefore, the external validity of the experiments is accepted.

The experiments designed using the framework satisfied experimental considerations, thus accepting the performance validity of the experimental framework. Therefore, the experimental framework showed both structural and performance validity in the laboratory experiment, adhering to the validation criteria.

7.4. Verification of the research hypothesis

The conducted research enabled the verification of the research hypothesis:

Virtual reality technologies within teamwork
augment understanding of the transition processes during product
development and improve execution of evaluation/planning activities
throughout development projects according to defined metrics.

This hypothesis is verified in two parts, thus answering the third and fourth RQs. Subsection 7.4.1 describes the verification of the first part of the hypothesis, while Subsection 7.4.2 describes the second part of the hypothesis.

7.4.1. VR augments understanding of team transition processes

Introducing VR in the studies of team transition processes provided several new insights, such as a better understanding of the social aspect of transitions, a new characterisation of the information content, and a deeper understanding of the effect of transition goals.

The introduction of VR helped identify the importance of the social aspect during transitions, as teamwork (i.e., working mode, verbal communication structure) has been shown to depend on the environment that transition teams utilise. The results showed that working mode and environment were associated (Subsection 5.5.3.1), suggesting that a change in the environment would elicit a different working mode. More specifically, the planning actions in a high-immersion environment were often executed with all members together, while the same actions in a low-immersion environment were often executed in a sub-team. These results confirm the prior finding that working mode varies across actions [154] and extend it by proposing that the environment might moderate this relationship. Furthermore, the two reviewers started speaking after each other more often in a high-immersion environment than in a low-immersion environment (Subsection 5.3.2). Altogether, these results align with the social presence theory [454] and empirical findings that the use of high-immersion environments might support teamwork [27–29, 484]. Therefore, introducing VR in this context might augment understanding of the social aspects of transitions.

Furthermore, the utilisation of VR resulted in a new characterisation of the information content. More specifically, the model of team transitions distinguishes between environment and artefact factors (Subsection 3.2.1), contrary to prior suggestions that the environment is characteristic of the artefact [224]. Distinguishing between environment and artefact factors enables the use of various interaction means with the same artefacts, as proposed by the model. For example, the same artefact (e.g., a 3D CAD model) can be reviewed in different environments (e.g., VR, augmented reality, desktop interface). Therefore, VR augmented understanding of the effect that information content has on transitions.

Transitions studied with VR support also deepened the understanding of transition goals' effect on activity execution. For example, the effect of the transition goal was found to moderate the relationship between the environment and the transition execution, as the teams in a high-immersion environment benefited from the transition sessions oriented towards understanding the design problem (i.e., validation). More specifically, teams using a high-immersion environment conducted more transition actions related to the design problem than those using a low-immersion environment (Subsection 6.4.2). Therefore, the use of VR enabled the identification of previously unknown relationships between the environment, transition goals, and transition outcomes (Section 6.3).

VR-supported transitions might even provide more opportunities than physical ones. More specifically, its possibility to vary spatial and social cues and interaction types might provide additional insights that might be difficult to identify without this technology. For instance, VR technologies might open new questions regarding the impact of avatar representation or the new interaction possibilities (e.g., getting viewpoints not possible in a physical environment with hand-defined section cuts). Future work can also use VR to explore the differences in various interactions with the environment and augment understanding of these action types.

Therefore, this part of the hypothesis is **confirmed**, as VR augmented understanding of several aspects related to transition processes, namely the differentiation in the working mode and teamwork aspect of transition actions and the reconceptualization of the information content – a constituent element in the model of team transition processes.

7.4.2. VR improves execution of evaluation/planning activities throughout product development

The use of VR affected the execution of evaluation/planning (transition) activities throughout PD in terms of teamwork and outcomes. Studying the effect of VR on teamwork showed that transition teams worked more all-together when utilising the high-immersion environment (Subsection 5.5.3). This working mode was mostly emphasised in the planning actions, suggesting that VR might improve the execution of transitions by priming collective decision-making. In addition, external members exchanged more verbal turns in high-immersion than in low-immersion environments, suggesting that the decision might reflect their collective feedback.

