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Advanced Methods for User Evaluation in AR/VR Studies

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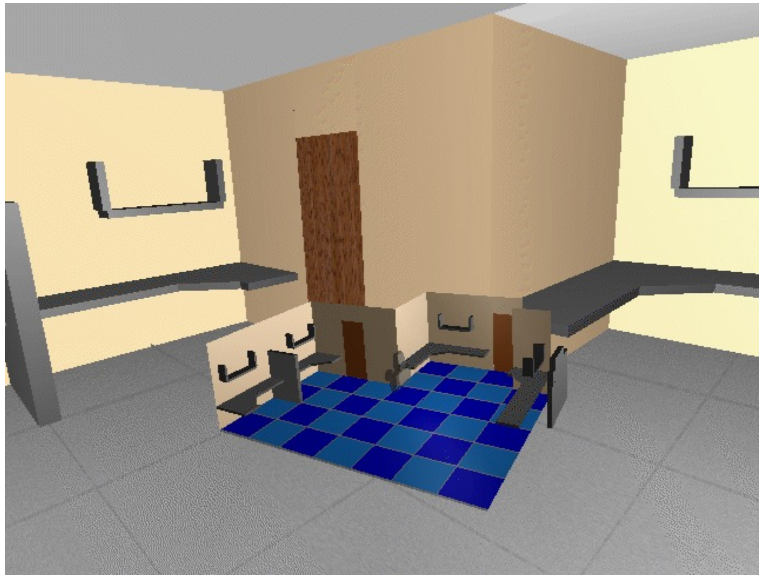
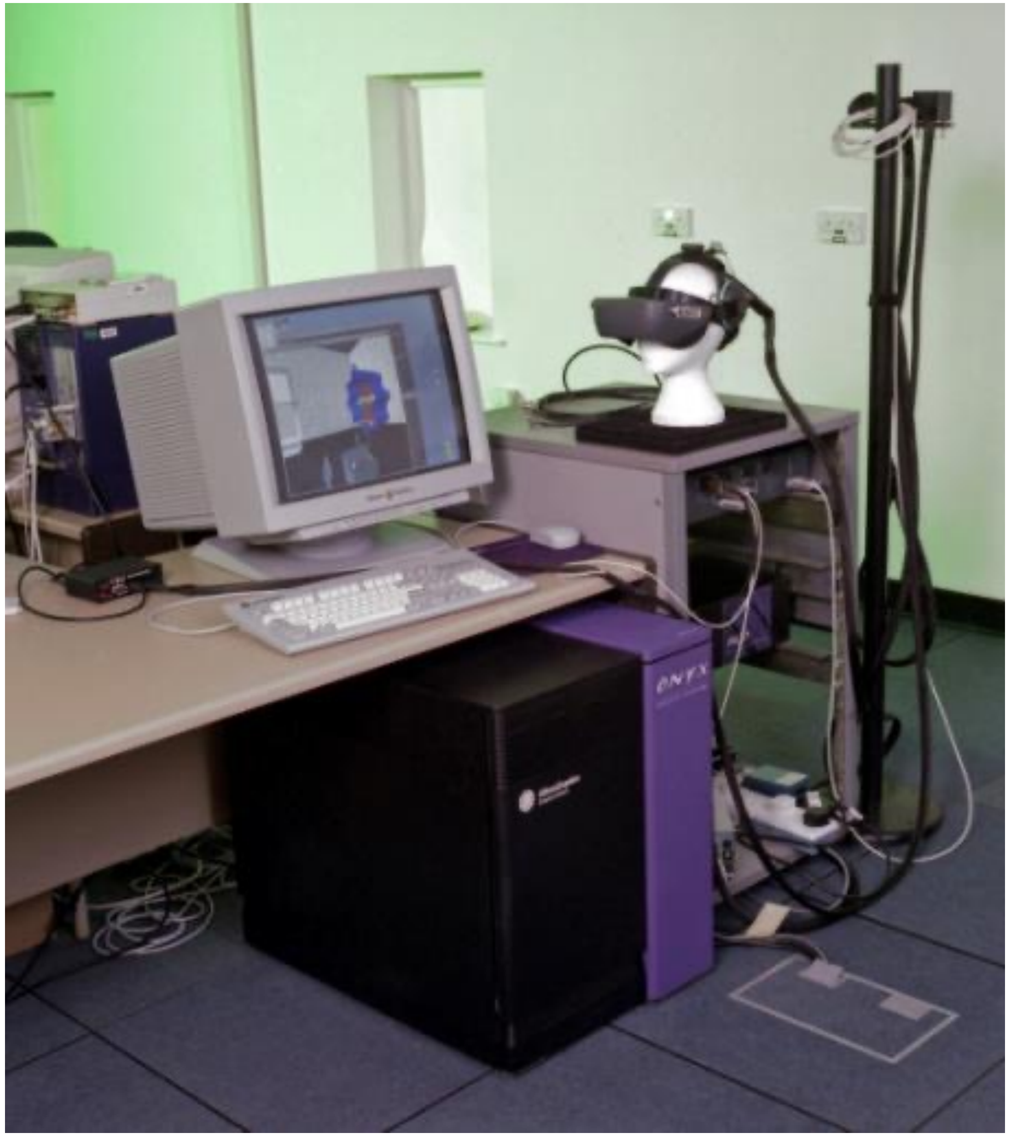
Desktop VR - 1995

- Expensive - $150,000+
- 2 million polys/sec
- VGA HMD – 30 Hz
- Magnetic tracking





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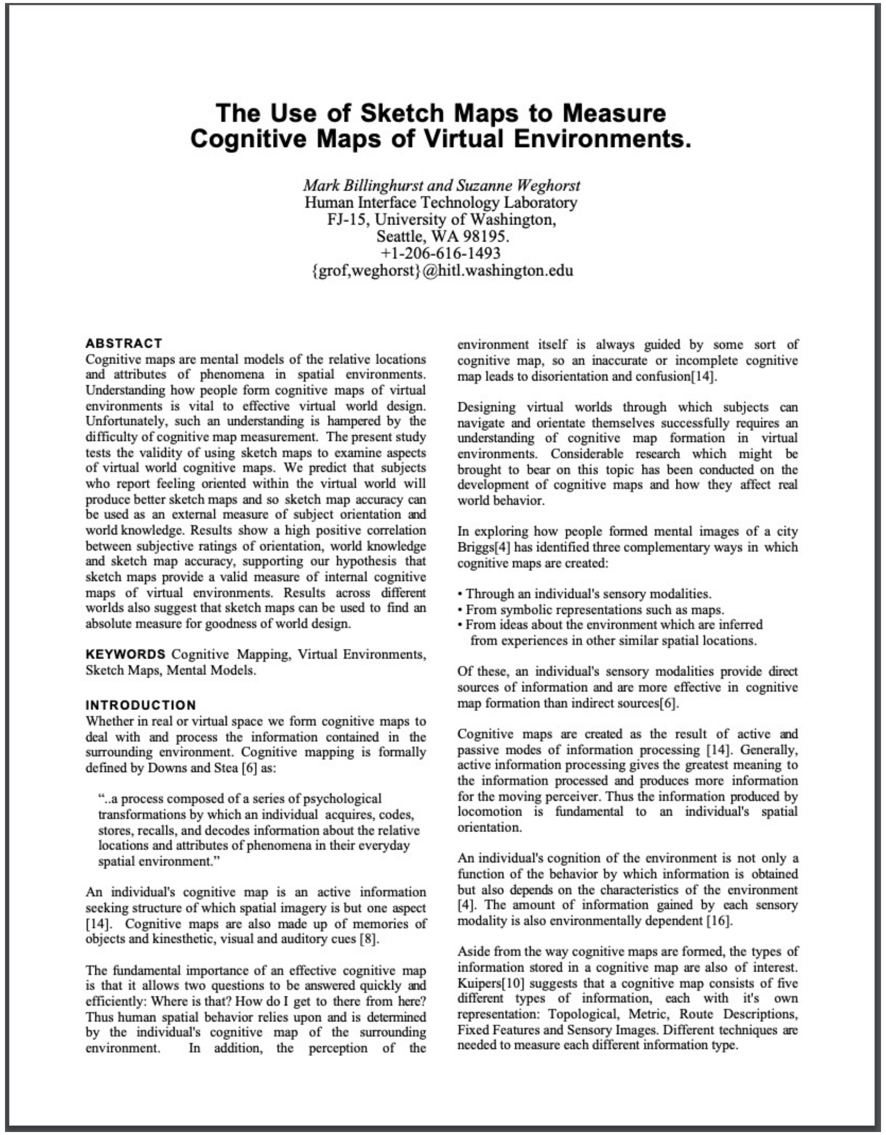
First Published Experiment (1995)

Explore if sketch maps can be used to measure cognitive maps of Virtual Environments

Hypothesis: people better oriented in VE will produce more accurate sketch maps



The Use of Sketch Maps to Measure Cognitive Maps of Virtual Environments.

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ABSTRACT
Cognitive maps are mental models of the relative locations and attributes of phenomena in spatial environments. Understanding how people form cognitive maps of virtual environments is vital to effective virtual world design. Unfortunately, such an understanding is hampered by the difficulty of cognitive map measurement. The present study tests the validity of using sketch maps to examine aspects of virtual world cognitive maps. We predict that subjects who report feeling oriented within the virtual world will produce better sketch maps and so sketch map accuracy can be used as an external measure of subject orientation and world knowledge. Results show a high positive correlation between subjective ratings of orientation, world knowledge and sketch map accuracy, supporting our hypothesis that sketch maps provide a valid measure of internal cognitive maps of virtual environments. Results across different worlds also suggest that sketch maps can be used to find an absolute measure for goodness of world design.

KEYWORDS Cognitive Mapping, Virtual Environments, Sketch Maps, Mental Models.

INTRODUCTION
Whether in real or virtual space we form cognitive maps to deal with and process the information contained in the surrounding environment. Cognitive mapping is formally defined by Downs and Stea [6] as:

> "..a process composed of a series of psychological transformations by which an individual acquires, codes, stores, recalls, and decodes information about the relative locations and attributes of phenomena in their everyday spatial environment."

