Enabling Low-cost Co-located Virtual Reality Experiences

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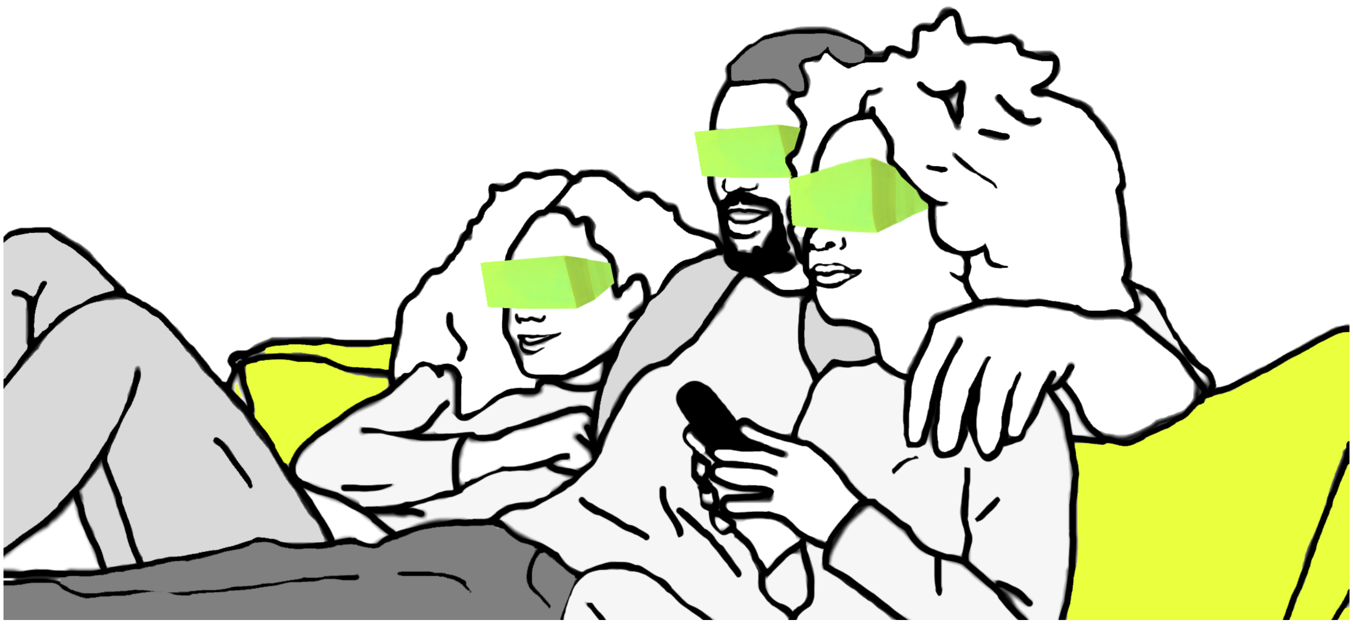

Figure 1: Concept illustration of a family watching a movie together in VR.

ABSTRACT

In this thesis, we imagine virtual reality (VR) experiences in busy public spaces with co-located users through exploring pass-through camera interaction techniques and head mounted display (HMD) design concepts. Through our designs, we propose that allowing easier and faster visual access to real world information and views will foster an enhanced feeling of togetherness among participants and create less-awkward co-located VR experiences. This thesis shares a selection of designs and prototypes aimed at solving some of the common challenges VR users in co-located and collaborative scenarios face. Our concepts are informed by a literature review of social and collaborative VR research and three motivational scenarios with prototypes. Our contribution with this work is to provide inspiration and discourse around common challenges with wearing HMD in public spaces with strangers, at home with family, or in a busy office with co-workers.

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CCS CONCEPTS

• **Human-centered computing** → **User studies**; **Virtual reality**; **Collaborative interaction**.

KEYWORDS

virtual reality, co-located, social, low-cost, head-mounted display, body representation

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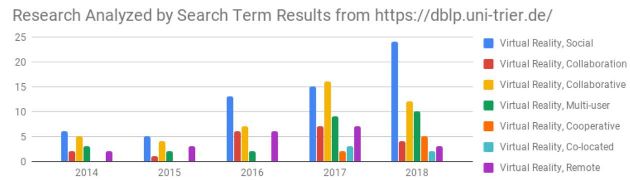
1 INTRODUCTION

Since the conception of virtual reality (VR), much research has been done to replicate life in VR through understanding how people feel presence and experience. Much of this work is from the perspective of single VR users and remote VR participants. Social VR experiences with co-located participants will be an increasingly important area of interest as commercial VR devices become more common in homes with families and in the workplace. As it stands, real-life interactions with a co-located person in VR are awkward and VR collaborations with co-located people lack the richness and flexibility familiar from real-world interactions.

