Helping Hands: Exploring Multimanual Interaction in Virtual Reality

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Hand tracking allows users to interact with their real hands in VR. As this technology is now easily accessible through standalone Head Mounted Displays (HMDs) like the Oculus Quest series, it grows in popularity in the unofficial Virtual Reality (VR) app store 'SideQuest'. Through an analysis of existing apps we found that many apps using hand tracking tend to add abilities to the digital representation of the real hands such that they become more powerful in a virtual environment. The empowerment of the virtual body is well accepted by the users and thinking of the increasing merging of digital and real world through Mixed Reality (MR) technologies, it sounds promising to enhance the virtual representations of our real bodies. A possibility that arises through accessing digital hand representations is to generate multiple virtual instances of them, allowing the user to not only use two hands to interact with their environment but an arbitrary amount. Such multimanual interaction system could increase productivity and ease-of-use through growing multitasking capability. A main challenge of such a system is to not overwhelm users with too many processes to keep an eye on, thus making additional hands independent of the user's conscious observation. Additional hand instances could be independent by being static, prerecorded or empowered with artificial intelligence. To systematically investigate multimanual interaction in VR, we span a design space using morphological analysis. We further show the practicability of our design space by implementing a VR prototype designed for multimanual VR interaction. In a user study we found that multimanual interaction in VR is accepted as a practical tool that increases productivity and user experience (UX) while not increasing cognitive load. Our work shows the potential of multimanual interaction as a fundamental paradigm of interaction in MR systems. We further show that it is worth to explore further concepts of enhanced interaction that make use of increased immersion and modern MR technologies to improve satisfaction and efficiency of the users. We also provide a design space that in future research can be optimized and explored.

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1 INTRODUCTION

Recently, VR HMDs became more accessible through increased usability and mobility, as well as lower acquisition costs. The rapid development of Computer Vision techniques enables reliable inside-out tracking which allows experiencing VR without peripheral equipment, thus standalone. In current VR systems, the cameras required for environment tracking can now also be used to track the user's hands to integrate them in the virtual environment and improve immersion. Current state of the art hand tracking however is not as reliable as traditional controller tracking [8], as it is dependent of optimal lighting conditions. Oculus now made their hand tracking technology available for developing custom VR Apps in the Unity Game Engine [8] thus allowing independent developers to create Apps using this technology. Through an analysis we found that hand tracking Apps in the 'SideQuest' [11] App store tend to experiment with the digital hand representation's abilities. For example, users can change the look of their hands (e.g, tentacle hands), as well as size or finger appearance [3]. In other applications it is possible to cast spells by performing certain hand gestures [19].

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This observation becomes particularly interesting when thinking of the proceeding merging of digital and real world through rapidly advancing MR technologies. An empowerment of our virtual body representations might very soon also be beneficial in augmented reality scenarios. The mentioned development is of course also driven by the 'ultimate display' mentioned by Ivan E. Sutherland [14] which would allow a complete merging of physical and digital worlds in which any sort of digital human empowerment would directly impact real abilities. Having digital representations of the user's real hands also allows for new interaction paradigms as they are more accessible and more intuitive to use than traditional abstractions through digital hand models that rely on dedicated hand held controllers. The idea of having more than two hands to interact with could lead to increased productivity through improved multi-tasking abilities. Moreover such interaction paradigm might also borrow enjoyment of use, such to use it as a fundamental interaction paradigm for i.e., games.

It is common sense that human hands are more flexible and versatile that their equivalents of other species [[18], [15]]. When looking at specific tasks, human hands get easily outperformed by more specialized equivalents, however, from a pure physiological perspective, no other species can do as many different things with their "hands" as good as the human. It is also common sense that the mentioned versatility boosted the cognitive development of the human [18]. It is obvious that further enhancing hand abilities and variety is an interesting approach when thinking of human computer interaction. Having multiple hands leads to various associations. In some eastern cultures for example, gods often are depicted as having multiple heads, limbs or hands [13]. Even in western culture, supernumerary limbs are considered as something powerful and intimidating. Examples can be found in super hero movies or games where especially powerful characters sometimes can control supernumerary limbs (Compare "Dr. Strange" or "Dr. Octopus" from Marvel or "Machomei" from PokéMon). On the other hand, multiple legs, arms etc. can also trigger a feeling of danger, aversion or even disgust when thinking of insect phobias (Entomophobia [17]) in regard to e.g., spiders, scorpions etc. The concept of multimanual interaction therefore comes with a set of benefits and challenges. Benefits could be: multi-tasking, efficiency, productivity and power. Challenges could be: coordination, predictability, controllability and unnaturalness for humans. A system for multimanual interaction should make use of the benefits while addressing the challenges. The main challenge presumably is cognitive overloading of the user through coordination, which can be reduced by decoupling the hands' actions from the user's conscious observation e.g., by applying predefined information to them or let them act in a passive manner without requiring active input. Still, users should be able to relate to their additional hands.