An individual's cognitive map is an active information seeking structure of which spatial imagery is but one aspect [14]. Cognitive maps are also made up of memories of objects and kinesthetic, visual and auditory cues [8].

The fundamental importance of an effective cognitive map is that it allows two questions to be answered quickly and efficiently: Where is that? How do I get to there from here? Thus human spatial behavior relies upon and is determined by the individual's cognitive map of the surrounding environment. In addition, the perception of the environment itself is always guided by some sort of cognitive map, so an inaccurate or incomplete cognitive map leads to disorientation and confusion[14].

Designing virtual worlds through which subjects can navigate and orientate themselves successfully requires an understanding of cognitive map formation in virtual environments. Considerable research which might be brought to bear on this topic has been conducted on the development of cognitive maps and how they affect real world behavior.

In exploring how people formed mental images of a city Briggs[4] has identified three complementary ways in which cognitive maps are created:

- Through an individual's sensory modalities.
- From symbolic representations such as maps.
- From ideas about the environment which are inferred from experiences in other similar spatial locations.

Of these, an individual's sensory modalities provide direct sources of information and are more effective in cognitive map formation than indirect sources[6].

Cognitive maps are created as the result of active and passive modes of information processing [14]. Generally, active information processing gives the greatest meaning to the information processed and produces more information for the moving perceiver. Thus the information produced by locomotion is fundamental to an individual's spatial orientation.

An individual's cognition of the environment is not only a function of the behavior by which information is obtained but also depends on the characteristics of the environment [4]. The amount of information gained by each sensory modality is also environmentally dependent [16].

Aside from the way cognitive maps are formed, the types of information stored in a cognitive map are also of interest. Kuipers[10] suggests that a cognitive map consists of five different types of information, each with it's own representation: Topological, Metric, Route Descriptions, Fixed Features and Sensory Images. Different techniques are needed to measure each different information type.

Billinghurst, M., & Weghorst, S. (1995, March). The use of sketch maps to measure cognitive maps of virtual environments. In *Proceedings Virtual Reality Annual International Symposium'95* (pp. 40-47). IEEE.

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Experiment Design

VR Experience

- Three small simple virtual worlds
- SGI Graphics + VPL HMD Hardware

Between subject's design

- Each person experiences only one world
- 24 – 35 subjects in each world

Experiment Process

1. Training in sample world
2. Complete 24 question survey
3. 10 minutes in test world
4. Produce sketch map
5. Complete 24 question survey

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Measures

Objective Measure

- Map analysis
  - Map goodness
  - Object classes present
  - Relative object positioning

Subjective Measures

- 24 question survey
  - navigation, orientation,
  - interaction, presence
  - interface questions
  - 10 point Likert scale

Subject comments

APPENDIX: SUBJECT SURVEY

The 24 survey questions given to subjects are listed below. For each of the questions subjects were asked to rank their responses on a scale from one to ten. The anchors for these scales are shown under the each of the questions. Responses were collected automatically using a Hypercard stack on a Macintosh computer and participants were also given theopportunity to add their own comments at the end of the survey.

Questions

1. Sense of being there:
None -> Total

2. Ease of interaction:
Impossible -> Effortless

3. Comfort of the display hardware:
Unbearable -> Comfortable

4. Enjoyment:
Boring -> Very enjoyable

5. How easy was it to navigate?
Very difficult -> Very easy

6. Sense of orientation relative to the laboratory:
No sense of direction -> Completely orientated

7. Sense of orientation in the virtual world:
No sense of direction -> totally orientated

8. Feeling of being lost:
All the time -> Never

9. Sense of dizziness:
Never -> All the time

10. Image brightness:
Way too dim -> Way too bright

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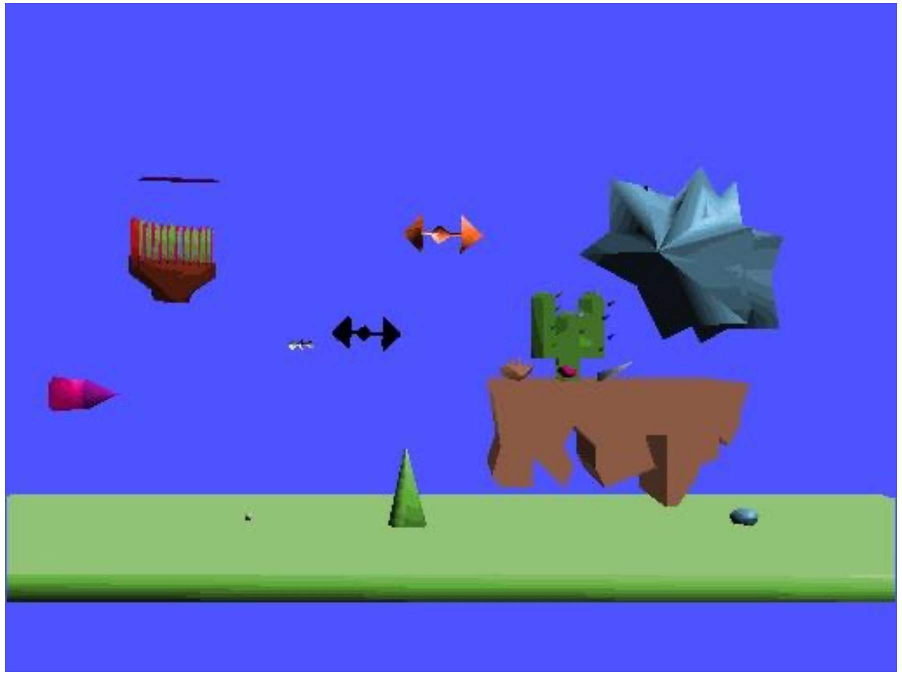
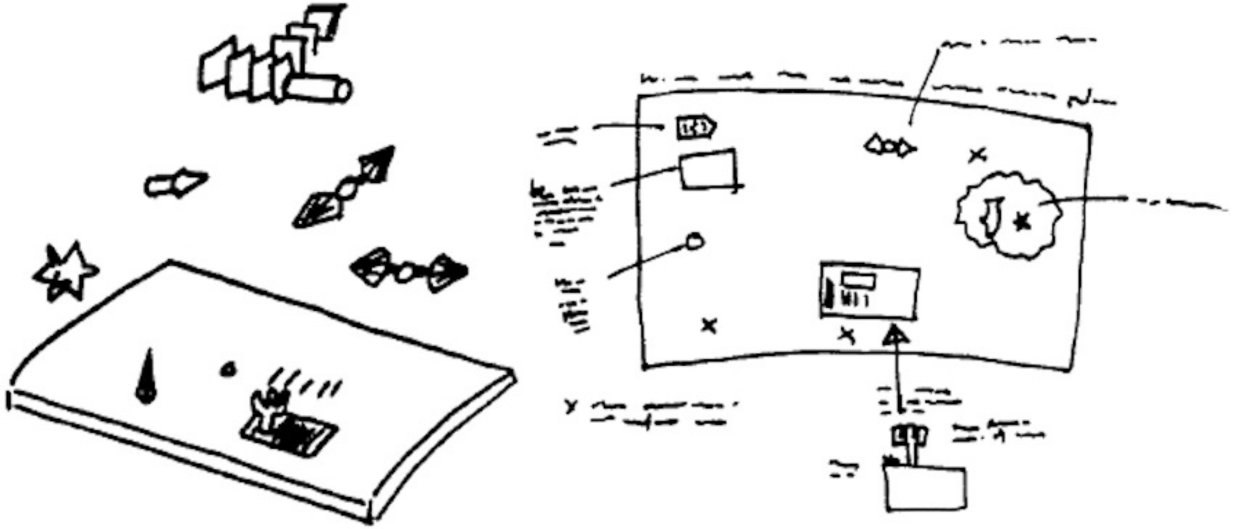
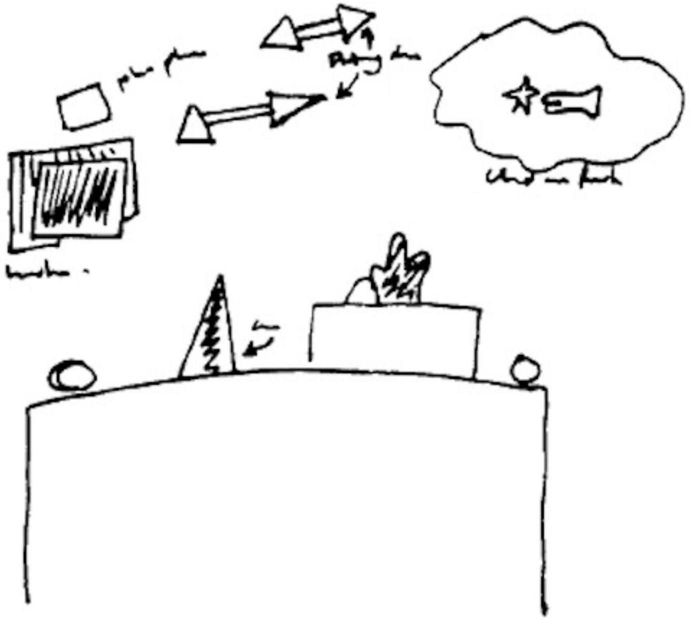
Sample Map



Cloudlands





"produce a map of the world that someone unfamiliar with the world could use to navigate around the world"

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Results

	Virtual Valley		Neighborhood		Cloudlands	
	Class No.	Map Goodness	Class No.	Map Goodness	Class No.	Map Goodness
World Knowledge	.480	.635	.427	.405	.242	.193
World Orientation	.567	.738	.397	.524	.353	.290
	$n = 12, p < 0.05, r = 0.56$		$n = 21, p < 0.05, r = 0.38$			