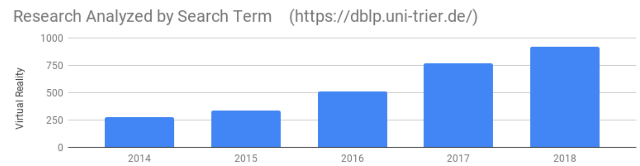
Our motivation is to design hardware and interactions that allow participants' easy visual access to their environment and co-located team members, friends, or family. We conceive that designs which allow users' easy access to reality, may ease the burden of interruptions during VR work and also encourage feelings of togetherness with others in their immediate vicinity. This could, in the future, make wearing VR in public more feasible and practical. We are exploring this concept in three ways: 1) By providing avatar representation recommendations for co-located collaborations. 2) By creating visualizations that replicate co-located participants' and non-VR collaborators body position and movements in the virtual scene based on low-cost, smartphone-based pose recognition. 3) Through a design exploration of HMD concept designs that provide easy visual access to the physical world.

In this thesis, we begin with background on social virtual reality experiences. We then describe a literature review where we have evaluated the research along common themes among social virtual reality. Based on these collected themes, we have created concept designs that address common issues in co-located virtual reality experiences. We motivate these concept designs through the creation and evaluation of three prototype applications within three scenarios. With each scenario, we connect the opportunities for better co-located VR interaction with design concepts that address ideal mobile avatar representation, visualizing co-located VR users and nonusers through low-cost body tracking, and HMD hardware modifications for public VR use. We conclude this thesis with a discussion and conclusion describing the limitations of this work and recommendations for future study.

Our contribution with this design exploration is to inspire virtual reality designers and researchers to consider supporting co-located social interactions with better visualizations of the real environment and co-located people in their experiences.



(a) Analysis of virtual reality research papers with key search terms in the paper title: social, collaborative, collaboration, multi-user, cooperative, co-located, remote



(b) Analysis of research papers with 'virtual reality' in the paper title.

Figure 2: Analysis of research paper search results from the DBLP database.

2 BACKGROUND

Interest in virtual reality and social collaborative activities in virtual reality has steadily increased over the last 5 years, as seen in Figure 2. We define collaborative VR as a social virtual reality experience where participants work together to achieve a desired result. Social collaboration in virtual reality environments, or collaborative virtual environments (CVE) have been a common topic in VR research for many years, with a history of addressing the design challenges of 3D spaces in an attempt to support natural social interactions [2, 3, 5, 6, 10, 30, 47, 53]. Current research in social VR collaboration continues to explore scenarios related to dispersed [40, 41, 44, 54, 61] and co-located [31, 33, 34, 49] teams as these situations provide an interesting challenge for many disciplines, from the technical implementation to the emotional impact of social dynamics in the virtual space. These scenarios are generally concerned with the VR user's experience of presence and immersion [14], but increasingly, research is focusing on other nuanced social aspects of the virtual experience like the effect of avatar realism [8, 15, 24, 41, 48, 51, 60], the psychological impact of embodiment [1, 13, 16, 52, 59], and the effects of mixed immersion activities on collaborative tasks [9, 21, 26, 56].

As consumer interest in virtual reality collaboration tools increases, we can imagine that common issues with virtual reality interface design for collaboration like text input, file access, and task management will need to be better supported. Additionally, logistical considerations for long-term, in-office VR head-mounted display (HMD) wear will also need design standards for common issues like collision avoidance [43, 50], notification management [17], interactions with co-located colleagues [35] and motion sickness[36].

With our design concepts, we aim to address a few of these logistical concerns by building on and bridging gaps between existing research ideas.

3 SOCIAL VR LANDSCAPE

Social virtual reality research is an increasingly popular topic in the field of HCI as it becomes more common for virtual reality technology to support multi-user experiences (see Figure 3(a)). To inform our design concepts, we conducted a review of 46 papers from the *Human-centered computing* domain. In this review, we provide an overview of themes common among the literature, a collection of measurement metrics and techniques for social VR applications, and a distillation of opportunities to resolve common issues facing social virtual reality experiences.

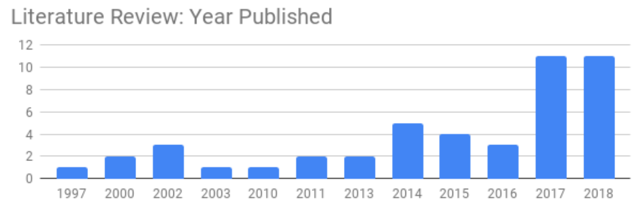
Methodology

Collection. Our team collected and evaluated 71 papers through a systematic search of the DBLP computer science bibliography website (October 2018). Our search terms included 'co-located virtual reality', 'social virtual reality', 'collaborative virtual reality', and 'interaction design virtual reality'. In addition to this approach, our team included relevant papers found in the reference section of these works.

