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A Mixed Reality Tool for End-users Participation in (Early) Creative Design Tasks

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Abstract While Mixed Prototyping has proved to be effective for the assessment of prototypes, this research aims to explore the use of Mixed Prototyping for the generation of early prototypes. To satisfy end-user's needs, new products need to be designed with an early integration of end-user requirements. An efficient way to achieve this is to directly integrate the end-users in the design process and give them an intelligible and interactive tool to perform specific design tasks. Current interactive tools to integrate end-users in the design process provide either a high level of immersion (e.g. CAVE) or a high level of control over the virtual prototype (e.g. Configurators). We designed a new Mixed Reality design tool which simultaneously allows end-users to be immersed in a virtual environment (immersion) and to interact with a virtual prototype and to modify it (control), resulting in effective end user-interactions. In two design use-case scenarios, we assessed the end-user experience and satisfaction while using the tool and we also evaluated the impact of the tool on the creative process and the design outcomes. The findings show that, when users are provided with a tool that allows to directly perform design tasks and modify a virtual prototype, as compared to when they have no control, they are more engaged in the design tasks, more satisfied with the design process and they produce more creative outcomes.

Keywords Design tool · Mixed Reality · Mixed Prototyping · Virtual Prototyping · Co-design with end-users · User control · User satisfaction · Interactive Design Process · Tangible User Interface

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1 Introduction

The work in field of Virtual Reality (VR) has allowed the application of 3D designs and scenarios with enhanced perceptibility, and the work in the field of haptics has allowed the study of physical interaction with such scenarios making simultaneous designing a possibility by creating a feedback chain mechanism, e.g. [1, 8, 16, 28] etc. These advances have helped in decreasing the knowledge-gap between design engineers and end-users, allowing end-users to be active participants in the Product Design Process (PDP) [4]. Knowledge-gap is a result of ineptness of end-users in terms of technical skills/understanding required in PDP. At least at the front end, such advances help in avoiding daunting technical jargon and complex methods for end-users.

With Computer Aided Design (CAD) tools, design-engineers can simulate interaction between users and newly designed products, in a real time environment [53]. But, CAD tools have steep learning curve due to their various functions specialised for different requirements. The VR environment when combined with CAD tools, enables its users to visualize the product design in shape and form with 3D experience in a virtual space. Combination of advanced CAD tools with statistical methods and VR tools, makes development, selection and evaluation of new design concepts experimentally [29]. While Augmented Reality (AR)tools enable users to visualise digital information in the real space. They provide intuitive methods for creating design concepts when combined with functional 3D CAD models/modelling tools [40].

Hence, the combination of VR and AR (also referred as Mixed Reality (MR)) makes it possible to interact with the design models virtually, using real-time data. In short, with MR 3D information like product features and designs can be implemented over real space, as if it were in reality as a real product. MR practices can be implemented for quick design assessments of new product design as discussed in the work of Bordegoni et al [9], by using different methods and technologies depending on the design aspects. MR shows potential to facilitate users to access complex technical knowledge through simplified processes. VR and AR tools, have become recently affordable and available in the market and they can be configured to suit different needs making them a good solution for implementing design tasks at the early stage of PDP.

Usage of MR has yet to be standardised leaving wide scope to explore its usage and application in research fields. Its impact on PDP, may facilitate people and simultaneously allow modifications in work organisations. People from varying backgrounds can participate in the design process and optimize it to produce products closer to their concepts. Design methods based on VR-simulations, gaming principles and scenarios, enable non-designers (e.g. users, production engineers, marketing managers, maintenance workers) to be proactive in designing the real product [48]. MR with right interfaces and implementation, should have potential to turn people as active designers of their own lives and surrounding.

Involving end-users at each step of PDP is crucial in maximizing their contributions in cumulative way [46], especially at early part or Fuzzy Front End (FFE) [44, 56]. However, the characterization of user requirements in the early design stage or FFE is not an easy task due to its subjective nature and the communication gap between users and designers. End-users often describe their subjective preferences verbally, which might be imprecise [33] or not suitable for existing systematic design methods. FFE is a phase of ambiguity where it is decided how the product should be and sometimes how it should not be designed [44]. Also, designers suffer a trade-off between their ability to accurately represent the user experience for future product and their capacity to offer simple interfaces for the end-user to manipulate [3]. Using virtually simulated design environment designers might be able to derive reliable conclusions based on user's preferences for a good design solution [48].

To resolve this problem, we have introduced a new modular-design tool (MR tool) that will allow users to be active participant at FFE. Active participation is required to involve user activities, leading to productive

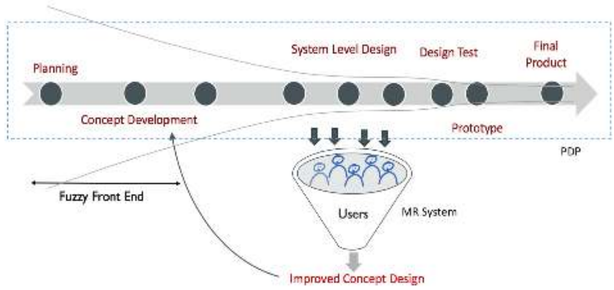


Fig. 1: Schematic representation of theme for tool design

or design-wise critical contributions to the outcomes of the final design solution. It will allow users to modify design space and communicate with designers simultaneously. In other words, users activity should have a direct impact on design process instead of just common evolutionary contribution which helps to get various feedbacks only. Figure 1, shows the schematic of function of such a tool. It focusses on providing high level of both, perception and control. The tool consists of a VR environment for perception and intuitive physical interfaces for direct control, resulting in a MR hardware/software system. The hardware is made of modular Tangible User Interfaces (TUIs), custom-made by 3D printing and powered by a 3D game engine while the interactive content is displayed in VR environment.

In order to analyse the level of control provided to its users with little technical assistance, we implemented two design use-case scenarios. The use-case scenarios focussed on assessing ease of usability of the introduced MR tool for a design problem and to assess the ability to interact and test the designed prototype virtually. Firstly, an interior design use-case and evaluation protocol was implemented. We compared the design activity done by the users themselves and the design activity done with the help of designers. The second design use case based on 'intelligent product design interaction' was implemented. Here, we compared the ability of interacting and assessing the product design (an intelligent lamp) to evaluate effectiveness of prototyping virtually vs rapid prototyping done by conventional methods.

2 Design methods/tools to include end-users

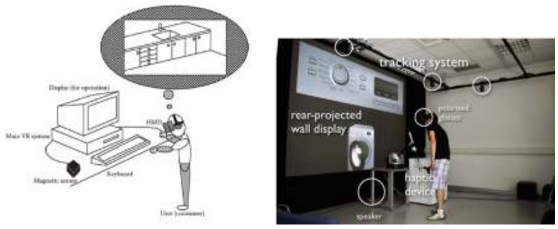
In PDP end-users' integration is achieved by different means like Virtual Prototyping (VP) methods. VP is an essential approach to meet design requirements and to determine design problems at FFE in PDP [10,13]. VP approach facilitates easier communication between customers and design engineers [14]. It helps in visualizing future products before their design is finalized and analysing its demerits. Virtual models are easily modifiable, as they are extension of CAD in VR environment and can be easily shared with others with relatively less expenditure of time and money [10, 20]. As a result, effectiveness of VR environment becomes crucial for successfully implementing VP, which depends on parameters: immersion and presence [47]. Immersion is the experience of visualisation, provided by any particular system, portraying natural perception of real world through vision, hearing and touch. Presence is the ability of user to detect and discern in the virtual world. The effectiveness of the tool primarily depends on these parameters. Multimodal-immersive VR systems have shown to produce a good satisfaction for users during modelling and assembly processes [49]. Hence, we are specifically interested in presence parameter - ‘ability to control’, provided by the tools for designing concepts.

For user integration, various tools having unique features for improved experience and implement ability, have been discussed in current on-going studies. A few of them which suit this research’s purpose are discussed as follows:

2.1 Kansei collection tools using VR

Kansei data collection at FFE is hard because of simultaneous collection of physiological and psychological data. Using traditional Kansei/Affective engineering framework [36], users can experience the design in two-dimensional modelling. The level of understanding of the design is limited in this case. Introducing Virtual Prototype (VPe) helps in collection of users’ feeling, as they are able to visualise the prototype resulting in clear expression of their feelings, afterward. Integration of VR and Kansei Engineering (KE) is called KE type IV [37]. KE type IV utilises the immersion being provided by the VR system for relatively better accumulation of kansei data because of detailed and realistic illustrations by VP.