Secondly, VR affected the outcome of the transition. The outcomes in terms of the number of feedback items were negatively affected in the first experiment (Section 5.4). However, the second experiment did not confirm this relationship (Subsection 6.3.2). Therefore, VR might not improve the execution of transitions in terms of the number of feedback items. Additional analysis showed that the VR transition increased the number of specific types of feedback items. More specifically, VR improved the identification of feedback items that consider the relationship between the design solution and environment (e.g., increasing the height of the handle so that it is more ergonomic) while worsening the identification related to the design itself (e.g., this material is not suitable) (Subsection 6.3.3). Moreover, VR transitions resulted in more issues related to the problem space, while the number of issues related to the solution did not significantly differ between the environments (Subsection 6.3.4). These results suggest that VR might improve execution when the goal is related to the problem and the environment that interacts with the product (e.g., users). The analysis of the efficiency, effectiveness, and goal-related efficiency for the two transition goals (i.e., verification and validation) confirmed these suggestions (Subsection 6.4.2). More specifically, VR transitions resulted in more goal-related discussion during the validation transition (one related to the design problem), while the verification transition was not significantly affected (Subsection 6.4.2). Therefore, improving execution would depend on the transition goal. The current results indicate better suitability of VR-supported transitions for the early phases since they rely heavily on the co-evolution of problem and solution spaces [131].

Considering all the findings together, the second part of the hypothesis is **partially confirmed**, as VR might not always improve the execution of transitions. Its suitability for the transitions would depend on the contextual (e.g., validation or verification) and performance (e.g., collective decision-making or identifying detailed issues) goals. In addition, prior findings suggest that the effect of VR might depend on the design size and complexity [33, 488], thus proposing that the design product might moderate the relationship between VR and transition execution. Finally, the prior findings also suggested that VR might better support agents with less experience [21], implying that VR might be more suitable for transitions involving inexperienced members (e.g., end-users). Therefore, the effect of VR on the transitions is complex, and the here-identified relationships have various implications.

7.5. Revisiting the research questions

The thesis is guided by the four RQs. Each of them was thoroughly answered throughout the thesis (see Table 1.1), and their answers are summarised here.

7.5.1. RQ1: How to describe the multifaceted nature of team transitions in product development?

The multifaceted nature of transitions has been described through three facets (see Section 2.3): evolutionary, agent-based, and social. These facets have been incorporated into the two theoretical models, one at the micro-scale (3.1 Theoretical model of team transition processes) and another at the meso-scale (3.2 Theoretical model of team transitions).

The model of team transition processes is developed in the context of evaluation/planning (transition) activities, consisting of transition action sequences that gradually change the transition state towards the transition goal (see Figure 3.9 for a visualisation of the final model). The transition state comprises agents, information content, design space, and other transition elements. In line with the agent-based facet, agents were detailed with uncertainty and affect states. The information content was described through the environment and artefacts related to the design problem, design solution, transition report, transition goal, and avatars. These artefacts are commonly utilised during transitions. Furthermore, the design space was elaborated through the current and future designs. The modelled transition state advances through the taskwork of transition actions. Even though actions can change any state, the most common ones relate to understanding or evaluating the current design and planning the future design. Finally, in order to model the social facet, these actions can be executed with all members involved or in a sub-team, describing the working mode of team members.

The empirical results provided evidence to include various facets in the model. More specifically, modelling both agents' uncertainty and affect levels were found to significantly better predict the transition actions than uncertainty alone. In addition, uncertainty, affect, and working mode (all-together, sub-team) were found to significantly better predict the transition actions with the controlled environment (low-immersion like CAD or high-immersion like VR). Therefore, these results supported the inclusion of various facets in the model (see Section 5.5 for a more detailed description of the results). This model was validated through theoretical discussion and empirical confirmation of the main relationships (for a more comprehensive validation, see Section 7.1).