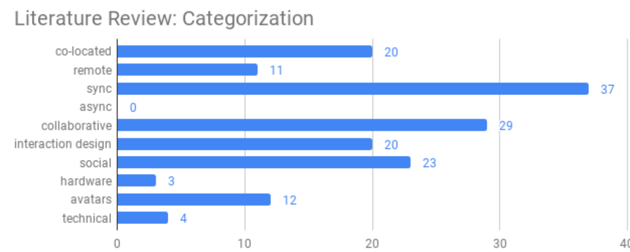
Filtering and Inclusion. To ensure we selected appropriate papers, we defined filter and inclusion criteria to include papers with interactions in a social setting with one or more user in augmented or virtual reality. We also limited papers to those published at conferences and journals in the last 25 years. After filters and inclusion criteria were applied, we had a total of 46 papers for analysis.

Categorization. We used a top-down approach for the initial tagging of paper categories by identifying whether a paper involved co-located participants, remote participants, or both and involved synchronous or asynchronous activities. The secondary top-down categorization method we applied involved tagging with an overall theme related to the paper's contribution. Theme categories we applied include: avatar, collaborative, co-located, hardware, interaction design, motion tracking, social, and technical. Categorization was done by all team members individually and collectively (see Figure 3(b)).

Analysis. Analysis of collection was done in two ways: (1) a time/space matrix evaluating remote/co-located and synchronous/asynchronous applications and (2) themes of key topics to show patterns of interest and issue. Through this analysis, we identified four themes within the literature: (1) the representation of an avatar impacts collaboration, (2)



(a) Of the 46 analyzed papers, 22 were published in the last two years.



(b) Papers were categorized by 10 different key terms, and multiple terms could be applied to each paper.

Figure 3: Charts depicting literature review analysis of 46 papers related to collaborative virtual reality research.

there is a growing interest in supporting collaboration between immersed and non-immersed users, (3) the design of collaboration systems are focused only on synchronous activities within the VR environment, and (4) the lack of awareness of reality in VR HMD designs is a usability issue.

Theme 1: Avatar representation impacts the success of collaborative activities

From a review of consumer applications, we evaluated avatar representation on a scale from least to most user agency and realism (see Figure 4). As shown in this chart, avatar designs range from very minimal primitive shapes to complex models with motion tracked gestures and expressions. The high percentage of papers in our review interested in understanding social implications of avatar representation and the effects of this representation on the user's perception of embodiment suggest that avatar appearance is an important factor in collaborative activities. Several of the papers reviewed explicitly state that realism enhances the quality of the communication and feelings of embodiment within the VR environment [15, 41, 48, 60].

There is also an interest in the literature to understand the psychological impact of avatar representation on communication and collaboration within and outside of the virtual environment [1, 13, 16, 52, 59]. Though this is not surprising, there is little research available that specifically addresses