To explore the possibilities of multimanual interaction together with possible interaction metaphors, we span a design space using morphological analysis. From that we develop an interactive system that is a partial implementation of our design space and serves as an example of how the implications of the design space can be applied. An evaluation with respect to the main benefits and challenges of our concept has shown that the system is well usable, improves UX and efficiency while not being too cognitive demanding for practical use. The results show that the concept of multimanual interaction has potential to serve as an underlying concept of interaction in VR. Our results further imply that it is worth researching new paradigms of interaction that make use of immersive MR technologies like hand tracking to improve efficiency and enjoy-ability of use of MR systems. Further exploration and development of our design space would contribute to the research and improve our approach of multimanual interaction.

2 RELATED WORK

Multimanual interaction is related to a wide field of topics in HCI as also fundamental concepts of interaction are addressed: precision of interaction, simplicity of use, natural use, interaction metaphors. Taking our VR approach into account, popular principles like distance interaction and immersion are related topics and are also discussed in this work. As we base our system on the hand tracking technology, we want to present the latest developments here. We also list work that already tackled the concept of multimanual interaction in Robotics as well as Virtual Reality.

2.1 Hand Tracking

Hand tracking is a rapidly developing technology that, with upcoming MR systems also grows in importance as it is an accessible way for the user to interact with digital content without being dependent on peripheral devices (e.g., controllers). Augmented Reality (AR) devices like the Microsoft HoloLens 1&2 [7] for example solely rely on hand- and gesture tracking for interaction. Consumer VR HMDs from Oculus also offer the possibility of hand tracking as a supplement interaction principle besides using controllers. Let older technologies like Xbox-Kinect aside, hand tracking firstly became accessible for e.g., VR systems with Leap Motion [5]. Facebook's effort to create their own hand tracking system for their Oculus VR devices shows the importance of it for future MR devices. In fact, Facebook research lab recently published a paper presenting a milestone system in hand tracking [12] that allows to track arbitrary hand poses and is invariant against occlusions, which in state of the art systems breaks the tracking. Their system however is not yet real-time capable. It still shows the potential of hand tracking with increasing computational power and Computer Vision developments.

2.2 Robotics

The idea of using multiple limbs for interacting with the environment is not new. Especially in physical demanding tasks, the idea of having additional, stronger limbs is promising. Saraiji et al. [9] presented a exoskeleton alike device that provides the user with two additional robotic limbs. Having additional limbs however brings up the question of how to control them. Llorens et al. [6] investigated how to control various limbs using e.g., feet to influence their behavior.

2.3 Virtual Reality

Schjerlund et al. [10] investigated the concept of using supernumerary digital hands in VR. The idea is to spread them in a 3D grid throughout the virtual environment so that, no matter where or what to interact with, there is always a digital hand copy in reach. Their system however does not allow for variability and certainly is inefficient as it also puts many unnecessary hand instances into space. Our system aims for versatile use that only creates hand copies in places where they are actually needed. Kulu et al. [4] investigated how having multiple hands in VR affects efficiency in use. To do so, they attached additional virtual hands to the VR player in various patterns and observed user behavior in different tasks. One specific task was to catch a moving object which was easier having multiple hands. This however could be due to the fact that having multiple hands simply increases the catching surface. Their system is static and does not allow for versatility either. Further, their hand copies are uncontrollable and can only be used passively. As in the Robotics section, Drogmuller et al. [2] built a VR system to remap a third artificial arm in VR so that it could be controlled using the existent arms. Their research aimed for precise control-ability of just one additional limb. Our goal however is to be able to control an arbitrary amount of virtual hands with less precision and therefore also less cognitive effort.

3 DESIGN SPACE: MULTIMANUAL INTERACTION

To analytically investigate the possibilities of multimanual interaction in VR, we systematically formed a design space that covers first principles of multimanual interaction using morphological analysis [20]. We first defined five dimensions