The model of team transitions (on the meso-scale) was developed by considering the model of team transition processes and the current models from the management literature (see

Figure 3.10 for mapping a micro-scale model to the meso-scale). The model consists of inputs, mediators, outputs, and outcomes. Inputs and outputs consist of design space factors (current design, future design), information content factors (environment, artefact), team factors (composition and context), and factors related to other transition elements (design process, transition task context, organisational context, culture). The difference between outputs and inputs is depicted by outcomes that consist of the changes in the design space (e.g., change in the design quality), teams (e.g., learning), information content (e.g., created artefacts), and design process (e.g., transition to a new design phase). These outcomes are achieved through mediators, divided into team behaviour and emergent factors. Team behaviour consists of taskwork (i.e., transition actions) and teamwork (e.g., working mode) factors. Finally, emergent factors represent the dynamic changes in cognitive and affective team aspects.

The empirical studies provided evidence for the effect of environment (i.e., VR) and transition goal factors on mediators and outcomes. More specifically, the VR affected the mediators by increasing the verbal communication sequence between reviewers (Section 5.3), increasing the average affect levels (Subsection 5.5.3.1), and increasing the number of actions conducted with all members working together (Subsection 5.5.4). Furthermore, the effect of VR on the transition outcomes was moderated by the transition goal. While the VR decreased (Section 5.4) or did not affect the number of feedback items (Subsection 6.3.2), it increased the number of goal-related discussed issues in the validation transition goal (Section 6.4). VR also increased the identification of specific types of issues, such as those related to the interaction between the design and users (Subsection 6.3.3) and those related to the problem space (Subsection 6.3.4). Finally, these differences in the output between the two environments (VR and CAD) resulted in design teams working more on creation actions in the subsequent activities (Section 6.5). The model of team transitions was also validated through theoretical discussion and empirical confirmation of the main relationships (for a more comprehensive validation, see Section 7.2).

7.5.2. RQ2: How to plan empirical studies related to understanding VR-supported team transition processes in PD?

As experiments engender confidence in the trustworthiness of causal findings [86], planning the empirical studies was described through the experimental framework (Chapter 4). This framework provided an opportunity to test the developed theoretical models [374].

The framework consists of four consideration categories: experimental, theoretical, methodological, and implementational. Experimental considerations describe principles and constraints that researchers need to account for, such as research ethics, resources at their disposal, reliability of the measurements, replicability of the experiment, and experimental validity. Theoretical considerations concern the transition perspective in order to define a research objective (e.g., research questions, hypothesis) and transition factors. Methodological considerations describe principles mainly related to the research rigour (reliability, replicability, and validity) aspect, including factor measurements, sample definition, experimental setting, and data analysis. Implementational considerations describe the characteristics to account for while developing experimental setups and procedures for VR-supported transitions. Finally, pilot studies can be executed throughout the planning process to test the experimental design. Each of these considerations has been described in more depth in Chapter 4.

7.5.3. RQ3: How do VR technologies augment understanding of team transition processes?

VR can augment understanding of team transition processes in several ways. Firstly, VR can help in understanding the social aspect during transitions, as teamwork (i.e., working mode, verbal communication structure) was shown to depend on the environment that transition teams utilise (Sections 5.3 and 5.5). Secondly, the introduction of VR while developing models resulted in a reconceptualisation of the information content, distinguishing between the environment and the artefact factors. This distinction in the model predicts that different interaction means (e.g., mouse and keyboard, VR) would affect the execution of transitions. Thirdly, the use of VR also helped to understand the moderating effect of transition goals on the relationship between the environment and outcomes. More specifically, teams in VR had more goal-related actions in the transition goal that is oriented towards understanding the design problem but not in the goal related to the design solution. Finally, VR's flexibility to vary spatial and social cues and interaction types might make it even more useful for understanding transitions than the physical environment. Therefore, introducing VR in this context might augment understanding of the social aspects, information content, and role of other factors (e.g., transition goal, design phase) in transitions. This discussion also confirmed the first part of the hypothesis, as VR augmented understanding of several aspects related to transition processes.