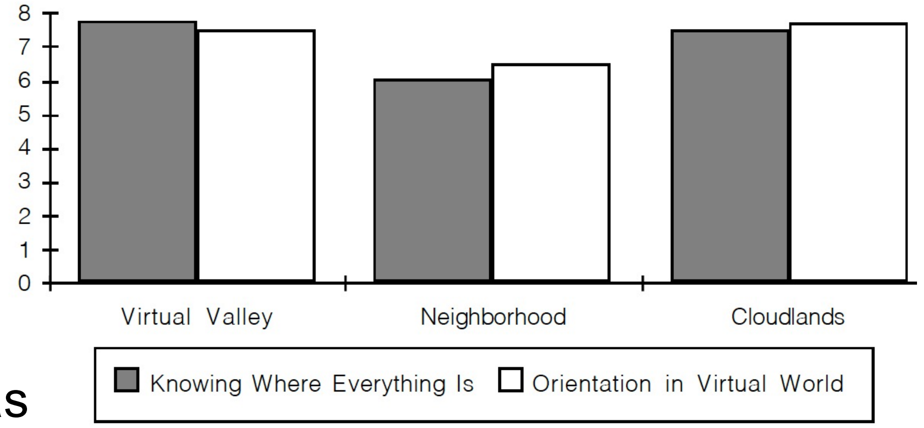
Within world correlation

- Goodness and Class No. correlated with virtual world orientation and knowledge (2 worlds)

Between world differences

- Sign. Diff. in understanding where everything was
- Sign. Diff. in placement of significant objects
- Sign. Diff. in sense of dizziness

World Knowledge and Orientation



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Lessons Learned

Positive Lessons

- Use mixture of subjective and objective measures
- Adopt existing measures from other relevant domains
- Can create own experimental measures

So many mistakes

- Missing data
- No spatial ability task
- Unbalanced Likert scale
- Simple experiment measures
- Poor statistical analysis of data
- No subject demographics reporting

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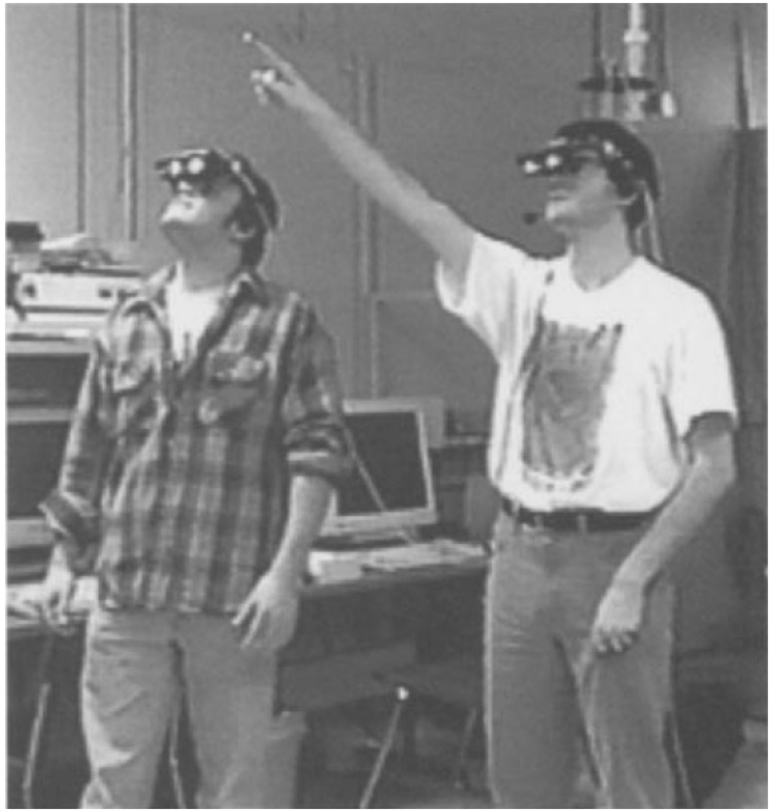
Shared Space (1998)

Collaborative AR/VR experience

- See through AR displays
- Exploring the role of seeing a partner's body in a shared task

Hypothesis: Seeing body will improve performance, AR better than VR



Billinghurst, M., Weghorst, S., & Furness, T. (1998). Shared space: An augmented reality approach for computer supported collaborative work. *Virtual Reality*, *3*(1), 25-36.

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Experiment Design

Collaborative Task

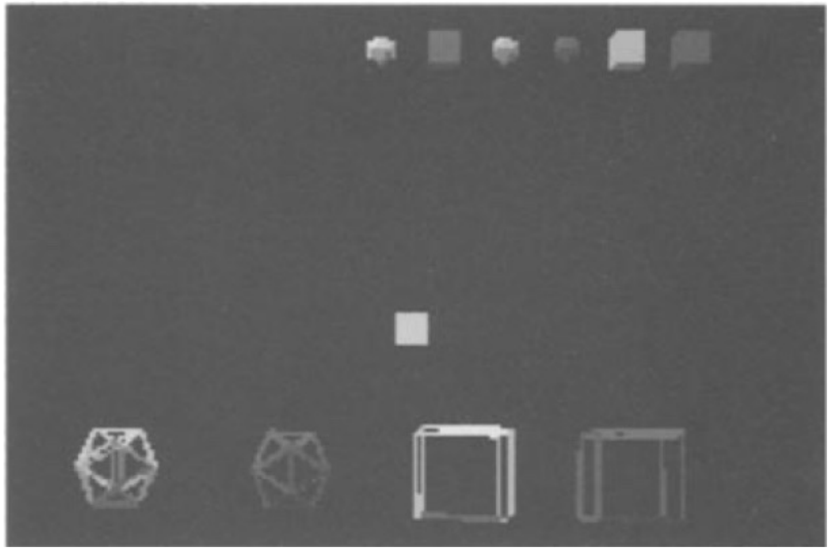
- Spotting, picking and moving objects
- Simulated speech recognition
- Role division: Spotter or Picker

Two Factor design

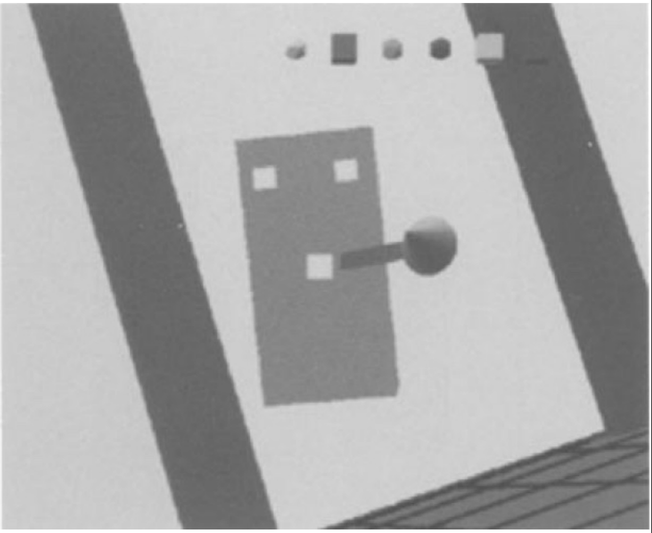
- Body/no body, AR/VR

Conditions

- RW+RB: AR - Real World + Real Body
- RW: AR - Real World/No Body
- VE: Virtual Environment - No Body
- VE+VB: Virtual Environment + Virtual Body
- VE+VB+NW: Virtual Environment + Virtual Body + No walls



Virtual Targets



Virtual Body

The University of Auckland · UNSW · University of Canterbury · Monash University · University of Otago · The University of Queensland · Victoria University Wellington · University of South Australia

Measures

Within subject's study

- 18 pairs, aged 19-45
- No prior experience
- 4 trials/condition = 20 trials

Performance Time

- How long to complete selection tasks

Subjective Surveys

- 5 Likert scale questions
- Ranking of conditions

1. How much did the search game have surprises and let you explore new things?
   1 2 3 4 5 6 7
   1 = not much 7 = very much
2. How good was your team at playing the search game?
   1 2 3 4 5 6 7
   1 = not good 7 = very good
3. Do you want to play the search game again sometime?
   1 2 3 4 5 6 7
   1 = no thanks 7 = very much
4. How well could you communicate with your Partner?
   1 2 3 4 5 6 7
   1 = not well 7 = very well
5. How easy was it to collaborate with your Partner?
   1 2 3 4 5 6 7
   1 = not easy 7 = very easy

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Results

Performance

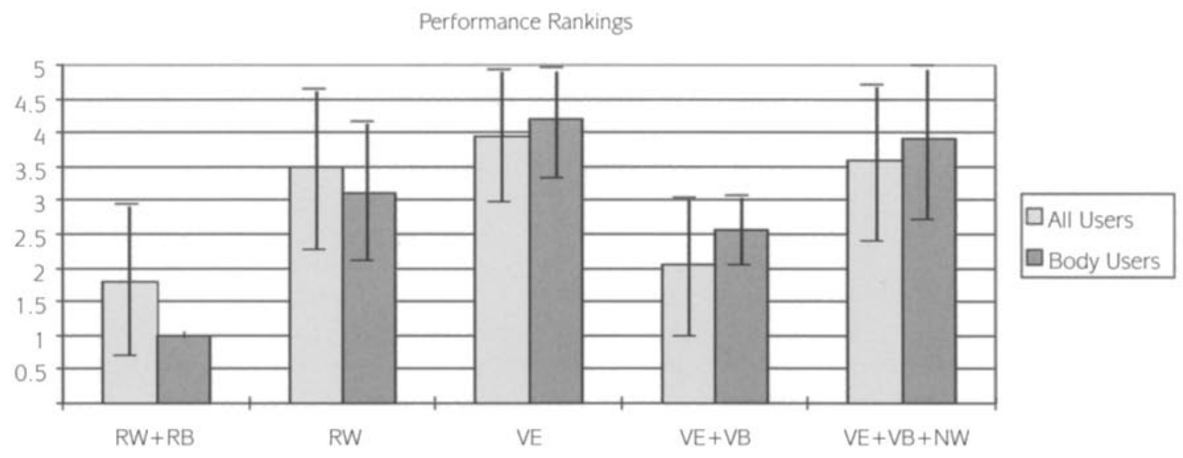
- No significant difference overall
- Sig. Diff. bet RW+RB, VE+VB
- Learning effect