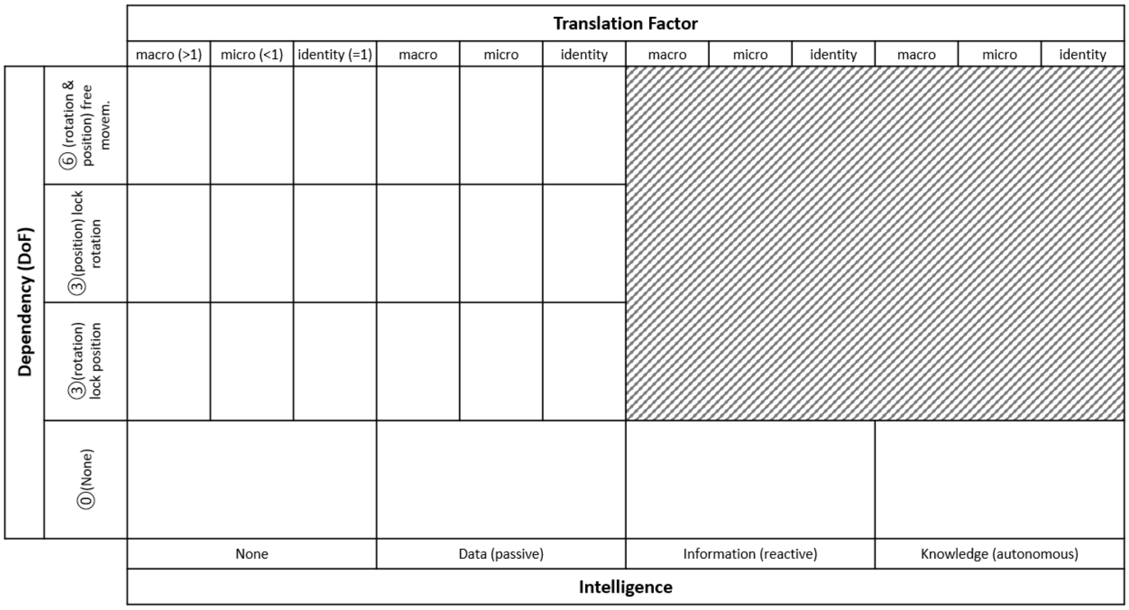

Fig. 1. Design space for multimanual interaction.

as underlying variables of a multimanual interaction system to then combine them to more complex metaphors. As dimensions we defined: "Dependency", "Intelligence", "Amount" "Translation Sign" and "Translation Factor" of hand copies.

3.1 Dependency

"Dependency" is a spatial component of the design space and describes the Degrees of Freedom (DoF) in which a hand copy is dependent of a user's main hand. There are four fundamental cases that can appear. 1. 0DoF: A hand copy is independent in every direction of the main hand. Moving the main hand in any way does not affect the copy in any way.

2. 3DoF (position): A hand copy is dependent in 3DoF in position (x, y, z) of the main hand. That means that a change of position in the main hand also causes some change of position in the hand copy.

3. 3DoF (rotation): A hand copy is dependent in 3DoF in rotation (tilt, yaw, pitch) of the main hand. That means that a change in rotation in the main hand also causes some change in rotation in the hand copy.

4. 6DoF: A hand copy is dependent in all 6 DoF of the main hand. Any change in the main hand's rotation or position also affects the hand copy in rotation or position.

3.2 Translation Factor

Translation Factor is tightly coupled to "Dependecy" as it describes how strong a movement in the corresponding dependency is transferred from the main hand to the copied hand. We define the translation factor tf to be either greater than one ($tf > 1$), equal to one ($tf = 1$) or smaller than one ($tf < 1$). We further call them macro control, identity control and micro control in the respective order. It further applies that $tf \in [0, \infty)$ where $tf \longrightarrow 0$ would result in movements of the main hand to be applied in a decreasing multiplicative manner down until no appliance at all ($tf = 0$) and $tf \rightarrow \infty$ in movements of the main hand being applied in a increasing multiplicative manner. A tf of 10 would result in a movement of 1 unit of the main hand causing a movement of 10 units in the copied hand. The type of movement then is defined via the "Dependency" Axis of the design space.

3.3 Translation Sign

Translation Sign ts is tightly coupled to the Translation Factor. ts is either -1 or 1 and decides whether a translation is applied positively or negatively. With the Translation Sign being negative, all movements of the main hand get applied negatively to the copied hand, thus resulting in a mirroring of the movements. A movement of the main hand in the top-left direction causes the copied hand to move towards the bottom-right if the Translation Sign is negative.

3.4 Amount

Amount is the measure for how many hand copies are active, as this could also have an effect on the way we interact in multimanual interaction system. To maintain a low complexity we only differentiate between "Single Hand" and "Many Hands. "Single Hand" is the state where only one hand copy is active while "Many Hands" describes the potentially unlimited amount of hand copies. This differentiation is interesting when looking at the concept of passive hands that are placed in space. Having only one such hand could be interpreted as having a third passive limb that can hold objects for the user. However having many of them could result in a whole own structure or model made of hands that not necessarily needs to be linked to a user.

3.5 Intelligence

"Intelligence" defines how intelligent a hand copy is. It also can be seen as how much and what type of information is contained on a hand copy. We based this dimension on the concept of the DIKW-Pyramid [16] that describes states of knowledge. For our design space we chose four information levels:

1. None: There is no information contained in a hand copy. Without influence from the outside (e.g., through spatial dependency), this type of hand will do nothing but exist.

2. Data: There is passive information "Data" contained in a hand copy. This data can e.g., be an array of positional and rotational data that describes the hand's position and rotation in space over time. In that case, a hand copy can move "on its own". It is however restricted to the passivity of the data on completely dependent on it.

3. Information: There is reactive information contained in a hand copy. Reactive data is dynamic and therefore able to react on events in an input/output manner. Reactive information for instance can be considered as a program that can dynamically find actions for the hand to perform. An example could be a sorting algorithm implemented on a hand copy. Such hand could sort objects according to their size in a virtual environment. It could dynamically adapt to different situations. It is however still restricted to the definition of its underlying program.

4. Knowledge: Knowledge describes the autonomous state of a hand copy. At this stage of intelligence a hand copy could completely act and decide on its own without any outer influence being required. It would not be dependent of any user input or user action but only on its environmental changes.