7.5.4. RQ4: How do VR technologies affect the execution of team transitions throughout the PD process?

The here conducted research yielded that VR improved only specific aspects of evaluation/planning (transition) activities. Firstly, VR affected the way teams work, such as executing actions with all members together rather than in sub-teams. This finding suggests that VR might improve the execution of transitions by priming collective decision-making. Secondly, the analysis of the outcomes suggested that VR improves the identification of issues related to the design problem while the identification of solution-related issues remains unaffected. In addition, the VR transition increased the number of issues that consider the relationship between the design solution and environment (e.g., users, weather conditions) and reduced the number of issues related to the design itself. These results suggest that VR might improve execution when the transition goal is oriented towards the design problem and use case scenarios – a common transition goal in early PD phases [131]. Indeed, VR transitions resulted in more goal-related discussion during the validation transition (one related to the design problem), while the verification transition (one related to the design solution) was unaffected. Therefore, improving execution in terms of performance would depend on the transition goal. The current results indicate its better suitability for the early phases since they rely heavily on the co-evolution of problem and solution spaces [131].

This discussion partially confirms the second part of the hypothesis, as VR might not always improve the execution of transitions. For example, contextual (e.g., validation or verification) and performance (e.g., collective decision-making or identifying issues) goals might influence the way VR supports transitions. In addition, prior findings suggest that the effect of VR might depend on the size and complexity of the design [33, 488] and the experience of agents [21].

7.6. Implications

The development of the model of team transition processes, the team transition model, the experimental framework, and the findings from the experiments have various implications.

7.6.1. Research implications

The introduction of transition in teams expanded previous work on design reviews and related activities that focused mainly on the evolutionary perspective. This could enable researchers to more holistically observe transitions and more quickly exchange findings from related activities. The model of team transition processes has various theoretical implications. Firstly, it shows the design as a multifaceted phenomenon, thus advancing design theory by incorporating multiple facets [71, 129, 501]. This approach might yield higher predictive power of the models and thus answer calls for making design models more predictive [70]. The findings and predictive models support and extend the social presence theory [454] by suggesting that this type of presence might also be activity-dependent. Therefore, researchers interested in the social aspects of transitions should carefully consider the utilised environment. The model also extends the understanding of transitions [50] by including drivers (uncertainty, affect, and working mode) of these essential pivot points in design [125]. The two of these (affect and working mode) are influenced by the environment, thus having significant implications. More specifically, as positive affect might persist across tasks and increase engagement in subsequent tasks [49, 208], the environment can be manipulated to get the desired team behaviour. Moreover, as working mode influences transition outcomes [49, 51], the environment might alter the outcomes by affecting working modes, a commonly hypothesised relationship [28, 32, 33, 489]. This work thus sheds more light on this commonly studied relationship between the environment and transition execution.

Transitions were also described at the meso-scale by determining factors relevant to this activity. This description extends current models from the management literature by introducing factors related to the product being designed and other contextual aspects of transitions. In addition, the description of transition at the meso-scale extends the current models of design communication [225] and shared understanding [252] by also considering the outcomes and outputs of this activity. The model of team transitions also provides theoretical insights that other researchers can use. Firstly, the model can be used to describe many of the identified relationships in the studies of transitions. While the presented work focused mainly on the relationships between the environment and transition execution, researchers might use it to investigate other relationships. Moreover, researchers can employ the model in order to test the similarities and differences across transitions in different design fields (e.g., architecture, engineering), phases (e.g., conceptual, detailed), or with different artefacts (e.g., drawings, CAD models, documents, simulations). Secondly, as the team transition model describes the transitions on a meso-scale, researchers might use the model to determine which factors to control in empirical studies. This model, coupled with the developed experimental framework, might provide a powerful methodological toolset that can help researchers better understand the transitions and develop theories regarding this multifaceted activity. Thirdly, the reconceptualisation of the IC by dividing it into the environment and artefact characteristics provides an opportunity to utilise VR for simulations of various scenarios (e.g., interaction with the user, manufacturing), thus yielding a better understanding of transitions [495]. This reconceptualisation enabled a better understanding of the role that new technologies might play in transitions. More specifically, VR showed the potential to augment understanding of the social aspects of transitions and to help researchers identify new relationships (e.g., the role of the design phase and transition goal on the effect of the environment on transition outcomes).