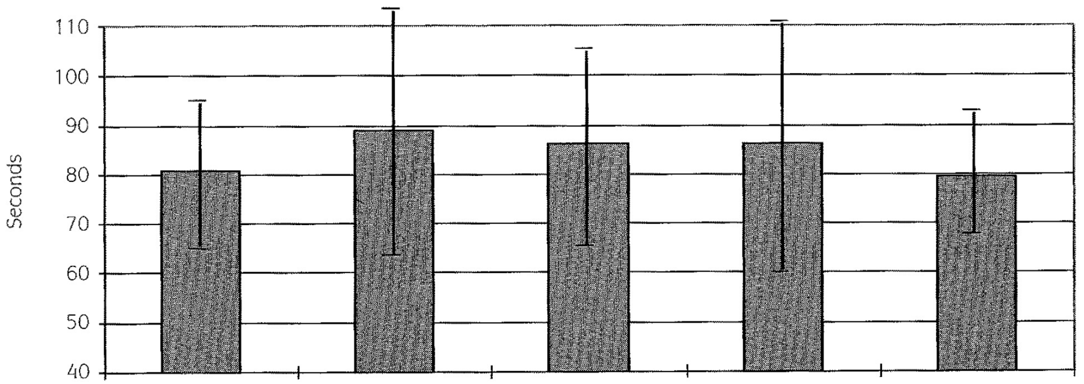
Subjective

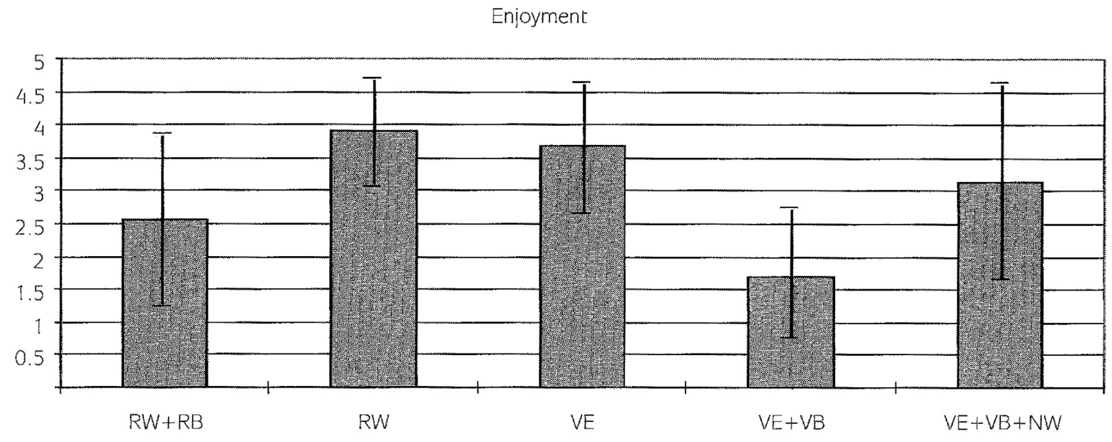
- Thought played better when body present
- Ranked RW + RB best for performance
- Ranked VE + VB best for enjoyment

All Trials			
Condition	Mean	Var.	t-val
RW+RB	83.37	325.03	−3.9*
VE+VB	102.15	816.89	

* Significant T-value at p<0.01, df = 9, t critical = 1.83







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Lessons Learned

Positive Lessons

- Combine Qualitative and Quantitative measures
- Performance time can be a poor measure in collaborative tasks
  - Many factors affect performance
- Use multiple subjective measures
  - Ranking + Likert questions

Still mistakes

- No user interviews
- No experimenter observations
- Didn’t consider learning effects in design
- Poor statistical analysis (no post-hoc analysis)

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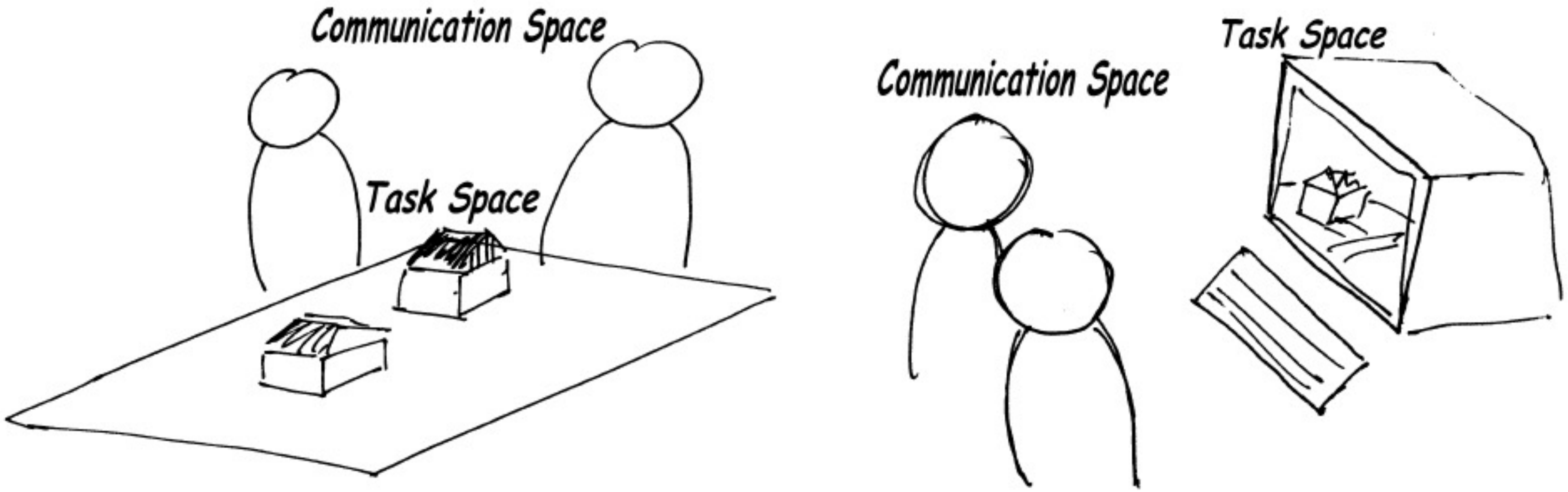
Collocated Communication Behaviours



Is there a difference between AR-based & screen-based FtF collaboration?

Hypothesis: FtF AR produces similar behaviours to FtF non-AR

Billinghurst, M., Belcher, D., Gupta, A., & Kiyokawa, K. (2003). Communication behaviors in colocated collaborative AR interfaces. *International Journal of Human-Computer Interaction*, *16*(3), 395-423.

Experiment Design

Face to Face

Projection

Augmented Reality

Building arranging task

- Both people have half the requirements

Conditions

- Face to Face – FtF with real buildings
- Projection – FtF with screen projection
- Augmented Reality – FtF with AR buildings

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Measures

Quantitative

- Performance time
- Communication Process Measures
  - The number and type of gestures made
  - The number of deictic phrases spoken
  - The average number of words per phrase
  - The number of speaker turns

Qualitative

- Subjective survey

User comments

- Post experiment interview

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Results

	Face to Face	Projection	Augmented Reality
Average Solution Time (Sec)	163.8	195.8	270.7
Std. Dev. (Sec)	52.3	60.9	61.8

Performance time

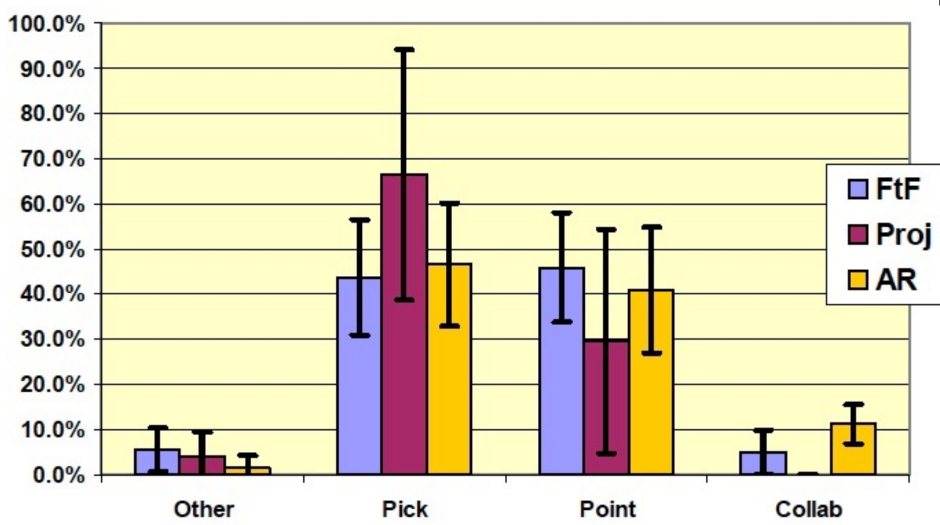
- Sig. diff. between conditions – AR slowest

Communication measures

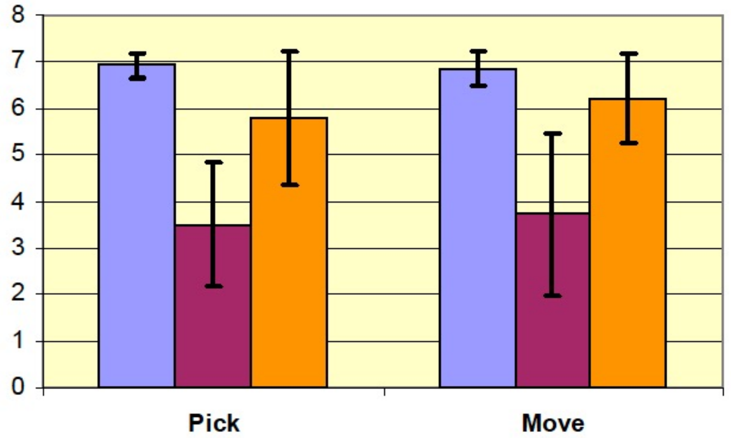
- No difference in number of words/turns
- Sig. Diff. in deictic phrases (FtF same as AR)
- Sig. Diff. in pick gestures (FtF same as AR)

Subjective measures

- FtF manipulation same as AR
- FtF to work with than AR/FtF



Percentage Breakdown of Gestures



Subject Survey Results

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Lessons Learned

Positive Lessons

- Communication process measures valuable
  - Gesture, speech analysis
- Collect user feedback/interviews
- Stronger statistical analysis
- Make observations

Fewer mistakes

- Surveys could be stronger
  - Validated surveys
- Better interview analysis
  - Thematic analysis

"AR's biggest limit was lack of peripheral vision. The interaction physically …was natural, it was just a little difficult to see.