Virtual KE has been implemented by Matsushita Electric Works for designing kitchen cabinet [39]. The use case of kitchen as a system domain is stated by Nagamachi [38]. It mimics the future kitchen space and provides an immersive environment for interacting with 3D objects in VR environment. The user is supposed to recommend modifications to a designer, who makes change in VR environment simultaneously. The changes are visualised in real time by the user. A quick assessment is possible while the user is still trying to come up with ideas for the new design. Outline of VR system and example of system execution is shown in Figure 2a.



(a) (b)

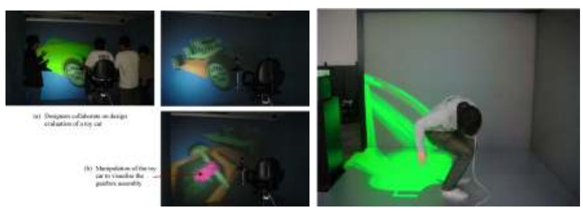
Fig. 2: a) Implementation of KE Type IV[38]; b) Implementation of VoC[14]

2.2 User need collection - VOC

Carulli et al [14]’s work showed ability to collect user needs, called Voice of Customers (VOC) through multimodal VP environments. The use case was to design a new washing machine’s interface. The interaction is shown in Figure 2b. Users of the tool were able to customise the interface directly by interacting with the VPe. This study affirms the use of VP at FFE to determine potential customers’ desire and thinking.

2.3 Visualisation and assessment tool: CAVE

A Cave Automatic Virtual Environment (CAVE) is a VR system with high level of immersion. It is a video theatre with walls on which images are projected and the projections can be visualised using a 3D glass. Product design evaluation of a toy car, Figure 3a, is implemented by Choi and Cheung [15]. The specified CAVE system is capable of assessment, and modifications of the product design. Another implementation of CAVE is illustrated by Ogi et al. [41], Figure 3b where users



(a) (b)

Fig. 3: CAVE implementations: (a) Toy car design evaluation [15];(b) Product evaluation by students [41]

(a) HomeByME©

(b) NIKEiD©

(c) Cooper©

Fig. 4: Customizers examples

visualised and evaluated the product designs assigned to them. It was used to introduce human-centered design to students using VR. Both of the implementation aimed at the product visualisation and its evaluation. User interaction with the design was limited in the mentioned examples of CAVE system. The data collection was done using feedback questionnaires.

2.4 Configurator Tools: Customizers

Mass customization is a marketing and manufacturing technique which combines the flexibility and personalisation of custom-made products with low unit cost as it gets associated with mass production. It is a strategy to differentiate products and services according to users' preferences which in turn increases the perceived value of the product and hence, profitability of the product increases [17, 24, 31, 54]. Popular companies provide mass customization services where buyers can select the parts of the product depending on their needs and preferences. However, it comes at a higher price compared to non-customized products. For example, is luxury cars like Rolls Royce© which offers customisations of the parts being used in terms of user experience and feeling.

Design of customizing tools requires it to be intuitive with higher level of usability, as the end-users spent only a limited amount of time on customizations [26, 27], so the tools are required to be intuitive and pleasant to use. Some popular on-line configurators using VPe (Figure 4) are: NIKEiD© (customization of shoes and accessories), MINI Cooper© website (customisation of a MINI©car), and HomeByME© (decoration of home interiors with furniture). Common feature being provided by these services, is the control over alteration in parts or positions of product components in a desirable way. Successful mass customization applications for strategies in many firms are Dell Computers© [34], Cisco Systems© [51], American Power Conversion©[25] or Reebok© [42]. Such customized products resulted in improving the customer satisfaction under specified contexts [21].

2.5 Synthesis of properties of the discussed tools

2.5.1 Based on VR parameters

VP implementation using KE Type IV, considers users as source of information gathering by making them passive contributors to the PDP. In these tools, user behaviour and feedback were studied and the changes in design were done by the design engineers (indirect control). As seen in case of CAVE and VOC systems, users did not modify designs based on their interactions and visualize it at the same time (low control). Revision in the design are carried out by iterating the design process using feedback from the user. It can take time and might not, always, completely satisfy the user due to language and description issues.

In case of product customizers, they provide ease of changeability with extensive options directly into the design (direct control), but the changes are limited to the availability of the component or its style. The designs modifications are dynamic and easy to manipulate for personalisation of ideas. However, the tools to interact with the customizers are limited to 2D/3D visualisation, using keyboard, mouse or touch screen in general.

The ideal tool should have both immersion and control parameters, at high level. The level of immersion and control parameter provided by the discussed tools is shown in Table 1. As a result, there is always a trade-off between immersion and control in order to achieve the goal. In short, VP design tools available at the moment lack in control and immersion at equal levels, at the same time. Discussed tools can be categorised as VR evaluation tools (high immersion) and Configurators (high control). The target ideal tool should have

Table 1: Level of immersion and control provided by the discussed tools

Design Tools	Immersion	Control
Kansei VR tool	high	low
VOC	medium	medium
CAVE	high	low
Customizers	low	high
Ideal	high	high

both high immersion and high control. Comparison of 'Configurators' and 'VR evaluations' for contribution in PDP is stated in Table 2. Based on the Table 1 and Table 2, configurators' $-ve$ point is low immersion, which if improved using visualisation tools, configurators will come under VR evaluations category. From the tables, for VR evaluations the $-ve$ point is mediated interactions .i.e. indirect control with immersion levels fairly equivalent. Therefore, our focus will be providing higher control (direct control) with already present high immersion levels.

2.5.2 Based on their generated prototypes

The discussed tools focus on early design phases, where users interact with the tool in order to create/ modify virtual concept designs as per their requirements. The design process in each of the discussed tools, does not have Physical Prototyping (PP) step involved in the process. PP may not be the case in discussed tool, but it is difficult to ignore the effect of physical interaction with the prototypes on the final design, as seen in the work of [23,60].

Prototyping in general, is an important part of user-centred design, it can enable designer sense 'felt-life' of users for whom they are designing [12,57]. It can be implemented at different levels in the product development stage. At the concept development stage, pen and paper techniques like storyboards and mock-ups are generally used. Catalog creation, Velcro modelling and user interviews can be done in order to ideate products [19]. At a later stage, rapid prototyping techniques like 3D printing, laser cutting, wood machining, etc. are implemented. In order to implement functionality, intelligent systems using electronic sensors and processors e.g. Arduino, LEGO Mindstorms, IoT devices, are used. These prototypes are also programmed to behave, in response to certain user/environment behaviour. As seen above, tangibility of prototypes increases with the progress in PDP, with low level at FFE to high level at testing part. High tangibility has been said to facilitate creativity, interaction and communication, by connecting actions and thoughts [18].

Both the prototyping types have their advantages and limitations, summarised as seen in Table 3. For VP, tangibility is the $-ve$ point. So, we try to minimise the need of tangible interactions.