7.6.2. Practical implications

The developed models have various implications for industry and education. Teams can use the models to understand what factors they can influence to change the execution of transitions. In this context, the environment factor is the one that transition teams can easily manipulate. Given the many confounding variables, teams should consider several aspects before deciding on the environment, such as the design goal [77, 132], transition goal, design complexity [488], and design size [5, 488, 489]. More specifically, if teams would like to have collective decision-making, they should use high-immersion environments. In addition, if the transition goal is related to users or exploring the problem, the teams and educators might also benefit from the high-immersion environments. In contrast, if designers would like to receive more solution-focused or intrinsic feedback, then a low-immersion environment might be more suitable. While these findings are applicable to teams that work in the same physical space, they also apply to distributed teams – an increasingly explored context by design researchers [449, 502].

The findings also have implications for developers of engineering tools. They show that the introduction of high-immersion environments might be a complementary "add-on" to the current software. Hence, developers might consider the support of various environments and artefacts while developing tools. In addition, developers should carefully consider the toolset that they implement in their software, as different functionalities might affect the execution of transitions. Finally, developers can use the experimental framework as a test rig for analysing the effects of various functionalities that are related to the software.

Finally, educators might benefit from a better understanding of the educational types of transitions (e.g., design studio, design crits, design critiques). They can use the models to better exploit the benefits of different environments in transitions, such as using different interaction techniques and immersion levels. For example, educators might utilise high-immersion environments to support the identification of problem space aspects, extrinsic aspects, or collective decision-making. Moreover, educators can use these findings as guidelines for using different environments. Also, they might educate future engineers on what other factors can affect their execution of transitions.

7.7. Limitations

Despite having various implications for theory and practice, the research has limitations that might affect its generalisability, such as limitations of the models and experimental studies. The main limitation of the models is that they are developed by considering narrow background work. Since they suggest a number of elements, factors, and characteristics relevant to transitions, a narrow background limits their structural validity, while the empirical studies confirmed performance validity only for specific relationships in the models.

The model of team transition processes might be further detailed. For example, detailing agents might include their roles [66, 503] and relationships between them (e.g., authority). Next, a more detailed description of the IC would be necessary to better understand the differences between the environments. Similar detailing would be necessary for the interaction between team members, such as division into action driver and action follower, assessing the quality of collaboration [504], and so on. Although the model showed satisfactory predictive power (AUC > 0.6), detailing these variables might improve the model's performance.

Another limitation of the model of team transition processes is that the design space is modelled as being detached from the agents. Although the design space represents the agents' current understanding of the design problem and solution, its initial state in transition is based on the current design, shaped by the design problem and solution artefacts that were previously developed by the design teams. Hence, even though only a design team representative might be present in the transition, knowledge from other agents is also present in the design space description. The design space was thus modelled outside the agents, which supported the modelling of transition actions and transition outcomes (e.g., the number of identified and discussed issues). Nevertheless, the introduction of situatedness (e.g., external, perceived, and internal worlds) might shed more light on the individuals working within transitions.

Next, the model of team transition processes assumes one action at a time and does not capture parallel actions (e.g., individual actions). Extending the model in this direction might be possible by increasing the number of actions that can change the transition state. However, as the focus of this thesis is on the teamwork aspect, individual actions are neglected. Despite having potential for improvement, the proposed model of team transition processes provides the first step towards a better understanding of the drivers of design work and might help explain these important pivot points in the design.

The limitations of the second model (i.e., the team transition model) are mainly related to the comprehensiveness of the included factors. More specifically, although the factors included in the model are validated, the lower-level characteristics do not represent an exhaustive list. Studying various characteristics might thus lead to different conclusions regarding each factor. For example, measuring the efficiency of the team might be conducted by analysing transition team reports or by observing teams during transitions. However, as many different characteristics might be studied, capturing all of them might not be feasible. Hence, the team transition model was developed to help researchers organise the characteristics into factors that are manageable within humans' information processing limits [487].