"working solo together".

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UNC Pit Room (2002)

Key Features

- Training room and pit room
- Physical walking
- Fast, accurate, room scale tracking
- Haptic feedback – feel edge of pit, walls
- Strong visual and 3D audio cues

Task

- Carry object across pit
  - Walk across or walk around
- Dropping virtual balls at targets in pit

http://wwwx.cs.unc.edu/Research/eve/walk_exp/

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Typical Subject Behaviour

Note – from another pit experiment

https://www.youtube.com/watch?v=VVAO0DkoD-8

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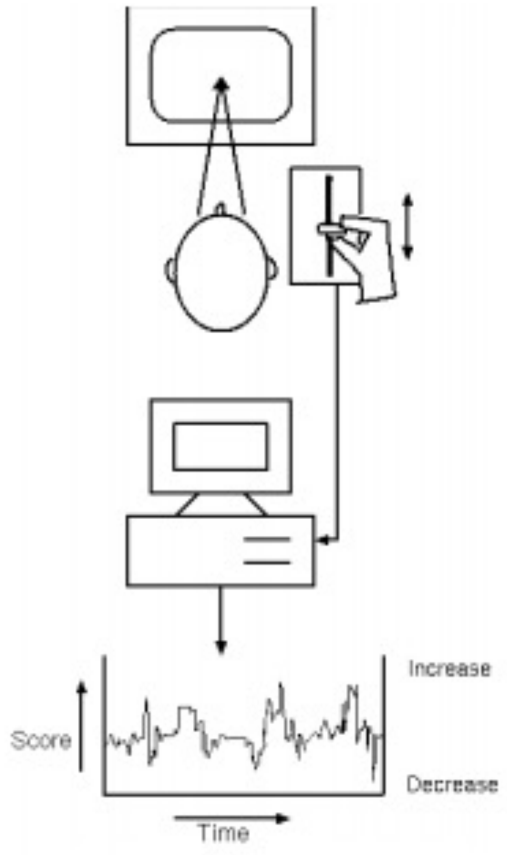
Measuring Presence

Subjective Measures

- Self report questionnaire
  - University College London Questionnaire (Slater 1999)
  - Witmer and Singer Presence Questionnaire (Witmer 1998)
  - ITC Sense Of Presence Inventory (Lessiter 2000)
- Continuous measure
  - Person moves slider bar in VE depending on Presence felt

Objective Measures

- Behavioural
  - reflex/flinch measure, startle response
- Physiological measures
  - change in heart rate, skin conductance, skin temperature



Presence Slider

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Experiment Measures

Physiological Measures

- Change in heart rate
- Change in skin conductance
- Change in skin temperature

Subjective Measures

- UCL Presence questionnaire (Likert Scale)
  - Focus on behavioural Presence

Meehan, M., Insko, B., Whitton, M., & Brooks Jr, F. P. (2002). Physiological measures of presence in stressful virtual environments. *Acm transactions on graphics (tog)*, *21*(3), 645-652.

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Experiments

Three experiments conducted

- Effect of multiple exposures
- Effect of passive haptics
- Effect of framerate (10,15, 20, 30)

Look at Presence correlation

- Correlation between subjective scores and physiological measures

Passive Haptics

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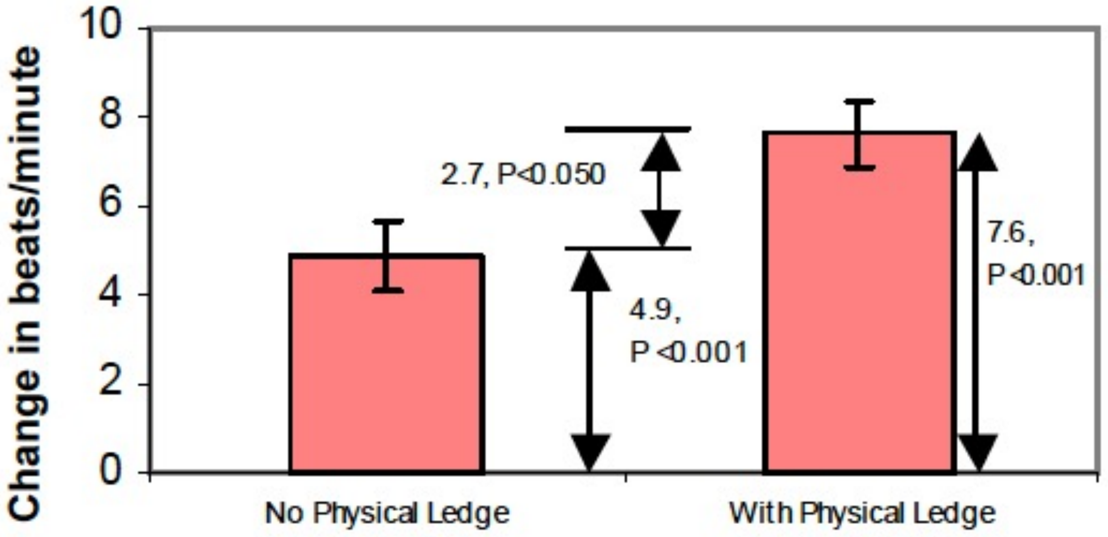
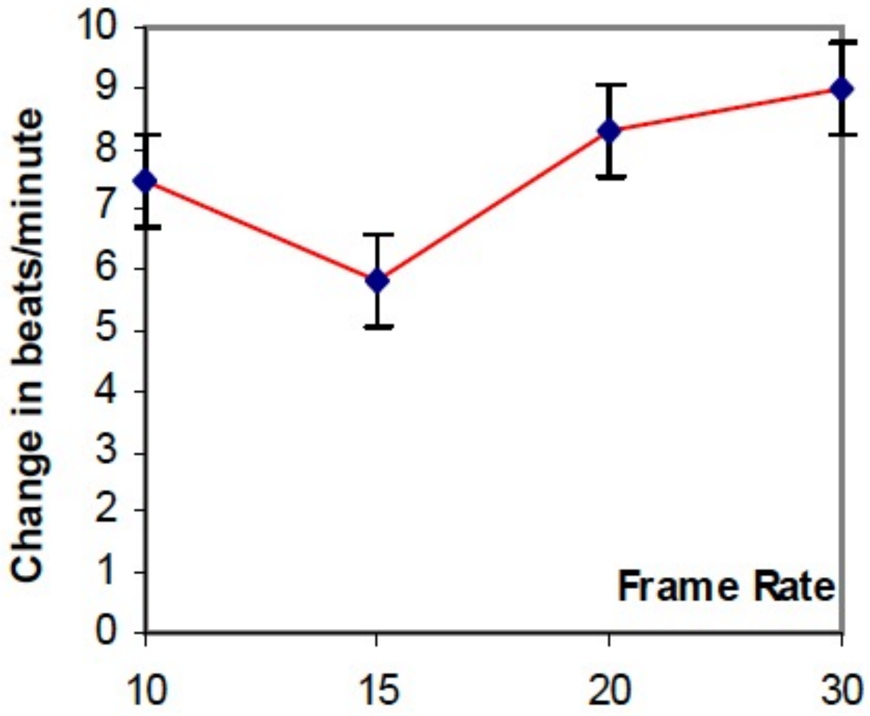
Results





Physiological cues

- Significant change in HR in haptics/frame rate experiments
- Decrease in scores with repeated exposures

Presence correlation

- Between HR and Presence in Frame Rate experiment
- Between Skin conductance and Presence in multi-exposure

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Key Lessons Learned

Positive

- Can use physiological cues as a process measure
- Can get agreement between subjective survey results and physiological cues
- Change in HR possible objective measure of Presence
  - Especially high Presence environments

Further work

- What other physiological cues could be used
- Between-subjects reliability
- Correlation with other Presence measures

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Neurophysiological Measures of Presence

Measuring Presence using multiple neurophysiological measures

- Combining physiological and neurological signals

Dey, A., Phoon, J., Saha, S., Dobbins, C., & Billinghurst, M. (2020, November). A Neurophysiological Approach for Measuring Presence in Immersive Virtual Environments. In *2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)* (pp. 474-485). IEEE.

A Neurophysiological Approach for Measuring Presence in Immersive Virtual Environments

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Jane Phoon† University of Queensland Australia
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ABSTRACT

Presence, the feeling of *being there*, is an important factor that affects the overall experience of Virtual Reality (VR). Higher presence commonly provides a better experience in VR than lower presence. However, presence is commonly measured subjectively through post-experience questionnaires, which can suffer from participant biases, dishonest answers, and fatigue. It can also be difficult for subjects to accurately remember their feelings of presence after they have left the VR experience.

In this paper, we measured the effects of different levels of presence (high and low) in VR using physiological and neurological signals. The experiment involved 24 participants in a between-subjects design. Results indicated a significant effect of presence on both physiological and neurological signals. We noticed that higher presence results in higher heart rate, less visual stress, higher theta and beta activities in the frontal region, and higher alpha activities in the parietal region. These findings and insights could lead to an alternative objective measure of presence.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Empirical studies in HCI; Human-centered computing—Visualization—Visualization design and evaluation methods

1 INTRODUCTION

Virtual Reality (VR) is a technology that enables users to be immersed in a fully computerised simulated environment, with interaction capabilities similar to that of the real-world and beyond. The experience of being in a virtual environment (VE) is largely affected by the feeling of *presence* [27,64] and *being there*, while physically being in a different location [1,48].

Earlier studies have indicated a few factors that positively influence presence in VR, such as the availability of multi-sensory input [14], audio spatialization [4], avatar fidelity [33], and interactivity [42], among others. There are also multiple validated questionnaires that are widely used to subjectively measuring presence in a Virtual Environment (VE).