Table 2: Configurators and VR evaluations

Category	Configurators	VR evaluations
Process	· Changes configurations · Generates the final product	· Experience the final product · Gives feedback to design engineer
$+ve$	· The users design themselves · Higher control	· Interaction and evoking of senses · Higher immersion
$-ve$	Only 2D visualization of prototype	Mediated interaction with VPe

Table 3: Physical vs virtual prototyping

Category	Physical prototyping	Virtual Prototyping
Process	· 3D printing · Normal machining processes · Quick and dirty etc.	· 3D CAD design · Interface design · Interaction programming
$+ve$	· Realistic appearance/ function/ feeling	· Functional ability, quick design changes
$-ve$	Time/ material dependant	Lack of/ low tangible interaction

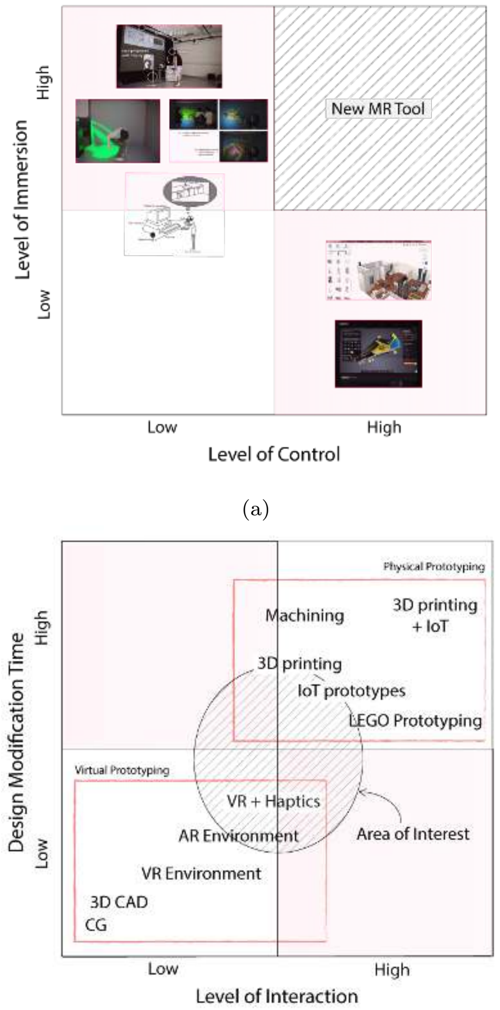
2.6 Research gap and objectives of this paper

Based on subjective review, we roughly mapped the discussed design tools, based on level of immersion and control (Figure 5a); and prototyping methods, based on the level of interaction and prototype design modification time (Figure 5b). Our objective in this work is to create and evaluate a new design tool to incorporate plus points from both comparisons, as shown in the Figure 5. We propose the usage of VPe to incorporate user at the FFE, as we are also interested in improvements in virtual interactions. A complete VPe should have three essential models: 3d representation, human product-interaction model and perspective test related models [55].

We define the following hypothesis:

Direct involvement of user in design process will result in product solutions closer to the user's demand/ requirements. A new design tool having high level of both, immersion and control achieved by minimal interaction interfaces, can enable the user to be part of the early design process.

In principle, the proposed MR tool needs to be compatible with existing design tools and methods. The tool needs to integrate the user in the design process by giving them simple interfaces to collaborate actively with the designers. The solution is to create the interfaces on demand for each use case and ensure their compatibility with the system with a modular architecture [5]. To check capability of tool with the mentioned solution, we implemented a design case focussing on 'interior design of furniture in a room', in a virtual



(a)

(b)

Fig. 5: Target Area of interest for the new tool (a) offers high level of control and immersion (b) w.r.t implementing prototyping

space. The on-demand interface might be convenient if it was completely virtual, i.e. intangible in nature by integrating gesture-based interactions (easily modifiable requiring less expenditure and time) only. To test this, we implemented a second design use-case of 'interaction with an intelligent lamp'. The following sections discuss implementation and analysis of aforementioned design cases.

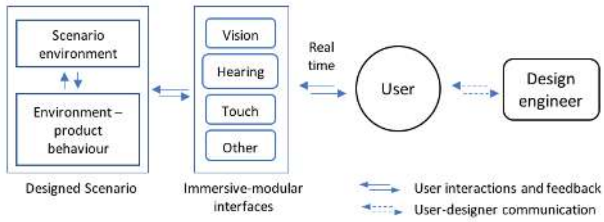


Fig. 6: Generic representation of tool interaction behaviour from users perspective

3 Proposed design tool and Use case implementations

3.1 Proposed design tools basic standard: Interactive, Compatible and Synchronous

Design tool needs to be interactive without the technical complexities. Its usage needs to be straight forward, in order to avoid any confusion occurring due unfamiliar nature of new technical details. In other words, it should provide simple interfaces and instructions that are easier to follow and are mentally less taxing. This will minimalize the unproductive effect on the design process due to gap in knowledge of the design team and end-users, by encouraging them to participate actively. Simple intuitive interfaces encouraging exploration may lead to a better user satisfaction [58] and therefore make the user willing to use the design tool and engage in design tasks.

For easier transition from current practices or inclusion of new practices, the proposed design tool need to be compatible with existing design tools in one way or another. In this work, we use digital tools and the manipulation of CAD data for a better integration. Physical behaviour and material properties being embedded in CAD itself, allows flexible exploration of design space [35,6]. CAD data when used with immersive environment can be used for stimulating users sense of vision, hearing and touch. System should be configurable as per various design needs and end-user behaviour. A modular configuration of visual and haptic interfaces, producible on demand should answer this need. Higher interaction with compatible nature should result in a continuous synchronous behaviour-response-feedback chain, making it possible to design live-scenarios to test various design problems. A generic representation of tool behaviour from users perspective, is shown in the Figure 6.

3.2 Design tool used: components and configuration

The MR tool used is an assembly of different components and sensors. The schematic of the system is shown in Figure 7. Head Mounted Display (HMD), Oculus Rift DK2, is used for visualising virtual scenario, and TUIs are used for haptic interaction within the virtual environment. The TUIs are 3D printed on demand and act as passive haptic objects, and their orientation is observed through a webcam using markers. Leap Motion sensor is used to observe the hand motion of users, which are represented virtually inside the virtual environment. The virtual scenario is designed in Unity game engine and the interaction behaviour of virtual objects are programmed using C#. Unity is a convenient platform to create and visualise 2D and 3D environments. Unity platform acts as the base to connect input/ output modules and process the interaction data in real time. This makes it possible to assign individual behaviours to virtual objects or physical TUIs, while implementing a design scenario. This makes it possible to design the environment and interfaces in modules. The MR system used is improved version, as discussed in the work of Arrighi et. al [4].

The detailed representation of design tool interaction with user is shown in Figure 8. It is divided into three parts: user interfaces, system controllers and unity assets. User interfaces act as input/ output for users to visualise and interact with the virtual scenario. System controllers handle the collection and transfer of data to/from the logical section of the tool. Unity assets acts as storage and logical section. It stores pre-defined representations of environment, objects and their attributes. Based on the data collected it selects appropriate behaviour to be outputted through user interfaces. Unity assets with accessible database, can be pre-designed for specific/new design problems. At the time of execution, the modules can be included or excluded depending on the needs for the given scenario. From users' point of view, they only interact with the system using provided TUIs and observe using HMD.

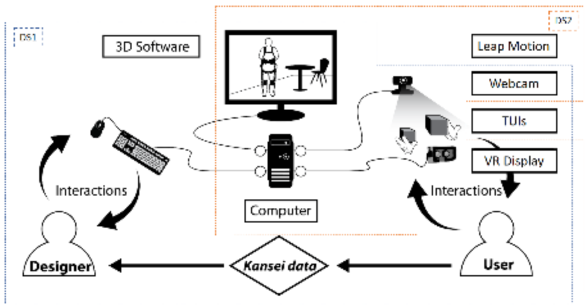


Fig. 7: Schematic of new MR tool

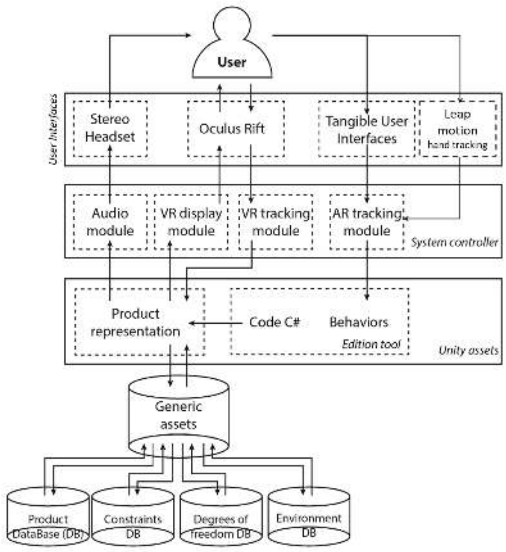


Fig. 8: Configuration of new MR design tool and tool interactions with user

3.3 Use case scenarios

3.3.1 Use Case I: DS1

Objective, here, was to measure impact of MR tool during early design steps. This use case inspects level of control provided the MR tool while users interact with the virtual environment. A better control would enable users to participate at the early stages of PDP. Based on this, we formulate the following hypothesis (H_{DS1}):

A prototyping tool that combines VR and TUIs, will provide high level of immersion and control for end-users to be able to design easily.