Furthermore, the experimental studies also have various limitations. Most significantly, the experiments described only a limited number of transition goals and only one point in the design process. Next, the sample was kept relatively small, thus prohibiting statistical generalisation. This sample has been chosen because the aim is to identify new relationships. Keeping the sample relatively small enabled a more in-depth analysis, while the theoretical argumentation enabled generalisation to various contexts. In order to cope with the sample size limitations, calculating the effect sizes provided evidence for their verification. Nevertheless, future work should test the identified relationships with a larger sample size, thus enabling statistical generalisation. Due to the small sample size and the focus on identifying new relationships, the sample was made homogeneous. Hence, the results might be different for users of different backgrounds [21, 67], other design sizes or complexities [33, 273, 488, 489], different environment functionalities [34], and other design phases.

7.8. Future work

Although providing several scientific contributions, there are various avenues for future work. Future work can utilise a more heterogeneous sample with a larger sample size in order to enable statistical generalisation. This heterogeneous sample can vary in team composition (e.g., novices, experts, users, managers), team settings (e.g., team size, hierarchy, different roles), artefacts (e.g., different fidelity, dimensionality, composition), environment (e.g., different functionalities), current design (e.g., complexity, sizes), design phases (e.g., conceptual, detailed), design fields (e.g., mechanical, industrial, architecture), level of integration into the design process, etc. Therefore, the heterogeneous sample can be used to allow generalisation among any of the factors and characteristics described in the model of team transitions (Section 3.2). Furthermore, researchers could provide more details on describing agents (e.g., personality, expertise), relations between agents (e.g., authority), environment (e.g., by detailing the affordances), design space (e.g., the difference between external, perceived, and internal design space), and actions (e.g., parallel action execution).

Researchers might also work on exploring other metrics to analyse the execution of transitions. More specifically, they could focus on the depth of the discussed issues, the importance of the feedback items, the difficulty of resolving the issues, and the analysis of the long-term effect of transitions. Researchers can also investigate to what extent the models developed for transition activities can be transferred to other contexts. More specifically, researchers can investigate the extent to which findings are applicable in development activities and in different approaches for doing the design. For example, future work can embrace extrapolating findings to hackathons [505], design sprints [506], or other agile approaches. In these time-intensive activities, integration of the environment into the overall PD might be more pronounced.

Furthermore, researchers can focus on analysing the effect of each factor. In that case, the effect of the environment factor should be more thoroughly analysed with other environments, varying the functionalities (e.g., section cut, sharing a view) and interaction types (e.g., mouse and keyboard, VR, physical environment). These analyses might inform the appropriate selection of the environment, depending on the planned transition. In addition, researchers are advised to work on improving factors in the transition model and, consequently, the execution of transitions. For example, the improvement of the artefact factor might result in the development of new representations that might be better suited for VR technologies.

Briefly, researchers are advised to consider any factor in the team transition model and work on understanding its effect on transition execution or consider work that can change the factor. A great starting point for this would be to gather current findings in one place by conducting systematic literature reviews and meta-analyses. Following these research directions might result in a better understanding of multifaceted activities (e.g., transitions) in PD and how new technologies (e.g., VR) might help their execution.

8. CONCLUSIONS

The final chapter provides a summary of the conducted work and concludes the thesis.

The presented research aimed to understand the effect of VR technologies on design reviews. As the findings related to design reviews are scarce, the presented research introduced transitions as an overarching concept of evaluation and/or planning activities in product development. Transitions were introduced by considering different facets with two models at different granularity levels. The model of team transition processes describes transitions on a micro-scale through a sequence of actions that gradually change the transition state from the current one to the desired one. The model of team transitions describes these activities on the meso-scale by presenting input, mediator, output, and outcome factors. Although at different granularity levels, both models consist of elements that describe the multifaceted nature of transitions. This multifaceted nature has been described by considering transitions from the evolutionary, agent-based (i.e., cognitive and affective), and social facets.