Several of the most widely used questionnaires have been developed by Slater et al. [52] and Usoh et al. [60], as well as Witmer & Singer [64]. The questionnaire developed by Slater and Ushoh et al. (commonly known as the Slater-Usoh-Steed (SUS) questionnaire) measures overall presence using six descriptive questions themed around three main areas – the sense of being there, the VE becoming a reality, and remembrance of the VE as a place in reality. Witmer & Singer's questionnaire collects the degree of presence felt by the individual in six sub-scales—involvement, natural, auditory, haptics, resolution, and interface quality—as well as the amount of influence over the four factors of control, sensory, distraction, and realism have on the experience [64]. Schwind et al. also provides a comprehensive list of 15 published questionnaires [48] that measured presence in VE.

While questionnaires are a widely used instrument in human-based research, the responses can be biased [8] and dishonest [16]. Slater noted that post-experience presence questionnaires cannot be heavily relied on and that researchers should consider alternative methods [50]. This is because leaving the VE to answer the questionnaire causes a break in presence (BIP), which in turn confounds the responses [46]. Schwind et al. found that answering presence questionnaires within the VE yields different results than answering them outside of the VE [48]. These findings provide the core motivation of the current research, which is to investigate both the neurological and physiological effects of presence as an alternative measure.

There have been some earlier efforts in measuring presence using physiological signals. For instance, Meehan et al. proposed physiological measurements—using heart rate, skin conductance, and skin temperature—of presence using a scary VR environment [37]. They noticed change in heart rate and skin conductance. Whilst, Wiederhold et al. found significant correlations between presence questionnaire ratings and heart rate and skin resistance [63].

However, there has not been much previous research in terms of utilising neurological signals to measure presence within VEs. An earlier study using Functional Magnetic Resonance Imaging (fMRI) identified different types of neural activity in adults and children in response to high and low presence non-interactive VEs [2]. Kober et al. [29] identified a positive relationship between presence and parietal brain activation and a negative relationship between presence and frontal brain activation. Recently, Jeunet et al. [28] identified neurophysiological markers of sense of agency in VR environments. There are several studies that have used neurological signals to enable and/or measure rehabilitation of neurological conditions [6, 9,65], however, they did not focus on measuring presence.

To our knowledge, there have not been any other studies that have used both physiological and neurological signals to measure presence within the same VE. This investigation is important because understanding the neurological and physiological effects of presence will enable an alternative real-time method to measure presence and avoid shortcomings of post-experience questionnaires. Furthermore, a real-time measurement of presence can enable adaptive VR interfaces that can change its features to maintain a suitable level of presence based on the user's emotional and cognitive states.

Novelty and Contribution:

The main novelty of this work is the use of both neurological and physiological signals to measure presence in calm VEs and

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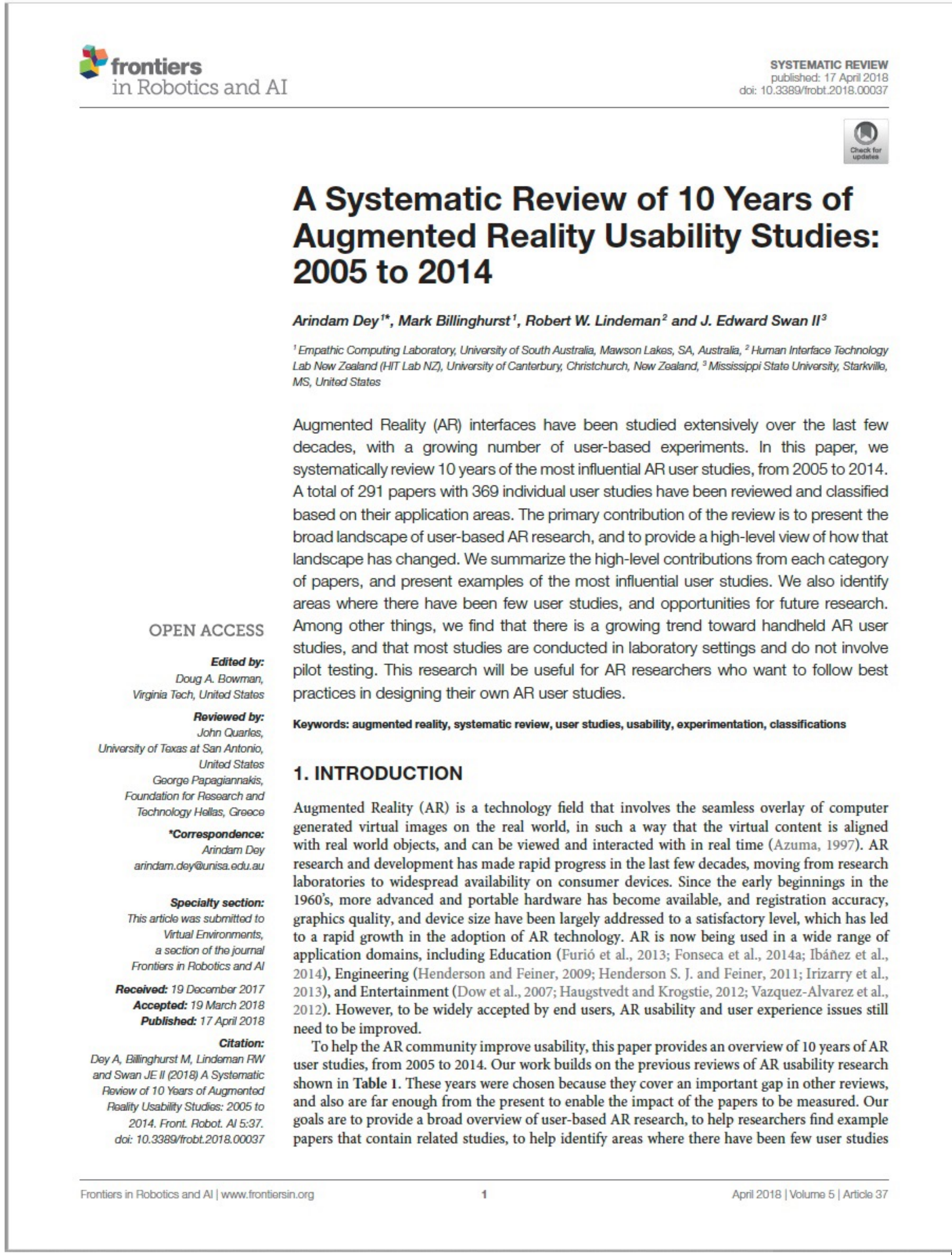
DOI 10.1109/ISMAR50242.2020.00072

Meta-Review

Review of 10 years of AR user studies

Dey, A., Billinghurst, M., Lindeman, R. W., & Swan, J. (2018). A systematic review of 10 years of augmented reality usability studies: 2005 to 2014. *Frontiers in Robotics and AI*, *5*, 37.



frontiers in Robotics and AI

SYSTEMATIC REVIEW
published: 17 April 2018
doi: 10.3389/frobt.2018.00037

A Systematic Review of 10 Years of Augmented Reality Usability Studies: 2005 to 2014

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Augmented Reality (AR) interfaces have been studied extensively over the last few decades, with a growing number of user-based experiments. In this paper, we systematically review 10 years of the most influential AR user studies, from 2005 to 2014. A total of 291 papers with 369 individual user studies have been reviewed and classified based on their application areas. The primary contribution of the review is to present the broad landscape of user-based AR research, and to provide a high-level view of how that landscape has changed. We summarize the high-level contributions from each category of papers, and present examples of the most influential user studies. We also identify areas where there have been few user studies, and opportunities for future research. Among other things, we find that there is a growing trend toward handheld AR user studies, and that most studies are conducted in laboratory settings and do not involve pilot testing. This research will be useful for AR researchers who want to follow best practices in designing their own AR user studies.

Keywords: augmented reality, systematic review, user studies, usability, experimentation, classifications

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1. INTRODUCTION

Augmented Reality (AR) is a technology field that involves the seamless overlay of computer generated virtual images on the real world, in such a way that the virtual content is aligned with real world objects, and can be viewed and interacted with in real time (Azuma, 1997). AR research and development has made rapid progress in the last few decades, moving from research laboratories to widespread availability on consumer devices. Since the early beginnings in the 1960's, more advanced and portable hardware has become available, and registration accuracy, graphics quality, and device size have been largely addressed to a satisfactory level, which has led to a rapid growth in the adoption of AR technology. AR is now being used in a wide range of application domains, including Education (Furió et al., 2013; Fonseca et al., 2014a; Ibáñez et al., 2014), Engineering (Henderson and Feiner, 2009; Henderson S. J. and Feiner, 2011; Irizarry et al., 2013), and Entertainment (Dow et al., 2007; Haugstvedt and Krogstie, 2012; Vazquez-Alvarez et al., 2012). However, to be widely accepted by end users, AR usability and user experience issues still need to be improved.

To help the AR community improve usability, this paper provides an overview of 10 years of AR user studies, from 2005 to 2014. Our work builds on the previous reviews of AR usability research shown in **Table 1**. These years were chosen because they cover an important gap in other reviews, and also are far enough from the present to enable the impact of the papers to be measured. Our goals are to provide a broad overview of user-based AR research, to help researchers find example papers that contain related studies, to help identify areas where there have been few user studies