The first Design Use Case scenario 1 (DS1) focused on arrangement of given furniture, inside a room. It was derived from a design cognition study reported by Alexiou et. al [2]. Two design cases were conducted: one, user does the manipulation by themselves (direct, high level of control) and other, user asks designer to make the changes (indirect, low level of control).

3.3.2 Use Case II: DS2

Objective of this use case was to inspect the Virtual Prototyping can be done solely based on intangible interaction or not. Based on this, we formulate the following hypothesis (H_{DS2}):

A gesture-based interaction with the product in VR is perceived as realistic as tangible interactions in the real world, in terms of product functionality.

Design Use Case scenario 2 (DS2) was implemented from the work of Ross and Wensyeen [43], inquiring behavioural interaction of user and an intelligent product. This use case was used to inquire effect of gesture-based interaction for VP. It also had two design interaction tasks: tactile interactions with a physical prototype and gesture-based interactions with a VPe. Both tasks were designed to be similar in function and behaviours.

3.4 Use case assessment method

Kansei data obtained from psycho-physical measurements and self-reported questionnaires were used to analyse the use-case experiment data. Psycho-physical measurements were taken during the design process, while user was interacting with the MR tool. At the end of the design process, the satisfaction of the user was assessed by feedback questionnaire made using System Usability Scale (SUS), a Self-Assessment Manikin (SAM)[11] and Immersive Virtual Environments (IVEs) [22] questions.

3.4.1 Psycho-physiological measurements

Physiological measurements are metrics which can be used to measure potential behaviour of subjects and offer insights for the evaluation of the user experience [52]. They are also fitted to affective engineering practices [7]. Measuring the Skin Conductance (SC) is a commonly used method to evaluate emotional arousal, i.e. the intensity of the emotional reaction. Heart Rate (HR) is also a measurement of subjects' emotional arousal. Some researchers noticed a positive correlation between HR and the emotion of happiness, vigour and excitement [59]. Both SC and HR are also known to increase with the level of stress [52].

Physiological signal data are collected with ProComp Infinity System® and BioGraph Software® from Thought Technologies, monitored on a laptop. Along with the screen for the Virtual Reality System, a 20-inch monitor installed in front of the subject to display the prompts for explaining the procedures and instructions in each activity of the experiment. We also used a web-camera to record the subject's behaviour to help evaluate the user emotional states during the experiment.

3.4.2 Questionnaire design

In our study, the questionnaire consisted in questions about the user affective reactions, level of overall usability of system, level of satisfaction with the system and the design task. All questions were using 5-point Likert rating scales from 1 to 5 [32]. Items in questionnaire utilizing the SAM measured the level of pleasure, arousal and dominance respectively. In addition to these, one question (without a manikin) was added to measure the self-rated level of stress. These four items are processed as 'Emotional factor scores', to evaluate the emotions of the subjects in each task.

To measure the overall usability of the system, questions were extracted from the SUS. Usability includes the evaluation of perceived 'effectiveness', 'efficiency' and 'satisfaction'. The SUS is a robust and reliable evaluation tool based on a set of defined items. In our study, we excluded two items that we judged irrelevant in this context, i.e. "I found the various functions in this system were well integrated" and "I thought there was too much inconsistency in this system". We also used 'way of designing' instead of 'system', as we aimed at evaluating the usability of the co-design process with the MR tool, not only the MR tool itself.

Questions about user's satisfaction with the task itself were added, based on a modified version of the After- Scenario Questionnaire (ASQ) [30]. To match with the context of our study, the statement "I am satisfied with the support information (online help, messages, documentation) when completing the tasks " was changed to "Overall, I am satisfied with the results of my design in this task". Finally, in a "free comments" section, users were invited to provide comments about their experience with the system. Questions based on IVEs offer a sense of presence as in physical mock-ups and make evaluation of potential design choices possible in an efficient manner, as stated in the work of Heydarian et al. [22].

Based on the requirement of the implemented design use-cases, suitable metrics were used for assessment. Table 4, shows the metrics used for DS1 and DS2.

4 Use case implementation for assessing control

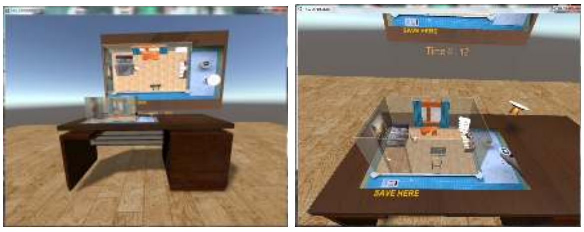
4.1 DS1 introduction

We want to demonstrate that with the right interfaces and immersion level, the user can directly perform design task and obtain better results compared to the more general use of such tools, which requires the user to give instruction to a designer for conducting the design. Hence the research question for DS1 is:

Can the MR tool providing high level of immersion and control, support creative design tasks?

Table 4: Assessment methods and relevant metrics

Type	Assessment method	Kansei data	DS1	DS2
Psycho-physiological measurements (while designing)	Heart beat frequency	Emotional arousal / stress	◦	
	Galvanic skin response	Emotional arousal / stress	◦	
	Video recording	Behavioural data	◦	
Questionnaires (after designing)	Self-Assessment Manikin	Valence, arousal and control	◦	◦
	System Usability Scale	Usability of the system	◦	◦
	Additional questions	Self-evaluated loyalty, stress and satisfaction	◦	◦
	IVEs	Immersion in VR		◦



(a) Designed Virtual space (b) Virtual room

Fig. 9: Designed virtual scenario

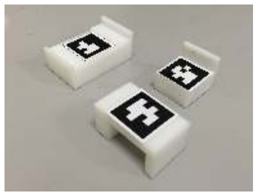
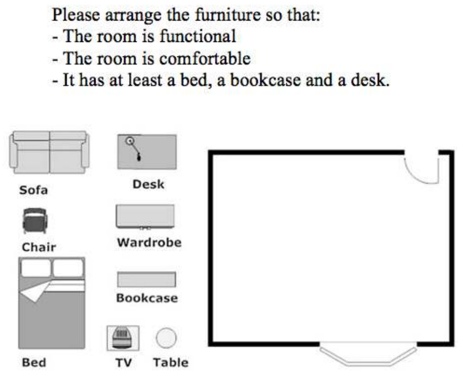


Fig. 10: Sample of TUIs used - bed, table and chair

Design case with haptic interactions was implemented and tested with a room interior design scenario, as illustrated in Figure 11. Alexiou et al.'s [2] study was referred to defining the contents of the task. We adopted their design task involving interior arrangement in a room as they are essentially spatial in nature and are very close to the type of task that has been employed to empirically study design cognition [2]. For our work, a virtual room environment was created; it includes walls, windows, decorative elements (tapestry, paintings) and floor (as seen in Figure 9). The user interactions are controlled with eight TUIs. Each TUIs is linked to a given piece of furniture (e.g. bed, chair, table, desk; see Figure 10) and can be used to control the location and the behaviour (motion) of the virtual representation of furniture. When the user manipulates a TUIs, the related virtual representation is placed and moved in the virtual room accordingly. Thus, through the use of TUIs, the user is able to test several design configurations and make design decisions in a natural and intuitive way.



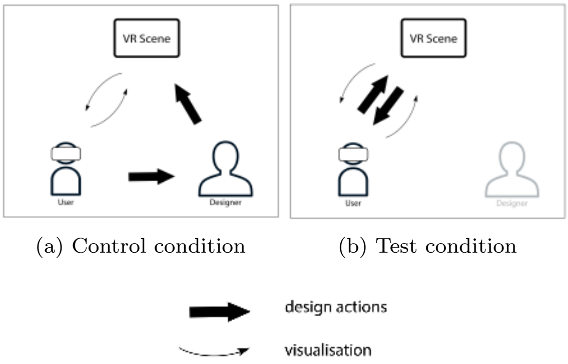
(a) Implemented design use case

(b) User interaction with the MR tool.