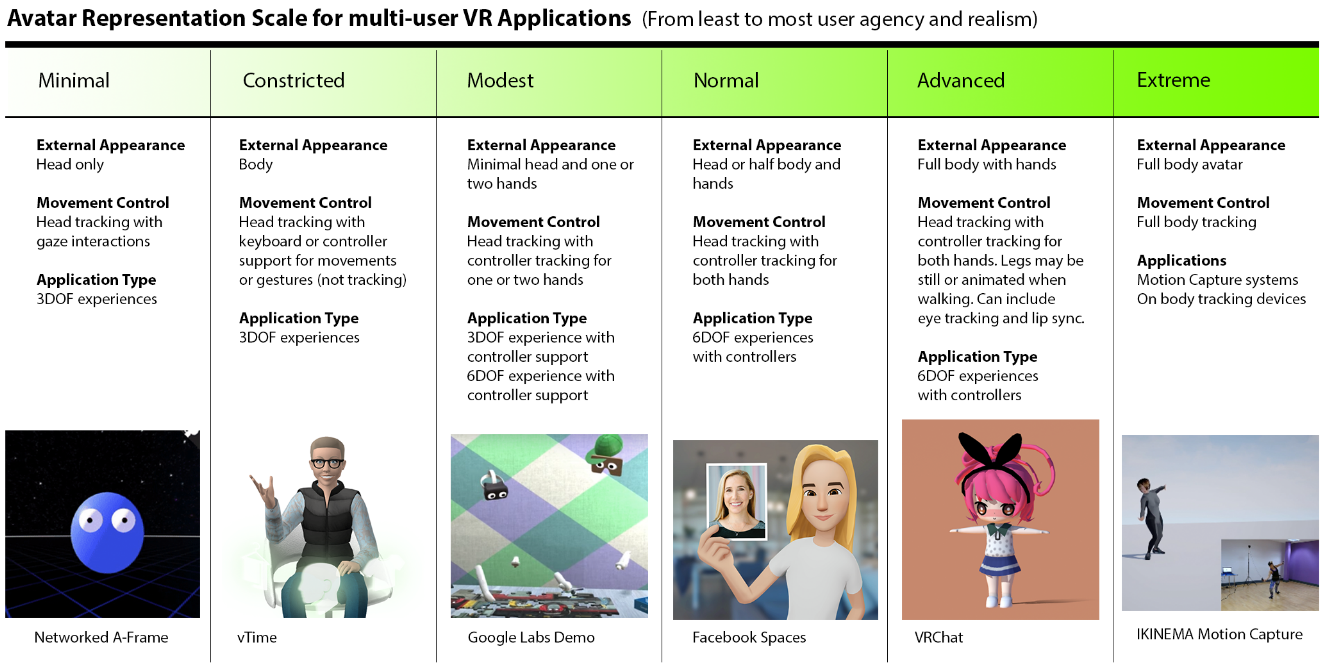


Figure 4: This chart shows the range of avatar representation types as found in commercial social VR applications. The style of avatar ranges from minimal primitive shapes to a fully motion tracked body with gestures and a realistic appearance.

ideal avatar requirements for co-located collaborative activities. While realism seems like a viable solution, additional high-fidelity requirements may not be necessary in this context. In Seele et al.[51], results from a study to test three eye models with increasing levels of fidelity, from a base model with programmed saccadic movements to a live user's actual tracked eye movements, suggests that in co-located environments, participants don't need a high-fidelity eye model on an avatar to experience a high level of communication in the social VR tasks. Given this information, it could be possible that other aspects of the avatar's appearance need not be the highest fidelity in co-located collaboration tasks in order to produce a high level of communication and presence. We believe it would be interesting to define what type of appearance should an avatar have for co-located collaborative experiences and in what contexts these designs are successful.

Theme 2: Desire to support collaboration between immersed and non-immersed users

While several of our reviewed papers discuss design considerations to support mixed-immersion VR experiences [9, 21, 22, 26, 56], few papers mention visual representation recommendations for non-immersed co-located collaborators and non-collaborators in the virtual scene. In one paper that does, McGill et al.[37] proposes a VR interface design that allows vr users control over and access to visualizations of co-located people and objects in the immediate vicinity from inside the virtual space. We believe there is an opportunity to explore these types of visualization techniques, but in the context of collaborations between immersed and non-immersed users.

Theme 3: Design of collaboration systems are focused only on synchronous activities within the VR environment

As seen in the categorization chart in Figure 3, literature related to collaborative virtual reality from the last two years suggests that research interests have remained predominantly in design for synchronous activity for both co-located and remote users. From the literature, common tasks for work settings included design or product review and discussion-style activities. For implementation in a work environment, design considerations around asynchronous work could provide a solution to some task management issues, like leaving video messages or task hand-off instructions.

Theme 4: Lack of accessible reality in VR HMD designs is a usability issue

Several papers in this literature review mention limitations and usability problems with VR HMD [19–23, 28, 35, 42, 46]. In their assessment of current HMD designs, many of these papers mention a disconnect between immersed users, non-immersed users, and the real world. In a few of the papers, the solution proposed is to provide a way for the non-immersed user to view or experience what the immersed user is seeing [19, 21, 46]. On the other hand, there are usability concerns overall due to the VR user's limited view of the real world that include collisions [50], poor input methods, handling objects [35], and social interactions.

We believe it is important for successful co-located VR collaborations to have visual access to reality within the VR experience and to be able to leave the VR experience quickly with minimal perceived burden.

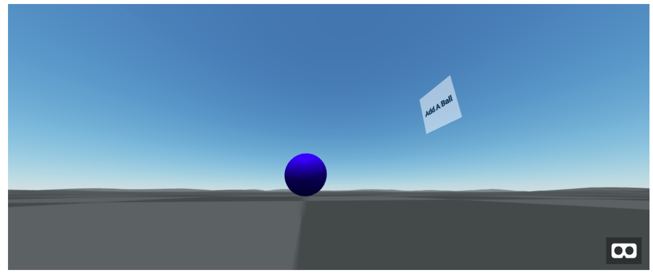
Measurements and Metrics

As a part of this literature review, we evaluated the studies shown in each paper to better understand how they have measured success of collaborative and social VR activities. Overall, we found that the main qualities being measured are presence [57, 58], embodiment [11, 18, 29, 45, 55], immersion [7, 32], and interaction [12, 27]. Social measurements like togetherness are not as common for evaluation in this domain, but the larger category of social quality [4] is addressed in evaluating social VR experiences.