3.6 Limitations

As seen in Figure 6, some areas in the design space are greyed out. This is due to a conflict of principles when combining high intelligence with high dependency. When applying intelligence in form of a program or an autonomous intelligence to a hand instance, it is hard to say what should happen when there is also a strong dependency on the user's real hand. At this point there is some form of definition of precedence necessary to clarify whether the user's input or the hand's own intelligence has priority in defining an action. Another approach could be to fuse the inputs that came from the intelligence and the ones that came from the user so that the output is a merged result. In terms of programmed intelligence however this is error prone as a well defined state in the program can be manipulated through an unexpected input from the user at run time. We thus define legal and illegal areas in the design space.

4 IMPLEMENTATION

For our VR system, we chose a subset of interaction metaphors from our design space. Implementing the complete legal design space would result in an overwhelming amount of interaction possibilities that would be hard integrate in a meaningful manner. We instead decided to rely on a few interaction metaphors that, as we believe, form a solid set of fundamental interaction principles together and are easy to understand and combine. Namely we focus in our implementation on Static Structures (Steady Hands), Unconstrained Identity Control (Main Hands & Distance Hands), Unconstrained Macro Control (Cursor Hands) and Automated Processes (Recorded Hands) as they can be found in our design space.

We realized the concept of creating hand copies by simply instantiating Oculus' OVRHand Prefabs. For further functionality we added C# scripts to the respective hand copies that define their behavior. Targeting for Distance Hands is realized using a Raycast from the user's chest through the respective hand. Static Hands do not need further implementation while Recorded Hands store positional information for each of the 21 accessible finger bones for each frame. As grabbing objects using hand tracking is not yet standardized, we designed a custom input system that mainly relies on pinching information to detect whether the user is grabbing or not.

5 CONCEPT: HELPING HANDS

We present "Helping Hands", a multimanual interaction system in VR. We define multimanual interaction in VR as the possibility to interact in a virtual environment using not only two but a potentially unlimited amount of virtual hands. Helping hands allows to create various types of hand copies. Those are 1: Distance Hands, 2: Static Hands, 3: Recorded Hands.

5.1 Distance Hands

As their name suggests, distance hands allow users to interact with objects from a distance. To create distance hands, we chose an implicit type of interaction. When a user stretches their arm to reach an object in the far, our system automatically creates a hand copy in direct grab range of the object. The instantiated hand copy then behaves in the same way as the user's main hands do but with a spatial offset. In our design space this type of interaction would be "unconstrained identity control".

5.2 Static Hands

Static Hands are hand copies without any contained information or relation to the user's real hands. To create a static hand copy, the respective wrist button needs to be pressed. When instantiating static hand copies, the respective hands get cloned in place and immediately frozen so that they passively stay in mid-air. If the user's main hands hold objects during the clone process, the objects will then be held by the static hands. In that manner, arbitrary objects can easily be placed anywhere in space and picked up again at any time later. We designed our system in such a way that static

Fig. 2. Sample objects from the "Building Blocks" study that had to be recreated and set into rotation by the users using multimanual interaction.

hands can also be ’collected’ again. As soon as a user slips his main hand in a static copy as if it were a glove, the static hand disappears and objects get transferred back into the main hand. In that manner the concept of static hands is easy to handle and control. In our design space this type of interaction would be "static structures".

5.3 Recorded Hands

Recorded hands are similar to static hands but they contain positional information. When starting a recording, our system logs all movements of the corresponding hand. Ending the recording will lead the system to instantiate a hand copy that loops the recording back and forth. With that functionality, simple processes can be easily automated. For instance, recording a hand that plays a piano melody will result in the recorded hand to repeat it automatically for an arbitrary amount of time. In our design space this type of interaction would be "automated processes".

Having these types of interaction leads to a large set of combinatorial possibilities or interaction sequences. For instance let’s assume an engineer that wants to prototype a simple 3D object out of smaller lego-like subobjects. They could, without walking around, precisely collect small parts from a distance using "Distance Hands" and arbitrarily lock them in place with "Static Hands". The result could then be animated using "Recorded Hands" e.g., by recording a hand that slowly spins the object around its y-axis.

5.4 Material

As a platform we used the Oculus Quest 2 mainly because of its integrated inside out hand tracking that is easily accessible for developing custom Apps. For development we used the Unity Game Engine together with the Oculus Integration Package (based on Open VR) that provides everything needed to access hand tracking.

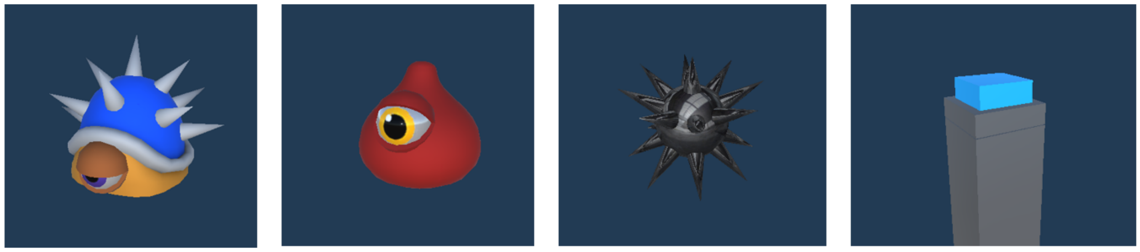

Fig. 3. Items and enemies from the "Game" part of the user study. From left to right: Shell-Enemy, Blob-Enemy, Spike, Buzzer.