Fig. 11: DS1 protocol

4.1.1 DS1 Participants

22 students from Tokyo Institute of Technology in age range 20 to 30, participated in the experiment. Before the experiment, all participants were required to fill out



(a) Control condition (b) Test condition

Fig. 12: DS1 schematic

a questionnaire about personal information and their experience in design and in Virtual Environments. The mean was between low and medium experience of design (8 had no experience at all), and between very low and low for VR experience (10 had no experience at all). No significant differences were found among the participant's experiences.

The participants were asked to wear HMD and to arrange furniture TUIs provided to them, within working space.

4.2 Design tasks and protocol: DS1

Subjects were asked to perform the task in two different conditions, named Mediated Design Task (MD) and Collaborative Design Task (CD). The design tasks were open-ended and required no predetermined final state or criterion for deciding the termination of the task, and we quoted the same instructions for the prompts in our experimental protocol (Figure 11). CD setup enabled subjects to move the TUIs and see them in the virtual environment at the same time, giving them maximum control while using the tool. They were asked to activate the save function switch once they were finished and satisfied with their design. In MD, by contrast, they had to explain positions of each furniture to the designer, who arranged the objects according accordingly. The schematic of design tasks is shown in Figure 12. Subjects were given 10 minutes to complete each task, and a three-minute break was provided between the tasks. At the start, subjects were given 5 minutes to get used to the designed virtual environment, this session was taken as baseline session. The purpose of the break was for refreshing their minds and for calibration of physiological measurements, so subjects were asked to stay still and relax as in the baseline session.

The participant users were divided into two groups: Group A and B, to counterbalance order effects. Group A participants performed MD task first, and CD task second. Group B participants performed vice versa. In their respective second task, subjects were asked to design a different room in order to prevent being biased by the results of the first task. After confirming the positions of each furniture, users (or designers) were able to save the design by sliding a switch (a TUIs) in the physical environment. The final data was exported in form of .xls and .png files respectively. After the scene was completed and saved in each task, subjects were asked to fill in a questionnaire based on their opinions of the specific way of designing. The same questionnaires were used for both tasks.

4.3 Data analysis and findings: DS1

We recorded each design task performed by the user. Recorded data includes psycho-physical measurements and video recording. Because of a software error we were not able to process the first user, so this analysis is only conducted with 21 users, for a total result of 21x2 recordings. Video recording was performed with a camera above the user so we are able to track their hand movements and the TUI manipulations, form the beginning to the end of the task. In the case of MD, we registered all of the designer's actions for the complete task duration. Table 5, shows mapping between analysis type, metrics and data collected/inferences.

Table 5: DS1 data analysis and metrics relation

Type	Metrics	Data parameters
Tool perception	Tool satisfaction	Questionnaire
	Stress, valence, arousal	SAM
	Usability	SUS
Design task	Creativity	original solution count
	Solution satisfaction	Questionnaire
	Workspace exploration	area covered by furniture
	Design interactions	interaction type counts/durations

4.3.1 User experience of the design tool

Table 6 shows the questionnaire data results for CD and MD. We calculated the paired t-test.

Table 6: DS1 questionnaire data analysis (*significant difference p ≤ 0.05)

Question Type	Metrics	Score MD	Score CD	Paired t-test result	
SUS	Usability	64.93	69.34	t=1.080	p=0.292
Self-Assessment Manikin	Valence	0.5	1	t=1.590	p=0.130
	Arousal	0.41	1.14	t=4.120	p=0.001*
	Control	0.09	0.68	t=2.200	p=0.039*
Stress Score	Stress	-0.5	-0.59	t=0.370	p=0.715
After-Scenario Questionnaire	Task-ease Satisfaction	3.64	3.82	t=0.699	p=0.492
	Task-time Satisfaction	4.09	4.14	t=0.176	p=0.862
	Task-result Satisfaction	3.73	3.95	t=0.952	p=0.365

Same or more satisfaction with CD compared to MD (quantitative)
For SUS, it was found that 13 of 22 (59.1 %) subjects rated CD > MD, 2 of 22 (9.1 %) rated CD and MD the same, 7 of 22 (31.8 %) rated CD < MD. We included the 2 subjects who rated CD = MD into the group of 13 subjects who rated CD > MD, and conducted a chi-square test to see if there was a significant difference between the number of subjects rating CD ≥ MD and CD < MD. There is a significant difference at 10% level between the number of people who rated CD ≥ MD and the number of people who rated CD < MD. Therefore, it seems reasonable to conclude that subjects in this experiment were likely to rate CD the same or higher than MD, in terms of usability. Among the subjects who rated CD scores extremely lower than MD scores, we found common comments pointing out visibility issues and technical errors in the system namely, they felt uncomfortable not being able to see their hands while moving the TUIs or making the objects disappear every time they hid the AR markers with their hands, and also reported the awkwardness of the unexpected behaviour of furniture in the virtual environment (e.g. floating, sinking, incorrect deposition). It is possible that these obstacles prevented the subjects to enjoy CD, but rather made them stressful. Those subjects preferred MD instead, in which they may have found it easier to explain to the designer about their preferred arrangements without encountering any hindrance.

Low stress, control, arousal and valence correlated with good SUS (quantitative)
In order to infer the meaning of high-arousal and high-control scores from users' perspective Pearson correlation coefficient between scores for valence, arousal, control and stress vs SUS were calculated, Table 7.

We saw a positive correlation of self-reported arousal and control scores with usability ratings (r = 0.554 and 0.644) and confirmed that our system has a potential to create a better user experience in compared to other existing co-design tools. Not all of the subjects rated CD higher than MD in terms of usability, they tended to inform being more excited and in control by a significant difference (p <0.05). Subjects who rated high scores in control or low scores in stress had a high tendency to rate SUS scores high. From this result, it can be said that among all questionnaire replies, there was a trend that higher levels of valence, arousal, control and lower levels in stress resulted to higher usability, i.e. a better user experience. Also, subjects who rated high scores in valence or arousal scores had a medium tendency to rate SUS scores high.

Table 7: Correlation between SUS and emotional factors for CD task

Type	Correlation coefficient	p	Strength
Valence	0.596	3.07E-05	Moderate $+ve$
Arousal	0.554	1.15E-04	Moderate $+ve$
Control	0.644	3.20E-06	Strong $+ve$
Stress	-0.721	3.44E-08	Strong $-ve$

The subjects rating valence, arousal and control scores higher had scored SUS scores higher. CD arousal scores and control scores were significantly higher than those of MD scores. Thus, in the questionnaire analysis, we confirmed the importance of user excitement and controllability during co-design using a VPe, and that our tool has a potential to create a positive user experience when used in CD condition.

Skin conductance correlated with arousal (quantitative)
Skin conductance data throughout each design tasks was recorded. The data before first design task was considered as baseline for comparison purpose. As seen in Figure 13, significant increase of SC value from Baseline to Task 1 in both of the groups was found. A significant

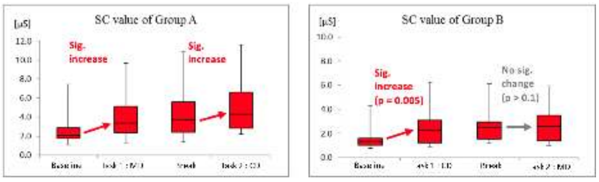


Fig. 13: Changes in skin conductance during the tasks

increase of SC value was also confirmed from Break to Task 2 only in Group A, break → CD. For Group B, significant difference between SC value at break and task 2 was not observed. We also saw a significant increase of SC value between Baseline and Break, in all of the subjects except one. In Group A: Break → Task 2 (CD), 9 out of 10 subjects increased their SC values. Among them, 5 subjects rated CD >MD, 2 rated CD = MD, and 2 rated MD <CD in SUS scores. It is difficult to conclude that SC value increased in CD because subjects felt more excited, i.e. had a better experience in CD than in MD. This because stress can also be a cause of SC increase, as shown in Lin T. et al.'s experiment [33].