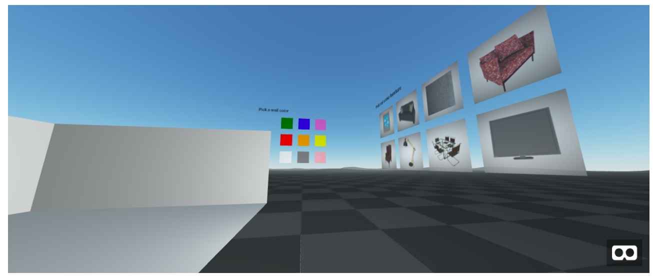
These evaluation criteria seem to be mainly focused on immersed participants with few questions about the co-located environment. We believe that evaluation of mixed-immersion and co-located experiences needs to account for the entire user experience, and therefore will need to adjust evaluation techniques accordingly.

Scope of Review

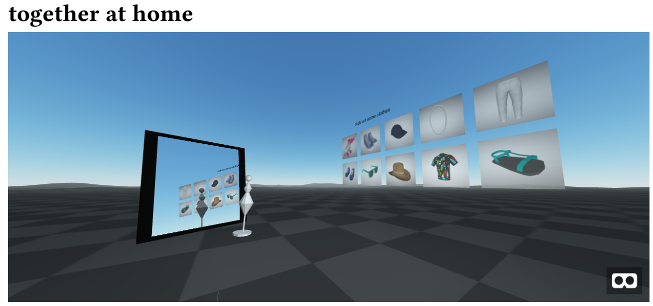
The goal of our analysis is to tease out trends in current social virtual reality research in order to identify areas of opportunity for our concept design focus. In our selection of literature, we prioritized papers from familiar conferences and with relevant titles. We realize that our review selection may not contain every work related to social virtual reality, but we believe we have selected the correct literature for our purposes.



(a) Motivational scenario 1: Playing toss the ball game on the subway



(b) Motivational scenario 2: A family decorate a virtual room together at home



(c) Motivational scenario 3: Pick out an outfit with a client in an office environment

Figure 5: Motivational scenarios and prototypes used to develop design concepts for co-located VR collaborations.

4 CONCEPT DESIGNS AND RECOMMENDATIONS

From evaluating the themes distilled from our literature review, we extrapolated the following design opportunities, or gaps, that relate to co-located VR collaborations: (1) avatar representation impacts collaborations, possibly in different ways for co-located collaborators (2) need better support for collaborations between immersed and non-immersed users, (3) need reality awareness solutions with minimal burden for co-located collaborators.

Our method for constructing our concept designs and recommendations began with the identified opportunities from our literature review. We then created three VR prototypes to evaluate multi-user co-located collaborative activities within three scenarios. Through these prototypes and scenarios, we developed a stronger sense of the interaction design challenges in co-located applications within the contexts of public, social, and collaborative co-located VR use.

In our concept designs, we propose (1) recommendations for effective avatar representation in co-located collaborative tasks, (2) techniques for representing immersed and non-immersed users and nonusers for public and mobile contexts, and (3) HMD design modifications to support access to reality in public and mobile contexts.

Motivational Scenarios and prototypes

To dive deeper into the motivations of co-located people in the context of VR collaborations, we explored three scenarios and developed three corresponding prototypes to better understand the challenges of co-located collaboration, see Figure 5. These scenarios and activities are: (1) Playing toss the ball game on the subway, (2) A family decorate a virtual room together at home, (3) Pick out an outfit with a client in an office environment.

By going through this exercise, we were able to think through specific usability and interaction challenges within each environment, like safety in public, perception of togetherness, and visualizing co-located nonusers. We then use these challenges to contextualize and define criteria for our design solutions.

Playing toss the ball game on the subway. For our first scenario, we imagine a single person passing time in a VR environment surrounded by co-located non-immersed bystanders. In this situation, we imagine that safety and collisions are a top concern for not only the VR user but for those in the immediate vicinity. To address this top concern, we believe that a pass-through display or quick access to a reality view is one potential solution (Design Concept 1). Another way to address this situation is to uncover one of the user's eyes (Design Concept 3 and 4). We hypothesize that reducing immersion in a busy public situation like this one, will help the user enjoy VR content while also feeling safe.

A family decorate a virtual room together at home. In this second scenario, we imagine a family with children decorating a room together in VR. Some considerations that we address with this situation are the desire to maintain presence and immersion in the activity while also maintaining a connection to the real world to ensure that food, drinks, and children are where they are supposed to be. As proposed in McGill et al. [35], a contextual blended view of the real world and virtual world might help the parents maintain order and safety (Design Concept 1).

Additionally, avatar appearance could be something to consider in this scenario, as this experience might benefit from encouraging feelings of family togetherness and bonding (avatar design recommendations). As suggested in the literature [15, 51, 52, 60] a realistic avatar with natural movements might encourage this sense of social presence and emotional connection.