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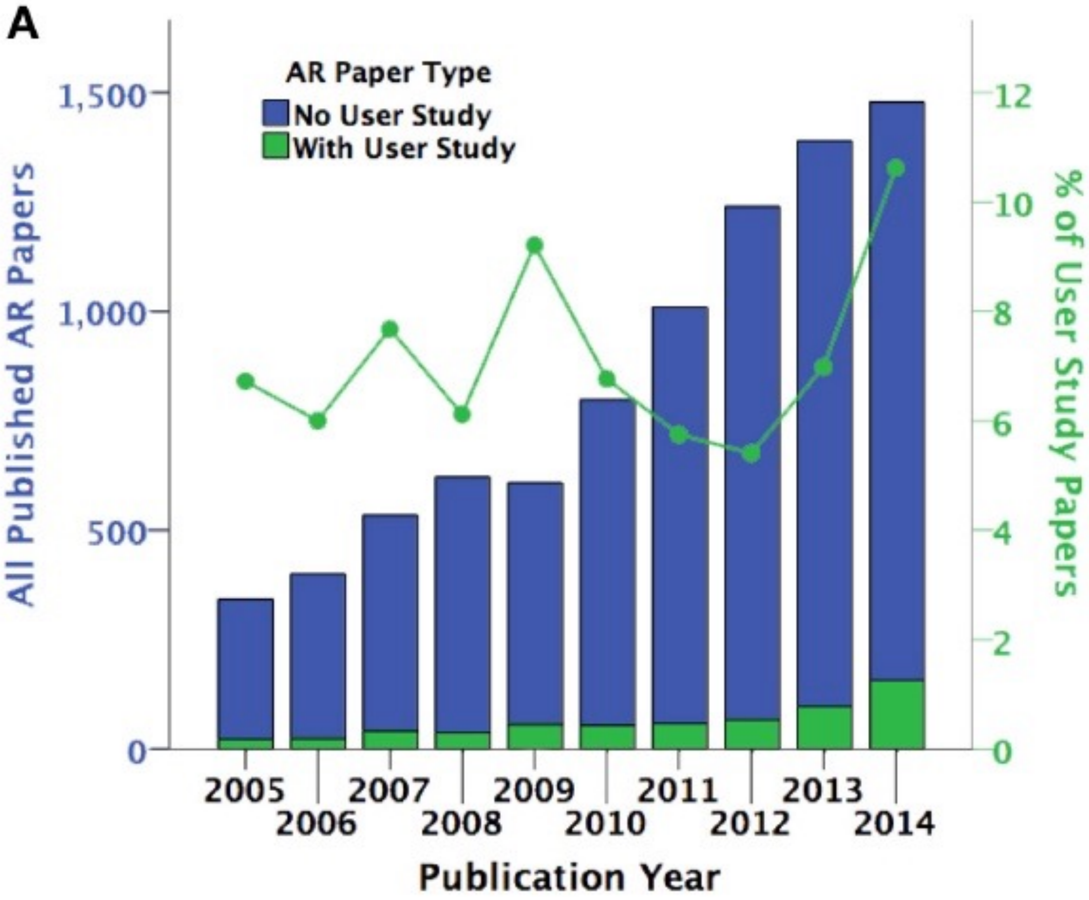
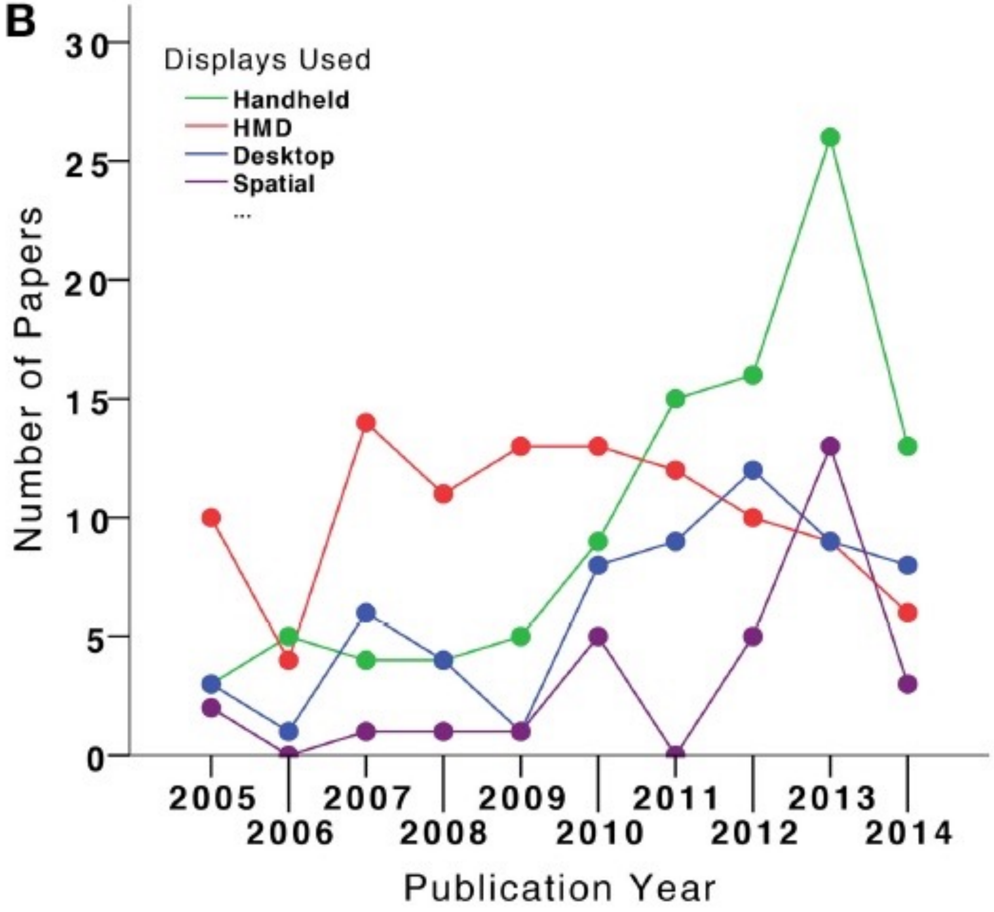
Paper Analysis



All AR Papers vs. User Study Papers



Displays Used

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The University of Auckland — Te Whare Wānanga o Tāmaki Makaurau — New Zealand
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Monash University
University of Otago — Te Whare Wānanga o Otāgo — New Zealand
The University of Queensland Australia
Victoria University Wellington — Te Whare Wānanga o te Ūpoko o te Ika a Māui
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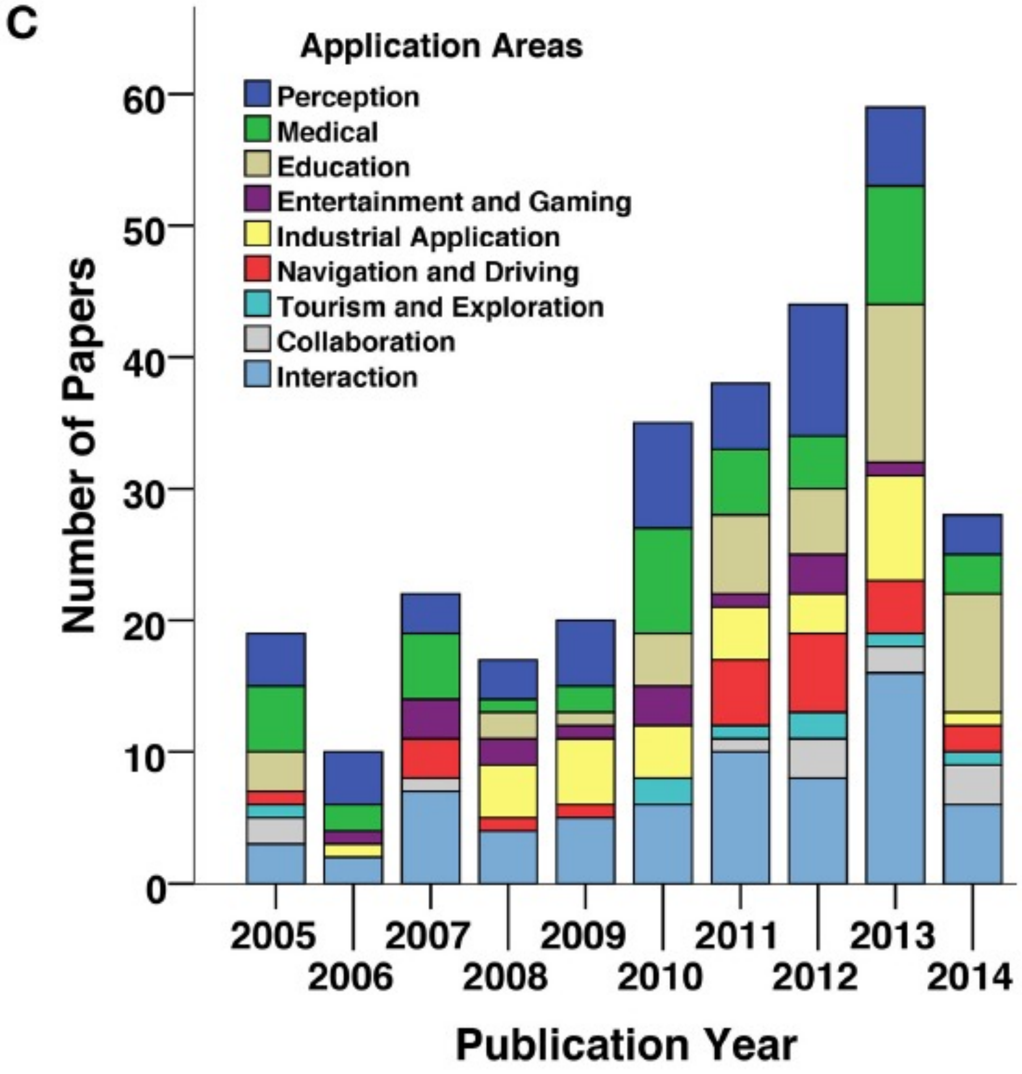
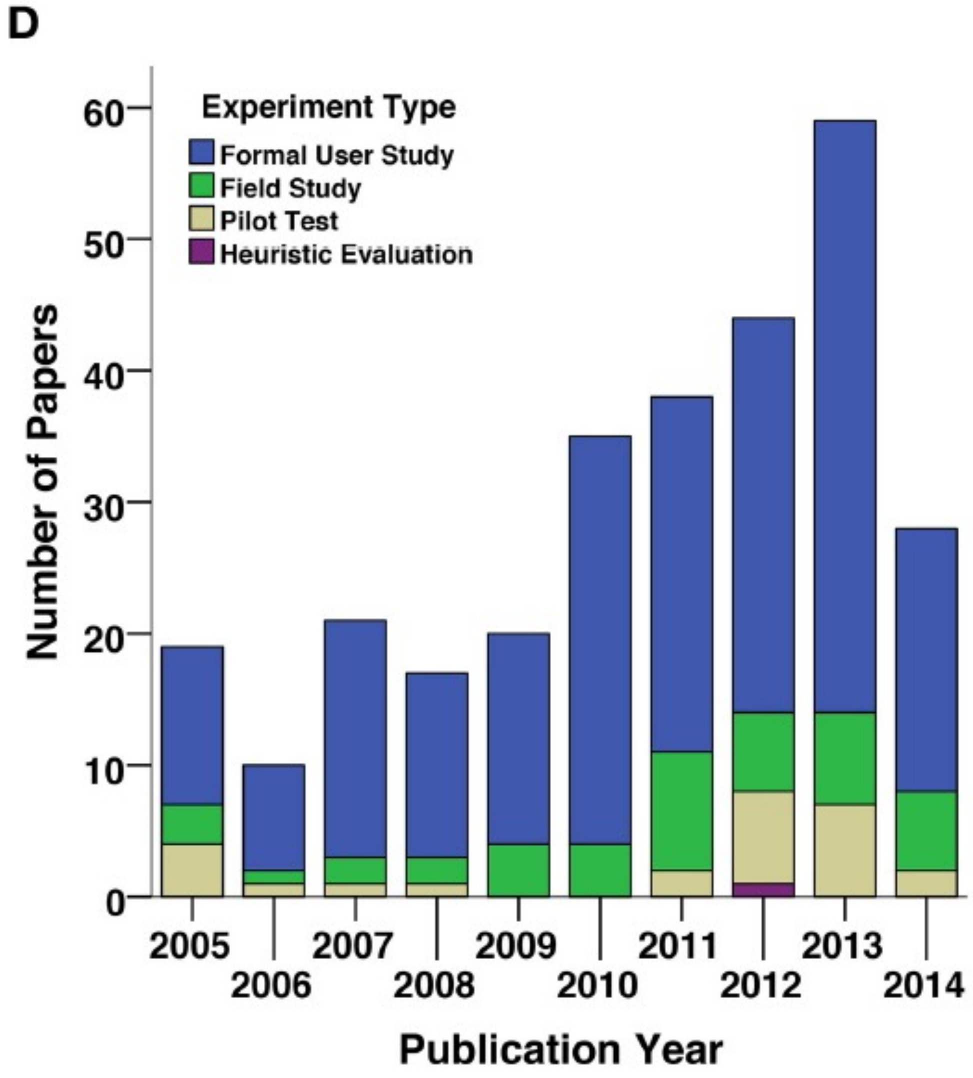