We attempted to track the subjects through seeking a correlation of SC value change and questionnaire scores, and by 'coding' their comments, but we did not have enough samples to establish whether the value changes of each subject were based on a positive or a negative experience. The significant SC value increase from break to Task 2 only observed in CD may have been caused by either excitement or stress but as mentioned in the results, we were not able to distinguish the type of this arousal if it was based on a positive or a negative experience. We assume that evaluating

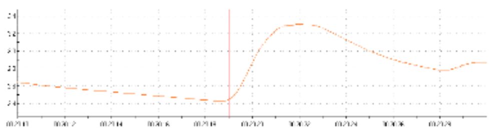
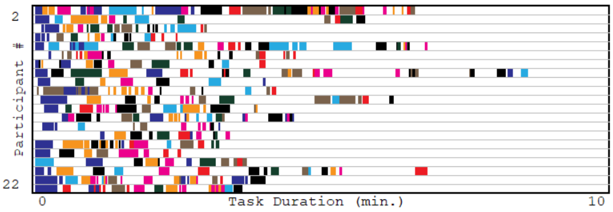
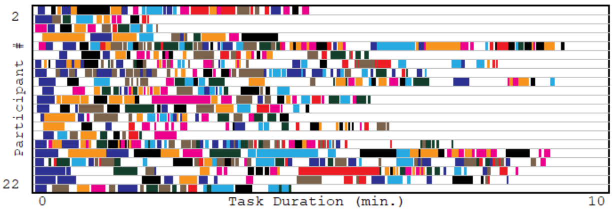


Fig. 14: An example of a 'Search Act' and SC response

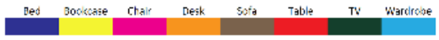
the SC mean value in each activity enables us to see the change of arousal level but is not sufficient to define the degree of valence. Nevertheless, we did observe some characteristic SC value changes during a specific behaviour in CD among some subjects. There was a peak in the SC graph when the subjects were searching for the positions of the TUIs without being able to see their hands. These "Search Acts", shown in Figure 14, were arousal events which triggered SC responses, consequently raising the SC mean in each activity 13.



(a) Design activity MD



(b) Design activity CD



(c) Object colour codes

Fig. 15: Design activity distribution over time

These responses may have been based on emotions like stress or anxiety as some subjects had trouble finding the objects and moving them to one place to another without interfering the other pre-positioned TUIs. Yet, certain reactions were found even among subjects who rated CD extremely higher than MD in SUS scores. Skin Conductance Response (SCR)s were also observed in MD conditions.

4.3.2 Analysis - Design interactions and time

We studied user activity across the design task duration, it is shown in Figure 15, for CD and MD. The figure represents activity of users for a duration of 10 minutes with left hand side being the starting point on horizontal axis. Each colour represents a specific tangible object used for the experiment, while white space indicates inactivity. The length of the coloured bar shows the time duration that object was used with a pitch of 1 sec as minimum time duration observed. The rows represent experiment/participant number. Figure 15a, shows activity for CD and Figure 15b, for MD task.

Total duration of the design task

We first measured the total duration of each design method. The mean duration of the design task performed with the CD method is 00:06:15, and with the MD method is 00:04:43. For 14 users out of 21 the design task took them longer to perform with the CD method compared to the MD method.

An action is defined as an interface manipulation. For the CD design task, all the actions are done by the user, for the MD design task all the actions are done by the designer, who follows the instructions of the user. The user or designer is considered active when they manipulate an interface. The activity ratio is therefore the active time divided by the total time. The closer to one this activity ratio is, the more active the user/designer was during the design task.

Total duration of active time

We measured ratio between the total duration of the design task and the active duration, i.e. the total time during the user or the designer is actually modifying the design of the room by using the interfaces. The average active time for the CD method is 55%. The average active time for the MD method is 39%. For 19 users, out of 21 the active time was higher during the CD method compared to the MD method.

In terms of action count, it was found that mean count for 'a user' during CD was 40, while during MD was 25. 17 users out of 21, in their individual experiments, were more active during the CD design task compared to the MD design task. One performed the same number of actions. It can be said, while performing the design task with the CD method the users are more active and perform more actions. They also spend more total time on the task.

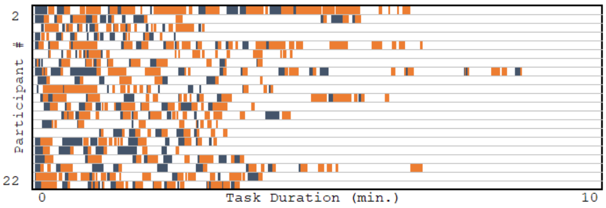
Different actions during the design tasks.

In order to analyse this gap of activity in duration during the design methods we also compared the design action, i.e. interactions with the user or designer and the TUIs. We divided actions in two types: High Level Design (HLD) and Low Level Design (LLD).

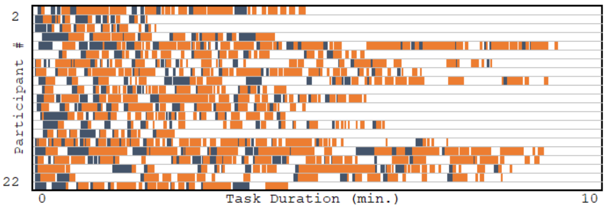
HLD represents actions having larger impact like moving of objects relatively larger distance and inclusion/ exclusion of objects in the solution.

LLD represented minor changes in orientation like rotation or translation to fit the objects relative to each other and environment itself.

Figure 16, shows distribution of these events of task activity duration. There were more LLD events than HLD events in total. For LLD, actions in CD >MD by 11.6 events on average. For HLD, actions in CD >MD by 4.5 events on average. It can be inferred that when users had chance do act they were willing to make adjustments while they were satisfied with the actions of designer after a few number of adjustments in MD. The HLD-LLD data is shown in Table 8.



(a) HLD vs LLD activity - MD



(b) HLD vs LLD activity - CD

Fig. 16: HLD and LLD event distribution for participants

Amount of time (quantitative)

We also identified that when users rate the time they spend on the design task they are more satisfied with the CD design methods. 18 users out of 22 find the amount of time required to perform the design task with the CD was same or better compared to the MD design method.

4.3.3 Design results and impact on creativity

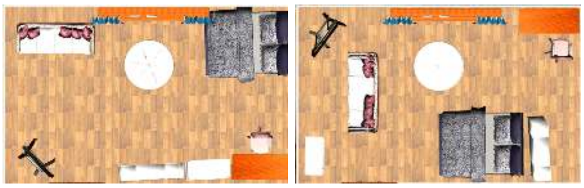
We wanted to measure the difference in creative output of the design process when users design with the CD method or with the MD design method. The output of the design process, for each method, is a unique combination of furniture inside the room. We collected all the floor blueprints and labelled them by user, design method and furniture. The result is a collection of 44 different floor plans with the position of each piece of furniture. A sample from the data is shown in Figure 17.

Criteria for creativity

Creativity can be assessed by various methods. Torrance [50] explained criteria for measuring creativity using 'originality, fluency, flexibility and elaboration', while Sarkar [45] emphasised on novelty and usefulness.

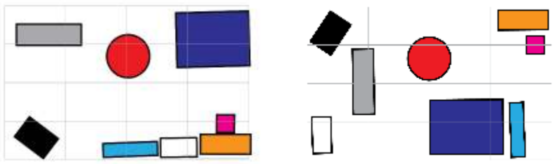
Table 8: Event count and User activity

	HLD events (mean count)	LLD events (mean count)	HLD active time (min)	LLD active time (min)	Task duration (min)	Total Active Ratio
CD	14.714	27.54	01:00	02:40	06:32	0.573
MD	10.19	15.905	00:43	01:18	04:57	0.408



(a) (b)

Fig. 17: Snapshot of solution generated in CD and MD



(a) Coded CD (b) Coded MD

Fig. 18: Coded version of generated sample solution

For our case, fluency is total number of solutions generated, flexibility is different solutions generated and, originality or novelty is related to the exploration of the option and how answers differ from one another. In our design case two solution are generated by the participants using CD and MD methods. This limits the fluency criteria to 1 for each method per participant. We have tried several methods of coding to differentiate the rooms generated with the MD and CD method but did not find any relevant differences. Therefore, we focussed on the criteria Originality to assess the impact on the creativity, by CD and MD methods. Usefulness is not considered, as it was one of the conditions for the room to be designed.

Coding originality

For the evaluation of the originality of the design outputs we compared for each design method and each furniture the exploration of the different alternatives, i.e. furniture positioning. From the saved snapshot data, positions (see Figure 18) and area explored (see Figure 19), for each room-object was calculated.