As the models assume various relationships, an experimental framework has been developed to consolidate considerations that have to be taken into account while studying VR-supported transitions. The framework consists of four consideration categories: experimental (research ethics, reliability, resources, replicability, experimental validity), theoretical (research objectives, transition factors), methodological (factor measurement, sample definition, experimental setting, data analysis), and implementational (experimental setup and procedure). Throughout the planning process, pilot studies can be executed to test experimental designs. This framework enables researchers to study VR-supported transitions systematically and thus collectively build knowledge about these activities.

Based on these grounds, two experiments within cases were conducted to investigate the effect that VR technologies have on design reviews. The studies utilised various metrics (e.g., number of feedback items, context of feedback items, efficiency, effectiveness) to measure the effect of VR technologies on transitions. In the first study, ten three-member transition teams (i.e., two industry professionals and one designer) reviewed a design either in a low-immersion (CAD) or high-immersion (VR) environment. The results show that the first-order turn sequence between reviewers was significantly higher while using VR technology (head-mounted display) as compared to the low-immersion environment (i.e., traditional user interface with mouse, keyboard, and monitor). In addition, transition teams working in VR executed significantly more actions with all members together. However, these teams identified significantly fewer issues than teams working in low-immersion environments. Furthermore, in both conditions combined, uncertainty and affect of agents better predicted transition actions together than the uncertainty itself. Under controlled conditions, uncertainty, affect, and working mode were the best predictors of the transition actions.

In the second study, fourteen four-member transition teams (two industry professionals and two design team representatives) conducted two design reviews of baby strollers using either a low-immersion (CAD) or high-immersion (VR) environment. The first review was related to the verification transition goal to check if the proposed solution adheres to the posed design problem. In contrast, the second review was related to the validation goal, i.e., checking a solution with regard to the values that users have (e.g., parents, babies). The results showed that the number of identified issues is not significantly different but that the context of the identified issues depends on the environment. More specifically, VR improved the identification of feedback items that consider a relationship between the design solution and environment (e.g., increasing the height of the handle so that it is more ergonomic) and items related to the problem space. Furthermore, analysis of efficiency, effectiveness, and goal-related efficiency for the two transition goals (i.e., verification and validation) showed that VR transitions resulted in more goal-related discussion during the validation transition (one related to the design problem), while the verification transition was not significantly affected. Finally, in the subsequent activities, design teams with a transition in VR worked more on creating new solution elements.

These results show the importance of introducing transitions and modelling them as multifaceted activities at different granularity levels. On the micro-scale, multifaceted modelling resulted in the identification that VR influences a social and affective facet of transitions. In addition, these facets were important to understand the execution of the transition actions in different environments. On the meso-scale, the effect of VR depends on the transition goal. VR improved execution when the transition goal was oriented towards the design problem and use case scenarios—a common transition goal in early PD phases. Therefore, VR technology and traditional user interfaces are not substitutable but rather complementary environments for design reviews.

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APPENDIX A: ETHICAL APPROVAL FOR CONDUCTING THE RESEARCH

Etičko povjerenstvo
Sveučilište u Zagrebu
Fakultet strojarstva i brodogradnje
Ivana Lučića 5
10000 Zagreb

Zagreb 26. travnja 2019.

Povjerenstvo za doktorske radove
Vijeća tehničkog područja
prof.dr.sc. Joško Parunov
Sveučilište u Zagrebu

Predmet: Mišljenje Etičkog povjerenstva Fakulteta strojarstva i brodogradnje Sveučilišta u Zagrebu o prijedlogu teme doktorske disertacije pristupnika Nikole Horvata

Upoznavši se s prijedlogom teme doktorske disertacije pristupnika Nikole Horvata pod nazivom ***Timski tranzicijski procesi podržani tehnologijom virtualne stvarnosti u razvoju proizvoda*** i činjenicu da će u istraživanje biti uključeni zaposlenici razvojnih organizacija i studenti FSB-a kroz HRZZ projekt TAIDE , Etičko povjerenstvo Fakulteta strojarstva i brodogradnje Sveučilišta u Zagrebu zaključilo je da su etički aspekti predviđenih istraživanja u okviru prijedloga teme detaljno razrađeni te da uvažavaju načela i norme Etičkog kodeksa Sveučilišta u Zagrebu.