6 EVALUATION

We conducted a user study to evaluate our system in terms of usability, versatility, cognitive demand and personal likes and dislikes. The main focus of our investigation lies on how well our system addresses the challenges – and how well it makes use of the benefits of multimanual interaction. The challenges are again: coordination, predictability, controllability, natural use for humans. And the benefits are: multi-tasking, efficiency, productivity, power. To investigate these concepts, we implemented interactive environments in which users could experiment with our system and give us feedback. To operationalize usability, versatility, cognitive demand and personal likes and dislikes, we chose questionnaires containing questions of six categories that were partially derived from the Player Experience Inventory [1]. Those categories were: Immersion, Cognitive Load, Productivity, Precision of Interaction, Enjoyment, Personal Likes & Dislikes. Answers were given on a 5-Point Likert Scale in the form of "Strongly Disagree", "Disagree", "Neutral", "Agree", "Strongly Agree". Besides of that we also took verbal user feedback during the experiment into account.

6.1 Study Design

We split the user study into two main parts to put a focus on different aspects of multimanual interaction. Further it helped us to understand how suitable our system is for cross-application use and therefore how well of a fundamental interaction concept it is. The first part consisted of a sandbox environment for experimentation while for the second part we provided a game in which the learned concepts could be put into action under time pressure and extensive use. As the second experiment required a deeper understanding of the available interaction concepts and had a much higher stress level for the player, we used within subject design without counterbalancing, so that each user first has the possibility to experiment in the sandbox environment before entering the game.

6.1.1 Experiment 1: Building Blocks. The first experiment was designed as a sandbox application that allowed users to first get used to the concept of multimanual interaction. It should mimic a practical use case scenario as it could be part of a productive sketching or construction app. We also designed it in such a way that the user learns about possible combinations of the different interactions. In the virtual environment simple objects (cubes and spheres) were placed all over the room. The task was then to use the available interaction metaphors to 1). as depicted in Figure 2, use simple objects to rebuild one of two demonstrated sample more complex objects, 2). put the created complex object into automated rotation and 3). build a custom complex object with animated parts.

6.1.2 Experiment 2: Game. The second experiment was designed for the user to extensively and repeatedly make use of the available interaction patterns, act under time pressure and find creative ways of using our system. In our game,

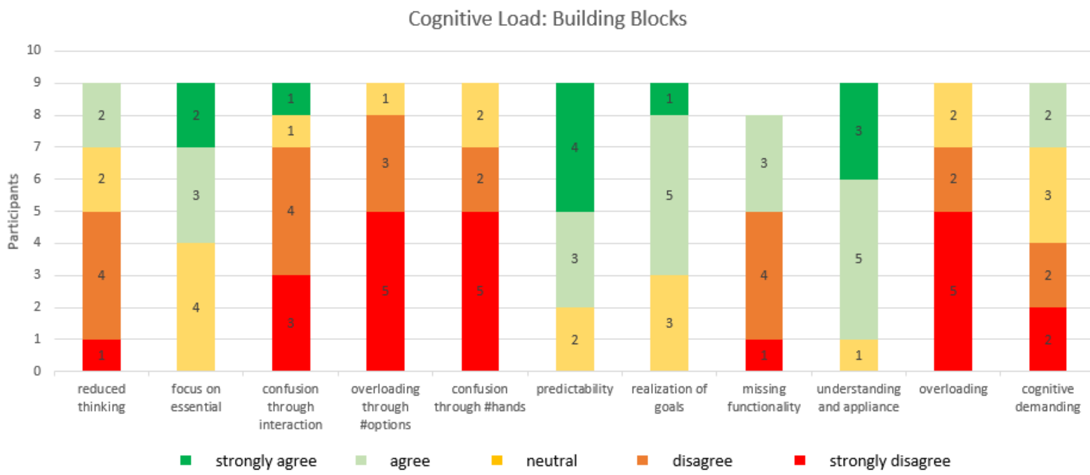

Fig. 4. Visualization of the likert answers on the "Cognitive Load" questionnaire in the "Building Blocks" part of our user study..

the main goal of the player was to defend themselves against incoming enemies. To make extensive use of each of our provided interactions, the game was split into four levels that each only allowed to use a specific interaction set. Level 1: Only Distance Hands, Level 2: Only Steady Hands, Level 3: Only Recorded Hands, Level 4: all hand types. Enemies (see Figure 3) were approaching the player from the front and took damage for any hit they got of any of the player's hands. After receiving three hits, the corresponding enemy was defeated. The player themselves could not lose the game or be defeated by the enemies. However, we used a score system that punished the player when enemies managed to get past them by decreasing the score. Every defeated enemy increased the score. For variation, we placed items (see Figure 3) in the game scene. The player had access to three "Spike" objects that would immediately knock out an enemy after touching them. There were also four "Buzzer" objects that could be pressed by the user to each time have a 10% chance to defeat a random enemy, which is especially interesting when considering recorded hands to automate the process of "buzzering". Over time, the spawn time of enemies decreased and the game thus got increasingly difficult.