Pick out an outfit with a client in an office environment. In our third scenario, we consider VR collaboration between co-located VR users in an office environment. For this situation, we imagine that collaborators are situated in an open and busy work space where foot traffic and interruptions are possible. The main issues we believe that this scenario brings up are maintaining sustainable and effective communication between collaborators as well as management of in-person interruptions by non-VR bystanders. To handle these issues, we believe there are two design opportunities: (1) appropriate avatar representation to support effective and equal communication (avatar design recommendations) and (2) visualization techniques for representing the co-located nonusers that may need the VR user's attention (design concept 1).

Recommendations for effective avatar representation in co-located collaborative tasks

Figure 6: Avatar recommendation examples. Left: Minimal Head and hands avatar from Mozilla A Saturday Night Demo. Right: Realistic Full body avatar from Adobe Mixamo.

Inspired by our findings from theme 1 in our literature review and motivational scenarios, we propose design considerations for avatar representation in specific co-located collaborative tasks. We propose that avatar design should vary by context and activity. As found in theme 1, generally avatar realism is seen as enhancing the quality of communication between people in VR, but as shown by Seele et al [51], co-located users already perceive a high degree of social presence and found that realistic eye appearance above the baseline conditions didn't increase quality of the co-located experience. Based on this information, we propose the following recommendations for co-located experiences.

Minimal Avatar (Humanoid head and hands). We suspect that minimal avatars will perform effectively in co-located activities around design review and discussion, as co-located participants may feel a higher level of social quality in collaborative experiences that are performed in the same physical space, see Figure 6 (left).

Realistic Avatar (Humanoid full body). We propose that more realistic avatars will produce more effective results for physical activities as tracked body movements may produce a more natural sense of coordination and reduce potential collision between the participants. We also believe this style of avatar will be more effective in tasks involving negotiation, as the psychological effects of embodiment may play into negotiation skills and the confidence levels of participants, see Figure 6 (right).

Fantastic/scary Avatar (non-humanoid). While obvious, we believe that certain situations are inappropriate for the use of fantastic or non-humanoid avatars. During collaborative tasks, the appearance may be distracting or intimidating. At a basic level, we assume that for non-humanoid avatars to function effectively in a collaborative setting, the characters should match in size, style, and capabilities as to foster a sense of equality among collaborators.

Techniques for representing immersed and non-immersed users and nonusers for public and mobile contexts

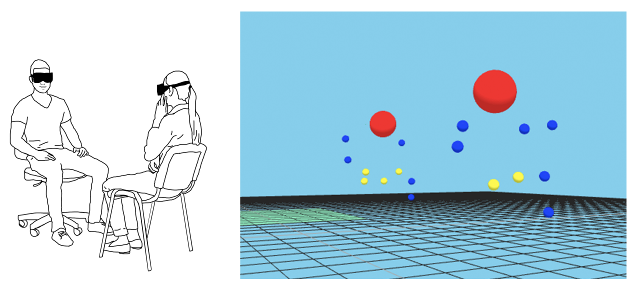


Figure 7: Two seated co-located users and their detected body points. Scene created through utilizing a mobile device camera-based body tracking technique using using tensorflow's posenet model for in browser pose detection with web-based VR framework.

Inspired by Theme 2 from our literature review, we have seen an interest in providing support for collaboration between immersed and non-immersed users, and through our motivational scenarios we have identified a two ways to support these users. The first is through full body camera-based motion tracking and the second is through camera-based face tracking for co-located users while wearing a HMD.

This motivation comes from work by McGill et al.[35] and Gugenheimer et al. [21, 22]. This research is concerned with the understanding that immersed VR users need to see things and people to prevent collisions and support communication with others while in VR. While these papers do provide design recommendations for managing immersed and non-immersed co-located users, we believe they do not address the need for visualizations to support collaboration between these users.

Through inside-out tracking in portable devices like mobile phones or wireless VR, we enable more effective interactions and higher usability with co-located teams. This approach also provides VR support in non-instrumented environments and public spaces. Camera-based body tracking could also provide other benefits for collaboration, like tracking lower limbs for full-body interactions.

Design Concept 1: Full body camera-based motion tracking for immersed and non-immersed collaborators. We have created initial prototypes using A-Frame and a tensorflow-based, open-source JavaScript library leveraging camera feeds to provide low-fidelity body tracking without environment instrumentation, see Figure 7 and 9. We intentionally target low-cost technologies and web-based multi-user applications in order to capitalize on the flexibility of mobile VR technology. By building on future web technologies, we also want to maximize user access to co-located VR experiences.

Figure 8: Use camera-based face tracking while in VR through taping a photo of a half face onto a VR headset.