We started by calculating the total area covered by each furniture for each design method. On average, participants explored 5.15 % more in CD as compared to MD. 7 of 8 room object have more explored area in CD. Original solution w.r.t individual objects were counted, by observation of coded snapshots. The solution was counted if the orientation of individual object was unique throughout the solution data. If the orientation overlapped, then the solution was counted only when overlapping is less than 50% of the object's dimensions. The all 22 solutions are considered for calculating area covered. The results for relative area explored ((area(CD)-area(MD)) *100/area(MD)) by the user for individual objects and original solutions w.r.t objects is shown in the Table 9.

(a) CD layout (b) MD layout

Fig. 19: Cumulative layout of 'Desk' for all participants combined

A t-test on a 5% confidence interval on the following hypothesis was done: With the CD method, the users tend to explore more (different) configurations for each furniture. We found $t_{\text{Stat}} > t_{\text{Critical}}$, at p=0.0003 significant difference. We can conclude that the user generates more original results when they use the CD method compared to the MD method. This result is backup by our qualitative analysis of the design processes recorded on the video.

It is very interesting to notice that 9 out of 22 users were more satisfied with the result obtained with the CD design method, 10 were as satisfied with CD method as they were with MD while 3 more dissatisfied with CD method compared to 3.

Not only the results obtained with the CD design task are more original, but the users are also more satisfied with it.

4.3.4 Same expert/exceptional behaviour (qualitative)

When we analysed the videos, we noticed that the designers tend to use their hand to simultaneously move

Table 9: Room object data analysis for original solutions

		Bed	Bookcase	Chair	Desk	Sofa	Table	TV	Wardrobe
Relative Area Covered (%)		8.18	5.15	5.57	-1.47	3.3	8.06	5.85	21.82
Original Solutions Count	CD	8	14	15	13	14	11	11	11
	MD	6	10	12	11	12	8	11	8

several interfaces at the same time, which could be described as an expert behaviour. To our surprise, we noticed that several users, even discovering the design tool for the first time, did the same thing. This happened for 4 users.

The specific behaviours were only observed for the CD design method. User sometimes put furniture in the room and removed them after several iterations, sometimes after adding another furniture or right before the end of the design task. This happened to 5 users. While no such case was found in MD tasks.

4.3.5 Same task ease

Regarding the test ease, we were not able to obtain statistically relevant results. 5 users rated no difference (neutral) while 8 rated the CD to be more difficult and 9 the CD to be easier, compared to the MD task. It is still interesting to note that the actual use of the system was not rated worst compared to simply explaining a design with words. Obtaining a similar result is already a good achievement.

4.4 Synthesis of DS1 data analysis and findings

Participants were more excited in CD tasks. The overall increase in arousal was identifiable in CD task, but inconclusive for MD task. Participants explored relatively more in CD task and had better control. The participants were willing to do fine adjustments in CD as shown by higher number in LLD tasks. The creativity of the solutions for CD tasks was found to be higher than that in MD. It can be concluded that the MR tool has the potential to support creative tasks. The results validate hypothesis for H_{DS1} and positively answer our research question for this design use-case scenario.

However, users faced some difficulty like visualising their hands and limited mobility. The hand visibility has now been solved in the current version of the system which was improved after the experiment. We solved the visibility issue afterwards by making the virtual room floor translucent, enabling users to see their hands while moving the objects and also implemented a hand tracking device, the Leap Motion. Initial designed environment had top view of the virtual room, but we implemented multiple view by adding the view of the furniture arrangement from inside the room as if the user was inside the room. An option was added to toggle between the two views. Also, we designed a realistic scene with grass, sky and trees outside the room to provide better immersion and context to the virtual scene (see Figure 20).

(a) Improved virtual scene (b) Virtual room - top view (c) Virtual room inside view

Fig. 20: Quick improvements in the virtual scene

5 Use Case Implementation for Virtual Interaction

DS1 focussed on relative inter-object interactions for interior design, i.e. the objects themselves were smallest elements and had no interaction among themselves. The positive results from DS1 may or may not hold for a multi-function virtual prototype. Hence, there was need to check design tools effectiveness through independent design use-case scenario. The tool focuses at FFE, there is no specific physical prototype while designing. As a result, we focus on gesture base interaction in VR environment. We use Leap Motion sensor to track hand activity of the user for virtual interactions.

5.1 DS2 introduction

The objective here, was to assess the applicability of gesture-based interaction in the current MR tool to interact with VPe as if it were a real prototype. For DS2, the research question was:

Whether a gesture-based interaction between user and product, can be implemented through VP or not?

A second design case, using MR tool was implemented without haptic interaction and tested with an

(a) 3D printing outer shell (b) Assembling: sensors, LEDs, Arduino (c) Final form with pressure dots at the back

Fig. 21: Prototyping the physical functional model

(a) intelligent lamp [43] (b) Implementation VPe

Fig. 22: Implementing Ross's Intelligent lamp [43] in VR

Intelligent Lamp scenario. Two prototypes of the intelligent lamp were created: a physical lamp and a virtual lamp. The lamps are designed similar to the lamp described in the Ross' work [43] (Figure 22a) with reduced features. Physical model consists of 3D printed parts of the lamp body, pressure sensors, LEDs and Arduino (see Figure 21). The sensors and LEDs are connected together to Arduino which simulates defined interaction behaviours. The tactile sensors (dots) are placed at the outer surface (sensing surface) of the lamp. The LEDs are placed at the inner surface of the lamp corresponding to the position of dots on the sensing surface.

Same behaviours have been implemented in the virtual model. We also designed the nearby surrounding to give context to the virtual model. Lamp implementation in VR is shown in Figure 22b.

The user's hand motion and behaviour are simulated using the Leap Motion integration into the MR system. Users can see a virtual representation of their hands in the virtual scene. The virtual hand is programmed for interaction with designed product. Product is designed to behave similar to physical prototype as if the interactions were in Reality. All ten fingers and palm can be programmed with finger joints as the actuators.

5.1.1 Participants

In DS2, 10 students from Tokyo Institute of Technology participated. Group A had 5 participants (3 male, 2 female), also group B had 5 participants (4 male and 1 female). Before the experiment, all participants were required to fill out a questionnaire about personal information and their experience in design and in Virtual Environments (self-rating on a 5-point scale). The participants had relatively less experience in using the VR system. The average scores were 3.4 and 1.9 for experience in design and using of virtual environment, respectively, out of 5. No significant differences were found among the participant's experiences.

(a) Physical interaction (b) Virtual interaction

Fig. 23: DS2 experiment user activity

5.2 Design tasks and protocol: DS2

Ross's intelligent lamp behaves differently with respect to tactile behaviour by the user. In order to keep the task easier to understand for participants inexperienced in VR, simpler lamp behaviour was implemented. We defined the interaction behaviour of the lamp as follows:

- When user touches a dot, corresponding LED lights up. It remains lit after user remove their hand.
- Maximum number of LEDs the user can lit up, were fixed to maximum 6. If user continues to interact with the dots, LEDs turn off in order they were lit up so that the maximum lit up LEDs at any time is 6.
- Exploratory behaviour: Free behaviour by user was allowed, in order to explore different combinations of static and dynamic product behaviour.

Example of user interactions with the intelligent lamp prototypes, is shown in the Figure 23. In DS2 also, participants were divided in two groups, Group A interacted with physical lamp first and then with virtual lamp first. Group B did vice versa. Participants were given a time of 5 minutes to complete one task with 3-minute break in between. Questionnaire was provided at the end of each task. Also, 7 minutes was provided for feedback interview with the participant.

Table 10: DS2 metrics and data analysis

Type	Metrics	Data parameters
Prototype perception	Satisfaction, usability	Questionnaire, SUS
	stress, valence, arousal	SAM + stress
	Individual experience	IVEs
Task evaluation	Relative experience	IVEs
Resource comp.	Development time, Consumable items	Time observation + BOM

5.2.1 Data analysis and findings: DS2

Table 10, shows mapping between analysis type, metrics and types of data collected/inferences. DS2 explored the ability to interact with a VPe by the users. We had questionnaire data from 10 participants, for physical prototype task (PPT) and VPe task (VPT) each. The focus of analysis was to evaluate emotion, controllability and immersion level of participant users while they were interacting with both of the prototypes. As the character of obtained data is not assumed as normal distribution and equal variance, Wilcoxon signed-rank test was performed for each of the scores in the questionnaires for interactions with both prototypes in Virtual Environment (VE) and Real Environment (RE). The comparison of the average score of each index were as shown in the Table 11.