6.1.3 Setup. We used the Oculus Quest 2 with active hand tracking and took care to fit the necessary lighting conditions. The study took place in a 10m² room with only the participant and the examiner being present. The VR content was streamed to a PC so that the examiner could watch the user's actions.

6.1.4 Procedure. The study started with a verbal introduction to the concept of multimanual interaction. Then participants had five minutes to make them self familiar with the interaction concepts in VR while being obliged to ask questions in case of uncertainty. After that hands-on introduction, experiment 1: Building Blocks was performed (10min) followed by our questionnaire (5min). Subsequently, experiment 2 was performed (20min) again followed up by our questionnaire. Finally, participants completed a demographic questionnaire. The whole procedure took 45 minutes and participants were rewarded with 7.50€ for their efforts.

6.1.5 Results. Here the results of our user study will be presented. Discussion will follow in the next chapter. To visualize the results of our Likert questionnaires, we used stacked plots encoded in color Figure 4. Green parts represent user agreement to the posed questions while red parts indicate disagreement.

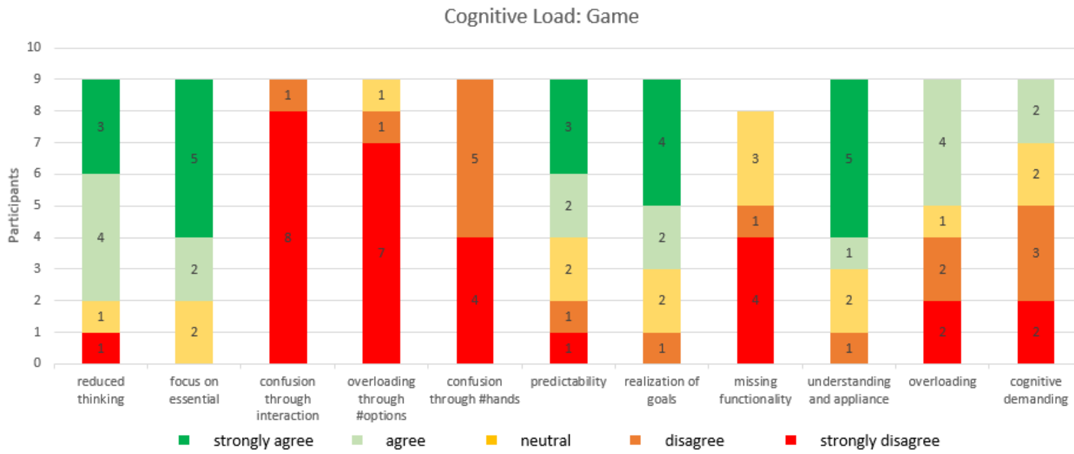

Fig. 5. Visualization of the likert answers on the "Cognitive Load" questionnaire in the "Game" part of our user study.

Participants. We ran our user study with $N = 2F, 7M$ participants. Ages ranged from 23 to 53 ($Mean = 27.1, SD = 9.2$). The majority (6) of the participants had used VR before but not regularly. Three participants had VR expertise. We had no participants that never used VR before.

Cognitive Load. Here we took a look into how cognitive demanding our system is when using it in both our experiments (see Figure 6).
Experiment 1 – Building Blocks: Taking a look at the plots Figure 4 shows that the statements "confusion through interaction" (CTI), "overloading through #options" (OTO), "confusion through #hands" (CTH) and "overloading" are predominantly disagreed upon by our participants ($M(CTI) = 2.1, M(OTO) = 1.55, M(CTH) = 1.66, M(overloading) = 1.66$). On the other hand the statements "focus on essential" (FOE), "predictability", "realization of goals" (ROG) and "understanding and appliance" (UAA) are mostly agreed on ($M(FOE) = 3.77, M(predictability) = 4.22, M(ROG) = 3.77, M(UAA) = 4.22$). "reduced thinking", "missing functionality" and "cognitive demanding" received balanced results.
Experiment 2 – Game: In Figure 5 there is a strong agreement on the statements "reduced thinking" (RT), "focus on essential" (FOE) and "realization of goals" (ROG) ($M(RT) = 3.88, M(FOE) = 4.33, M(ROG) = 4$)). "confusion through interaction" (CTI), "overloading through #options" (OTO) and "confusion through #hands" (CTH) still are disagreed upon ($M(CTI) = 1.11, M(OTO) = 1.33, M(CTH) = 1.55$). However, there is some agreement in "overloading" ($M(overloading) = 2.77$) in general.