Design Concept 2: Face Tracking for co-located VR collaborators. Using this same camera-based tracking concept, we created a prototype that tracks facial gestures using an external camera to analyze the VR user's face, see Figure 8. Generally, facial tracking is only available if the entire face is visible. Through this very simple method of taping a half face image on a HMD, two co-located collaborators can utilize facial tracking technology to animate avatar faces in VR when an instrumented environment or voice-based facial animation technology is not available.

Implementation. Currently, marker less motion capture systems are not portable and require a lot of environment instrumentation with multiple cameras and motion capture equipment. Portable camera systems capable of accurately tracking body movements are limited to certain body parts, like hands (Leap Motion), and are expensive (hololens). Better use of camera technology in a VR context is of interest in the research community [25, 38, 39], but there has yet to

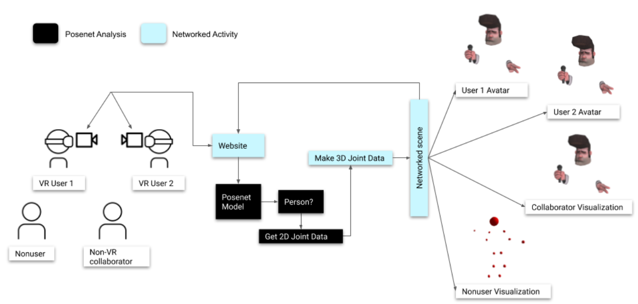
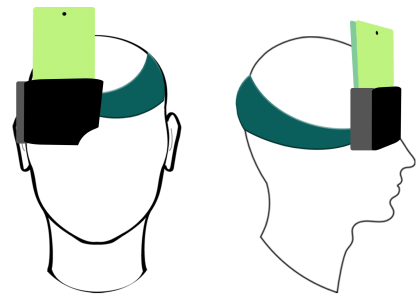
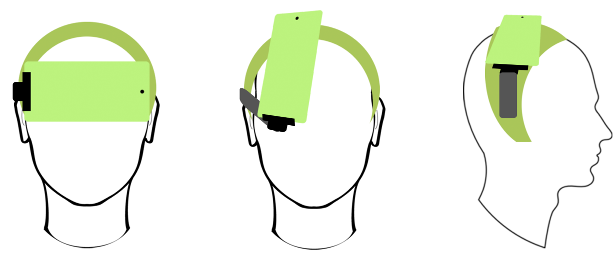


Figure 9: Chart shows the flow of information in a multi-user co-located VR experience using Posenet to detect VR user, non-VR collaborator and nonuser body positions.



(a) Pirate HMD Concept Design



(b) Slide HMD Concept Design

Figure 10: HMD hardware design modifications based on adaptations to allow VR users quicker and easier access to real world views and headset removal.

be a great solution for mobile and low-cost VR consumer experiences.

Machine trained models from projects like TensorFlow's Posenet and Open Pose provide a body tracking solution for mobile VR experiences through analyzing the phone camera's video feed against a trained model to detect human body poses, see Figure 9. The out-of-the-box models require more development in order to be fast enough for a sufficient VR framerate (60FPS+), but we believe this process could provide a good start for mobile low-cost VR body tracking.

HMD design modifications to support reality awareness in public and mobile contexts

Informed by our design explorations and Theme 4 from the literature review, our analysis has shown that many of the usability problems head-worn displays have is due to not adequately supporting awareness of people, objects, and obstacles in the real world. In addition, the headsets are not easy to remove quickly, and repeated removal for conversations with co-located users can be disruptive and uncomfortable.

Motivated again by work from McGill et al.[35] and Gugenheimer et al. [21, 22], our design solutions focus on ways to provide easy access to real-world views quickly and with minimal disruption for co-located collaborators. While the above research does address reality awareness directly through visualizations and hardware modifications, we believe our design approaches speak directly to the needs of collaboration between co-located users and VR use in public.

To explore HMD modification options in low-cost VR, we modified Google Cardboard headsets. Our designs include ideas for a one-eyed VR experience and a sliding visor. We propose that our designs will be ideal for longer term in headset collaborations as well as HMD wear in a busy social setting.

Design Concept 3: Pirate HMD. To address the usability issues related to difficulty quickly removing VR HMD, we conceive of an HMD that doesn't need to be removed. As seen in Figure 10 (a), the pirate HMD concept does not need to be removed to see the real world, as the virtual display only covers one eye. This design prototype was constructed out of a cardboard HMD and modified to hold a phone in the portrait direction. With this approach, the screen can provide a VR or pass-through display for the user.

While this design brings up other usability problems, we feel that this exploratory approach might serve as a starting point for designs that break a stereotypical view of HMD hardware.

Design Concept 4: Slide HMD. Building off of our pirate concept design, we developed a sliding HMD that incorporates an easy removal technique by sliding the phone up all the way or to the half immersion position. This design also utilizes VR through a mobile phone, which supports portable VR use as well as pass-through camera visualizations. As shown in Figure 10 (b), the phone is attached to a built in case harness, which is fitted to a heavy-duty headband on an arm above the right ear. The arm pivots at 3 joints in order to lift up and around the head.