5.2.2 Emotions, Control and IVEs

Valence, arousal and stress metrics were observed to evaluate emotion level for interactions. There was no significant difference for valence. However, for arousal and stress, scores were found to have significant differences between the prototypes. Higher arousal level was observed when users interacted with VPe, also observed in previous experiment. Control level was found to be lower in VPe with a significant difference $p = 0.014$. From the subjective feedback, we were able to conclude users felt lack of precision in the user's action and product's behaviour, when there was no physical contact. It seemed more time was required to get used to gesture based interaction for the participants.

The stated stress levels were negative for both the cases, slightly better for the physical prototype with $p=0.013$. Even though the participants showed low VE mastery, yet it did not increase their self-reported stress level. Another inference can be the ease of design interaction task. The stress level might increase if the complexity of task increases, though it was not high in this case.

IVEs, and subjective questions were used to check immersion metric for VPe. Immersion metric showed significant difference ($p=.035$). In VE, only gesture-based interaction was not able to provide enough immersion experience due to lack of haptic experience. However, realistic nature and consistency in behaviour of VPe, both, scored a mean of 3.77. It was as expected, because both the prototypes were designed to behave similar. Time taken for interaction with VPe scored a mean of 2.3 out of 5, with respect to interaction in real prototype, with value 3 representing same time taken in virtual interaction and real interaction.

Preference of real prototype vs VPe stood equally at 5 participants, for each. In general, VPe fared equal or slightly better than the physical prototype, except the control metric in post experiment interview. Some participants addressed the issue of mobility and sensation of physical touch in the VPe. The SUS scores showed significant difference at 10% level ($p \leq 0.1$) with relatively close absolute values. There were no strong agreement or disagreement for either of the prototypes in the metrics, which leaves space for improving the prototype functions and the work environment in future work.

As per the t-test results for VPe seemed to perform better than the physical prototype for arousal. This leaves a scope of improvement for control, immersion and stress scores. Improving the virtual scenario itself, would seem to improve the SUS score of the system, as stated in the subjective feedbacks from the participants.

5.2.3 Correlation comparison for metrics with significant difference

We conducted Spearman's rank correlation analysis on the metrics to infer effect of one metric over another. Table 12, shows correlation comparison among metrics (significant difference $p \leq 0.05$ observed) - SUS, control, stress and immersion. It shows strong +ve correlation between immersion and control and $-ve$ correlations between immersion and stress, and control and stress. Immersion and SUS showed moderate $+ve$ correlation but SUS metrics evaluation was found not to be significant as seen in Table 11.

5.3 Resource requirement analysis

Regarding time expenditure, man-hour scores were calculated for development of each prototype. VP required 32% less time than PP. Further breaking down the time

Table 11: DS2 questionnaire data analysis(*significant difference p ≤ 0.05)

Question Type	**Metrics**	**Score VE**	**Score PE**	**Paired t-test result**	
SUS	Usability	63	67	t=1.080	p=0.061
Self-Assessment Manikin	Valence	1	0.5	t=1.590	p=0.206
	Arousal	2	0	t=4.120	p=0.016*
	Control	-0.05	1	t=2.200	p=0.014*
Stress Score	Stress	-0.5	-0.59	t=0.370	p=0.013*
Median (Inter Quartile Range)					
After-Scenario Questionnaire	Task time Satisfaction	5	5	t=0.699	p=0.317
IVEs	Immersion	3	4.5	t=0.952	p=0.035*

Table 12: Correlation comparison with significant difference p ≤ 0.05

Metrics	**Corr. coefficient**	**p**	**Strength**
Immersion-SUS	0.482	.031	Moderate+*ve*
Immersion-Control	0.677	.001	Strong+*ve*
Immersion-Stress	-0.647	.002	Strong−*ve*
Control-Stress	-0.640	.002	Strong−*ve*

spent for PP, only 10% of its spent time was for 3D printing, the rest was for attaching sensors and related programming.

In terms of prototype creation only, VPe creation had no consumable materials while Physical Prototype (PPe) creation required: 3D printing materials, electronic components (sensors and LEDs etc.), and Arduino board were used for the PP. The cost of such consumables is dependent on the amount/ quantity used and increases with the increases in requirement.

5.4 Synthesis of DS2 data analysis and findings

Table 13: Synthesis of DS2 data analysis

	VP	**PP**
Metrics	· high arousal	· high control · high stress · high immersion
	· equal perceived reality	
Development time (unit: man-hour)	8.25	12.5
Consumable items	(none)	·3D printing material, pressure sensor (x14), 1W power LED (x28), Arduino Uno board (x1)

Table 13, shows the synthesis of DS2 metric analysis. The VPe performed better than PP for arousal only. Also, it was more convenient to create, as compared to PPe. But, it was comparable for other metrics as there were no major differences observed. Participants preferred interacting with virtual prototype equally to the physical prototype. This validates our hypothesis H_{DS2}, but to obtain absolute positive results more work is required in this field.

Combining the results with the subjective feedback received from the participants, as of now there is a need of some kind of haptic feedback from the design tool for interaction. Participants mentioned a need of feedback mechanism to emphasise points of contact in the VR. With a little improvement in the design of use-case and practice of intangible interactions, VPe can be implemented alone in the design process. It shows potential but it needs further evaluation.

6 Conclusion

A new CAD system was created using MR tools and TUIs, which facilitates the design engineers and users to communicate at early stage of product design process. Our system enables end-users of a future product to visualize a VPe in three dimensions, and to manipulate it or modify it in a direct and intuitive way. The stimulation of visualisation, hearing and touch ensures a high level of immersion. The TUIs allow direct and intuitive interactions within the virtual environment, therefore they offer a high level of control over the virtual environment and virtual models. The key benefit of this tool is that, it allows to involve users in the early stages of the design process and to directly include their taste, feedback and requirements in the design models. The VR environment and TUIs can easily be created to fit specific design cases.

Evaluation of MR tool confirms the effectiveness of the usage of MR Environment for generating design solutions. Evaluations also suggest that interactions between the MR system and visualization in VR were easy to learn and get accustomed to. The positive response from the participants of the evaluation experiments confirms the efficient involvement of the end-users in the design process, even though they didn't have prior knowledge of the usage of MR system. Usage of MR system for design solution was supported by the participants but it is difficult to conclude whether would like to use it on a daily basis for different product problems.

We also discussed application of gesture-based interaction in VP. A comparison was made between a physical prototype of an intelligent lamp vs its representative virtual form in VR environment. The results of experiment suggested the performance of VPe was equally good or slightly better than that of physical prototype while having issues over feeling of touch in the virtual world. Though this needs a larger empirical investigation.

Combination of gesture-based interaction and tangible objects would be a promising interaction interface allowing manipulation and modifications simultaneously. It is easily perceivable that the designed tool is capable of integrating end-users in the design process with ease and effectiveness, in spite of existing limitations. However, there are some limitations to the MR system like limited mobility, lower hardware capability of the system components, uncertainty over the causes of certain behaviour of participants, etc. Improvements are still required in development of design scenarios, as there is still gap between VR representations and real-life objects' appearance. Modularity and straightforwardness of the tool also presents another form of limitations. In order to maintain its intuitiveness and users active participation, the number of provided interfaces for interaction are fairly limited. Depending on the design problem more/multi-functional interfaces might be required, raising new problems for defining behaviours of modular interfaces and to keep their increasing complexity in check. This leads to another focus for further research.

Significance of proposed design method and tool lies in its modularity to implement design-problem use cases and directness for users to interact with it. Our future will work include a full experimental evaluation of the usability of the MR tool, as well as its impact on the design process and the design outcomes. Usage of gesture-based interaction will be focussed in order to reduce the number of haptic interface, and user's need to interact while being a part of design process. The development of such a digital tool is expected to help designers to closely co-design with end-users in a direct and efficient way and thus to create user-friendly products and satisfactory subsequent user experiences.

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