Productivity, Precision, Enjoyment. Here we take a look at how productive users estimate themselves when using our system. We also look hat how precise they can interact and how enjoying the interaction is in general.
Experiment 1 – Building Blocks: In Figure 6 A there is general agreement on "improved performance" (IP) and "improved efficiency" (IE) ($M(IP) = 3.25, M(IE) = 4$). "multi-tasking capability" is balanced while there is a disagreement on "dominance" ($M(dominance) = 2.44$). Users further agree on precise interaction in close distance (PIC) ($M(PIC) = 4.11$) while interaction on far distance is rated mostly neutrally. The majority of users also thinks that multimanual interaction is reasonable to use as a fundamental concept of interaction in 3D virtual environments (MIR) ($M(MIE) = 4.44$). There is also a general agreement that multimanual interaction increases enjoyment of interaction (MIE) ($M(MIE) = 4$)).

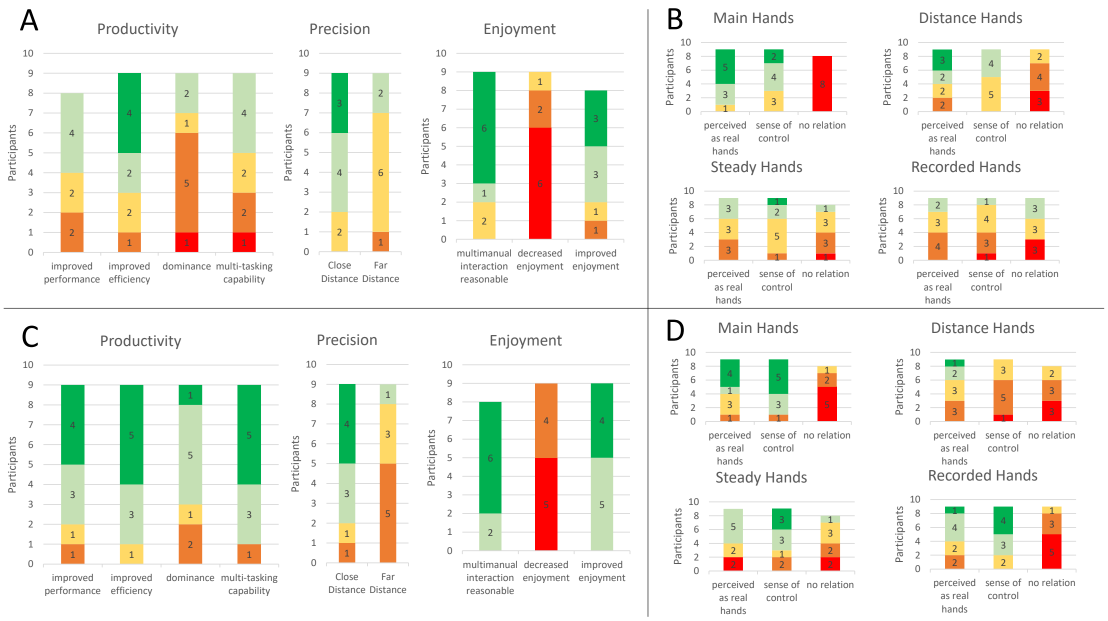

Fig. 6. Visualization of likert answers on the "enjoyment" questionnnaire.

Experiment 2 – Game: Figure 6 C shows that users strongly agreed upon all statements with respect to productivity using multimanual interaction ($M(IP) = 4.44$, $M(IE) = 4.44$, $M(dominance) = 3.55$, $M(MT) = 4.33$). Precision in distance (PD) however is generally disagreed upon ($M(PD) = 2.55$). Looking at the enjoyment plot clearly shows a strong agreement towards using multimanual interaction as a fundamental principle of interaction in 3D environments ($M(MIR) = 4.75$) and the improvement of enjoyment ($M(MIE) = 4.44$).

Immersion. Here we mainly look at how users can relate their different types of virtual hands to their own body using multimanual interaction.
Experiment 1 – Building Blocks: In Figure 6 C we can see that users agree upon the perception of their virtual main hands as their real hands ($M(PAR) = 4.44$). Correspondingly, there is also an agreement with respect to the sense of control of the main hands (SOCM) ($M(SOCM) = 3.88$). A similar but not as clear of a result can be seen for Distance Hands. Steady Hands and Recorded hands however are less perceived as real hands and there is also less agreement upon the sense of control. However, both statements are not completely disagreed upon.
Experiment 2 – Game: At the first glance, results in Figure 6 D look similar to the ones we saw just before. However there is an anomaly in the statement "sense of control" with respect to Distance Hands (SOCD) which shows a clear disagreement ($M(SOCD) = 2.22$). Also interesting is the observation that Steady Hands and Recorded Hands seem to be perceived more as the user's real hands and better controllable as in the first experiment.

Individual User Feedback. We asked our participants which aspects of our system they like and dislike. Specifically we asked what aspects were noticed negatively or positively. We also asked whether some functionality was missing to improve user experience and which functionality appeared unnecessary. Our received answers are quite similar throughout all participants and they can be clustered in categories. The categories were derived from the answers our participants gave and are a rough summary of the data. Categories are: Technical, Cognitive Load, Interaction and Multi-tasking. The majority of aspects that were noticed negatively were of technical nature. For instance, the hand tracking sometimes did not work as precise as expected. Also there were difficulties in interacting from a distance which mainly is caused by the implementation. And lastly, buttons were sometimes hard to access. The only critique with respect to the concept itself was that it sometimes can be hard to maintain an overview over all hand copies at the same time. Aspects that were noticed positively all are related to multimanual interaction and multi tasking. For example it was noted that hand copies are usable in a versatile manner and do not rely on a certain setup. It was also stated that the interactions are easy to understand and to apply. "Hand copies did a lot of work for me" was another statement for example. In the opinion of our participants there also was no functionality they desperately missed – however it was proposed that integrating some sort of gesture interaction could enrich the playing experience. Further, there was no functionality that was unnecessary according to our participants.