Predsjednik Etičkog povjerenstva FSB-a

V Soldo

dr.sc. Vladimir Soldo, red.prof.

Figure A.1 Ethical approval for conducting the research (in Croatian)

BIOGRAPHY

Nikola Horvat was born in Virovitica, Croatia, in 1992. He received a Master of Mechanical Engineering degree from the Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb (UNIZAG-FSB). During his study, Nikola was an intern at several companies (Bosch, Hilti, Rimac Automobili), an exchange student at the Luleå University of Technology, and a student tutor at the UNIZAG-FSB (Design and Product Development, Machine Elements, and Math). He also received several awards, such as the Hilti Spontanbonus, Rectors' award, Summa cum laude, Medal of the Faculty, 1st and 2nd places in Croatia for engineering mechanics, EIT Health 1st place in Croatia and 5th place in Europe, 2 Reviewers' favourite award, etc.

Nikola currently works as Research and Teaching Assistant at the Chair of Design and Product Development UNIZAG-FSB. His research interests include understanding team-based product development and how technology (e.g., VR, cloud-based tools) supports teams during this process. He published six journals, 15 conferences, and six technical papers. He reviewed 15 research papers and two textbooks. Nikola has also been working on scientific (Croatian Science Foundation), educational (Erasmus+) and industry (B&O Gruppe) projects. He is a member of The Design Society. Since 2018 he has participated in the organisation of the DESIGN conference.

Nikola assists in teaching courses related to the design process (e.g., Product Development, Engineering Design - theory and methods, and Computer-Aided Design). Besides these courses, he is involved in the organisation of a competition-based course involving four European universities. The team that he facilitated won the 2021 and 2022 challenges. In addition, he held two guest lectures.

ŽIVOTOPIS

Nikola Horvat rođen je 1992. godine u Virovitici. Diplomu magistra inženjera strojarstva stekao je na Fakultetu strojarstva i brodogradnje Sveučilišta u Zagrebu (UNIZAG-FSB). Tijekom studija je bio pripravnik u nekoliko tvrtki (Bosch, Hilti, Rimac Automobili), student na razmjeni na Luleå University of Technology te demonstrator na UNIZAG-FSB (Konstruiranje i razvoj proizvoda, elementi konstrukcija, matematika). Tijekom karijere, Nikola je bio dobitnik različitih nagrada, kao što su Hilti Spontanbonus, Rektorova nagrada, Summa cum laude, Medalja Fakulteta, 1. i 2. mjesto u Hrvatskoj za inženjersku mehaniku, EIT Health 1. mjesto u Hrvatskoj i 5. mjesto u Europi, dvije nagrade rada omiljenih recenzentima, itd.

Nikola trenutno radi kao asistent na Katedri za konstruiranje i razvoj proizvoda UNIZAG-FSB. Njegovi istraživački interesi uključuju razumijevanje timskog razvoja proizvoda i načina na koji tehnologija (npr. VR, alati temeljeni na oblaku) podržava timove u tom procesu. Koautor je šest radova u časopisima, 15 radova na konferencijama i šest stručnih radova. Recenzirao je 15 znanstvenih radova i dva udžbenika. Nikola je također radio na znanstvenim (HrZZ), obrazovnim (Erasmus+) i industrijskim (B&O Gruppe) projektima. Član je zajednice Design Society. Od 2018. godine sudjeluje u organizaciji DESIGN konferencije.

Nikola sudjeluje u izvođenju nastave vezane uz proces konstruiranja (npr. Razvoj proizvoda, Teorija konstruiranja i Konstruiranje pomoću računala). Osim ovih kolegija, uključen je i u organizaciju natjecateljski-orijentiranog kolegija koji uključuje četiri europska sveučilišta. Tim koji je vodio pobijedio je na izazovima 2021. i 2022. Osim toga, održao je i dva gostujuća predavanja.

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