VR Hardware with Camera Pass-Through Capability for multi-user VR Applications
(From least to most portable + removeable)

Playstation VR Vive Oculus Rift Windows VR	Cardboard	Samsung Gear VR	SlideVR (Design Concept)	PirateVR (Design Concept)
Instrumentation - headset & controllers - computer **Limitations** - not portable - difficult to take off	**Instrumentation** - Headset + phone - Cut a hole in the cardboard **Limitations** - Difficult to keep on head - 3DOF - restricted interactions	**Instrumentation** - Headset, phone and controller **Limitations** - 3DOF	**Instrumentation** - Headset + phone **Limitations** - 3DOF - restricted interactions	**Instrumentation** - Headset + phone **Limitations** - 3DOF - restricted interactions

Figure 11: VR Hardware spectrum graph

From a survey of current commercially available HMD designs, we have found that pass-through VR technology is becoming more common in many stationary headsets. In this chart, Figure 11, we have evaluated many commercially available headsets by their capability to be portable as well as by their ability to provide a real world view. While many headsets are starting to provide access to pass-through VR, they have yet to address issues with difficult headset removal. We believe that our designs provide a unique approach to the issue of reality awareness and potentially open up the conversation to finding better solutions to these HMD usability problems.

5 DISCUSSION

Our approach to this work comes from an exploratory curiosity around using virtual reality in public spaces with others. Through understanding current research on collaboration and co-location, we have developed a sense of what methods are being discussed and explored. Through our analysis, discovery, and design, we address some of these challenges as they specifically relate to co-located VR interactions.

The work of Bailenson et al.[59], Garau et al.[15],Smith et al.[52],George et al.[16], and Heidicker [24] have shown that representation of the body in VR can influence negotiations, impact real world self-esteem, and promote trust. Research has yet to provide guidance for avatar appearance related to co-located collaboration, so we provide a set of recommendations extrapolated from the collected literature about ideal avatar appearance for collaborative tasks with co-located partners. Through this activity, we have discovered that design considerations are contextual and depend on the task and goals of the collaboration. Through our recommendations, designers creating spaces for co-located collaborations can build spaces with the knowledge that avatar selection impacts collaboration success.

As proposed in McGill et al.[35], reality awareness is a known usability issue with VR HMD and with using virtual reality in busy social settings. While this research does not explicitly evaluate collaboration, we believe that providing better awareness of reality will also provide a better quality of communication between immersed and non-immersed collaboration members. We found from the literature that providing both visualizations of co-located people as well as HMD modifications provided two approaches to similar problems. Both solutions involve providing awareness of others to the VR user. We believe that using both tactics will help make using VR in public less awkward.

Our approach to this research began as an exploration of social VR interaction techniques and usability issues. After a systematic review of social, co-located, and collaborative VR literature, we were able to direct our exploratory designs specifically to address commonly mentioned VR usability issues and social themes. Through this method, we touched on a wide range of issues initially before diving into a select few designs to create prototypes. We believe this approach allowed us to think creatively while also gain domain knowledge to inform our design solutions.

Overall, we feel that our designs are meant to inspire conversation in this design space. Many of our concepts are preliminary and would benefit from being evaluated in a future study. We feel that our contribution is the collection and analysis of research within the social VR landscape and our subsequent design exploration to solve issues and bridge gaps in this space. We believe that our work should be seen as a starting point for discourse around the challenges and possible innovation in the co-located VR collaboration domain.

In future work, we recommend the following four actions: (1) a follow up study evaluating our proposed avatar recommendations and HMD design modifications, (2) evaluate and design for Theme 3 from the literature review, where we identify that the design of collaboration systems are focused only on synchronous activities within the VR environment, (3) expand on evaluation techniques for mixed-immersion and asymmetrical VR environments to include questions on social quality in co-location.

6 CONCLUSION

As VR becomes a more widely used technology for recreation, education, and collaboration, we believe that it will be increasingly important to address the current limitations of VR technologies in co-located collaborative environments. From our research of literature and evaluation through design exploration, we have identified the following challenges with co-located VR use: (1) avatar representation impacts the success of collaborative activities, (2) immersed and non-immersed co-located collaborators need support, (3) lack of accessible reality in VR HMD designs is a usability issue. To address the challenges, we have proposed the following (1) provided design recommendations for avatar designs based on literature and motivational scenarios, (2) suggested techniques for representing immersed and non-immersed users and nonusers body positions in virtual space, and (3) created design concepts for HMD design modifications that support reality awareness in public and mobile contexts. We believe that with these changes, VR use in co-located collaborative environments will feel less awkward and produce a better user experience for both immersed and non-immersed users.

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