6.1.6 Discussion. Having a look at the cognitive load results indicates that our system does not overwhelm the users with complexity or functionality. It rather supports the users as they state that the system helps them to focus on the essential and that hand behavior is well predictable. It also speaks for the usability of the system that goals can be easily realized and the interaction concepts are easy to understand and apply. In general the results of experiment 1 and experiment 2 went similarly. Still, there are some interesting differences between both experiments that are worth to be mentioned. In experiment 2, the participants rated "reduced thinking" visibly better than in experiment 1. That could be caused by the fact that experiment 1 had a simple layout where no multitasking capability was demanded. In experiment 2 on the contrary, the users needed to focus on many things at the same time. Probably users especially profited of the hand's increased multi-tasking capability in experiment 2 and thus the results are better there. Looking at the Productivity, Precision and Enjoyment results shows us that users perceived to be more productive and efficient using multimanual interaction. The precision for distance interaction suffers a bit probably due to a not optimal implementation. The outlier "Far Distance" in Precision of experiment 2 is probably caused by the fact that users had to act under time pressure. Difficulties in aiming thus could not be corrected by re-aiming a couple of times as in the first experiment. Our system doubtlessly increases enjoyment of interaction which was, especially in experiment 2, clearly visible in the data. Here, again, we see better results in experiment 2, which might also be favoured by a learning effect. For the immersion part we can takeaway that the virtual main hands are seen as being perceived to directly belong to the player's body, which makes sense as they accurately track the users real hands. The slight decrease in immersion for Distance Hands is also logical. They still directly react to user input but they have a spatial offset which might break immersion depending on the distance. For Steady Hands and Recorded Hands the immersive feeling reduces even more, as the player can not directly control them anymore after they have been placed in space. It is however interesting to see that in experiment 2, immersion for Recorded Hands and Steady Hands is rated visibly better than in experiment 1. "Sense of control" in Distance hands for experiment 2 is again rated badly probably due to the not optimal implementation. These results show that our approach of multimanual interaction in VR is overall perceived as something positive that increases enjoyment of use, efficiency and productivity when in VR. Alternative interaction paradigms seem to have potential not only for specific applications but as a fundamental paradigms of interaction. The possibilities of existing and upcoming MR technology in terms of interaction in virtual environments is not exhausted – in the contrary, the possibilities of immersive interaction paradigms in VR still offer much to explore. We saw that our system mainly lacks in ideal implementation and interaction metaphors to provide the best experience but we still obtained great feedback and multimanual interaction convinced our participants to be a valuable approach. Further research on optimization of our system in terms of usability, versatility thus is full of potential. A further exploration of our presented design space also offers research material as we only implemented part of it. Especially adding intelligence, optimizing the UI and interaction metaphors as well as progress in the hand tracking technology would fundamentally enhance our system and contribute to the research. The quantitative measurement of our system in comparison to existing interaction paradigms was out of scope of this work and would be interesting to investigate as well to get an impression of the competitiveness of multimanual interaction.

7 LIMITATIONS

The scope of this work did not allow us to completely explore our design space and to fully embed it in an application. We rather focused on a few fundamental concepts of interaction such as distance interaction, multi-tasking and enjoyment of use. Further ideas like adding intelligence to our hands-implementation was therefore not intended as it adds complexity to the system. Our system was developed in an iterative manner and received many conceptual changes throughout the different phases of this work. The end-product is the outcome of the limited scope and repeated revision. Due to time limitations we also were not able to evaluate our system in terms of quantitative measurements and to quantitatively compare it to other interaction approaches in VR.

8 CONCLUSION

In this work we investigated the concept of multimanual interaction in VR – the concept of interacting with not only two but many digital hands. As mixed reality technology rapidly develops, the gap between digital and physical world starts to shrink. This makes the idea of improving digital abilities an interesting concept as they soon might be able to impact the real world. Leading questions with respect to multimanual interaction is how to make use of the benefits (productivity, sense of power, efficiency) and how to address the challenges (cognitive load, unnatural use, aversion). To investigate the concept interaction, we implemented a VR prototype that relies on multimanual interaction. In a user study we evaluated our system with respect of the challenges and benefits. We found that our system was well accepted in terms of usability and UX while not being too cognitive demanding. We state that the exploration of alternative interaction paradigms in VR is full of potential and that the possibilities of MR technology in terms of interaction are not exhausted. Future work could be in developing and improving our design space, improve the implementation and interaction metaphors as well as adding further elements of the design space to a multimanual interaction application.

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