Application Areas



Experiment Type

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Breakdown by Application Area

TABLE 3 | Summary of the 291 reviewed papers.

Application Area	Paper	Mean ACC	Mean Author Count	Publication		Display*			Data Collected		
				Journal	Conference	HMD	HHD	Other	Quant.	Qual.	Both
Collaboration	12	6.4	3.58	1	11	5	6	4	1	5	6
Education	42	5.5	3.24	23	19	5	17	26	7	19	16
Entertainment and Gaming	14	4.2	4.71	2	12	3	7	6	2	5	7
Industrial	30	5.7	3.87	14	16	15	11	7	4	4	22
Interaction	67	5.1	3.64	8	59	28	30	17	11	14	42
Medical	43	4.2	6.02	35	8	15	1	27	20	10	13
Navigation and Driving	24	4.2	4.58	10	14	4	12	9	7	2	15
Perception	51	4.9	3.75	16	35	27	13	13	22	12	17
Tourism and Exploration	8	6.5	3.63	4	4		3	6		7	1
Overall	291	5.2	4.1	113	178	102	100	115	74	78	139

*HMD=Head Mounted Display, HHD=Hand-Held Display

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Breakdown by Application Area

TABLE 4 | Summary of the 369 user studies reported by the 291 reviewed papers.

Application Area	Study Type: Lab	Study Type: Field	Study Type: Heuristic	Study Type: Pilot	Study Design: Within	Study Design: Between	Study Design: Mixed	Study Design: Other	Study Location: Indoor	Study Location: Outdoor	Study Location: Both	Median Participants
Collaboration	12	3			14			1	14	1		12
Education	28	14		13	31	16	1	7	49	4	2	28
Entertainment and Gaming	13	5			14	2		2	13	4	1	17
Industrial	29	6		1	28	6		2	32	4		15
Interaction	71	5	1	6	70	2	6	5	75	7	1	14
Medical	39	7	4	4	36	11		7	54			13
Navigation and Driving	23	5			21	3	3	1	21	7		18
Perception	60	3	1	7	52	12	6	1	52	17	2	16
Tourism and Exploration	3	6			6			3	9			28
Overall	278	54	6	31	272	52	16	29	319	44	6	16

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Summary

Few AR papers have a formal experiment (~10%)

Most papers use within-subjects design (73%)

Most experiments in controlled environments (76%)

- Lack of experimentation in real world conditions, heuristic, pilot studies

Half of papers collect both Qualitative and Quantitative measures (48%)

- Performance measures (76%), surveys (50%)

Most papers focus on visual senses (96%)

Young participants dominate (University students) (62%)

- Females in minority (36%)

Most use HMD (35%) or handheld displays (34%)

- Handheld/mobile AR studies becoming more common

Most studies are in interaction (23%), very few collaborative studies (4%)

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Sharing: Virtual Communication Cues (2019)

Using AR/VR to share communication cues

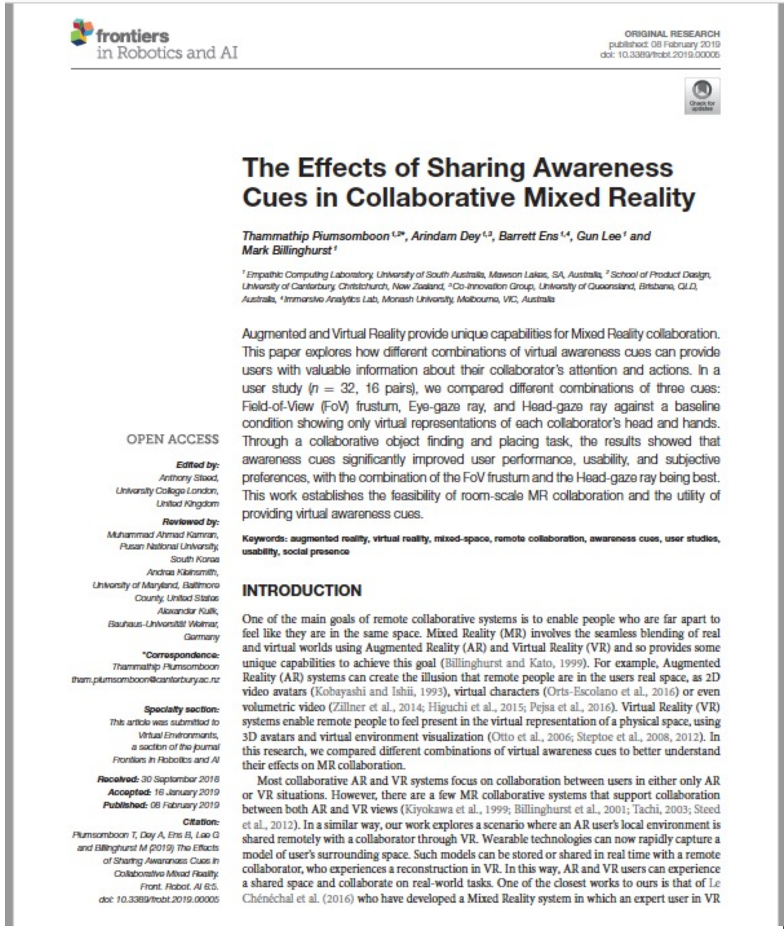
- Gaze, gesture, head pose, body position

Sharing same environment

- Virtual copy of real world

Collaboration between AR/VR

- VR user appears in AR user's space



frontiers in Robotics and AI

ORIGINAL RESEARCH
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The Effects of Sharing Awareness Cues in Collaborative Mixed Reality

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Augmented and Virtual Reality provide unique capabilities for Mixed Reality collaboration. This paper explores how different combinations of virtual awareness cues can provide users with valuable information about their collaborator's attention and actions. In a user study ($n = 32$, 16 pairs), we compared different combinations of three cues: Field-of-View (FoV) frustum, Eye-gaze ray, and Head-gaze ray against a baseline condition showing only virtual representations of each collaborator's head and hands. Through a collaborative object finding and placing task, the results showed that awareness cues significantly improved user performance, usability, and subjective preferences, with the combination of the FoV frustum and the Head-gaze ray being best. This work establishes the feasibility of room-scale MR collaboration and the utility of providing virtual awareness cues.

Keywords: augmented reality, virtual reality, mixed-space, remote collaboration, awareness cues, user studies, usability, social presence

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INTRODUCTION

One of the main goals of remote collaborative systems is to enable people who are far apart to feel like they are in the same space. Mixed Reality (MR) involves the seamless blending of real and virtual worlds using Augmented Reality (AR) and Virtual Reality (VR) and so provides some unique capabilities to achieve this goal (Billinghurst and Kato, 1999). For example, Augmented Reality (AR) systems can create the illusion that remote people are in the users real space, as 2D video avatars (Kobayashi and Ishii, 1993), virtual characters (Orts-Escolano et al., 2016) or even volumetric video (Zillner et al., 2014; Higuchi et al., 2015; Pejsa et al., 2016). Virtual Reality (VR) systems enable remote people to feel present in the virtual representation of a physical space, using 3D avatars and virtual environment visualization (Otto et al., 2006; Steptoe et al., 2008, 2012). In this research, we compared different combinations of virtual awareness cues to better understand their effects on MR collaboration.

Most collaborative AR and VR systems focus on collaboration between users in either only AR or VR situations. However, there are a few MR collaborative systems that support collaboration between both AR and VR views (Kiyokawa et al., 1999; Billinghurst et al., 2001; Tachi, 2003; Steed et al., 2012). In a similar way, our work explores a scenario where an AR user's local environment is shared remotely with a collaborator through VR. Wearable technologies can now rapidly capture a model of user's surrounding space. Such models can be stored or shared in real time with a remote collaborator, who experiences a reconstruction in VR. In this way, AR and VR users can experience a shared space and collaborate on real-world tasks. One of the closest works to ours is that of Le Chénéchal et al. (2016) who have developed a Mixed Reality system in which an expert user in VR

Piumsomboon, T., Dey, A., Ens, B., Lee, G., & Billinghurst, M. (2019). The effects of sharing awareness cues in collaborative mixed reality. *Frontiers in Robotics and AI*, 6, 5.

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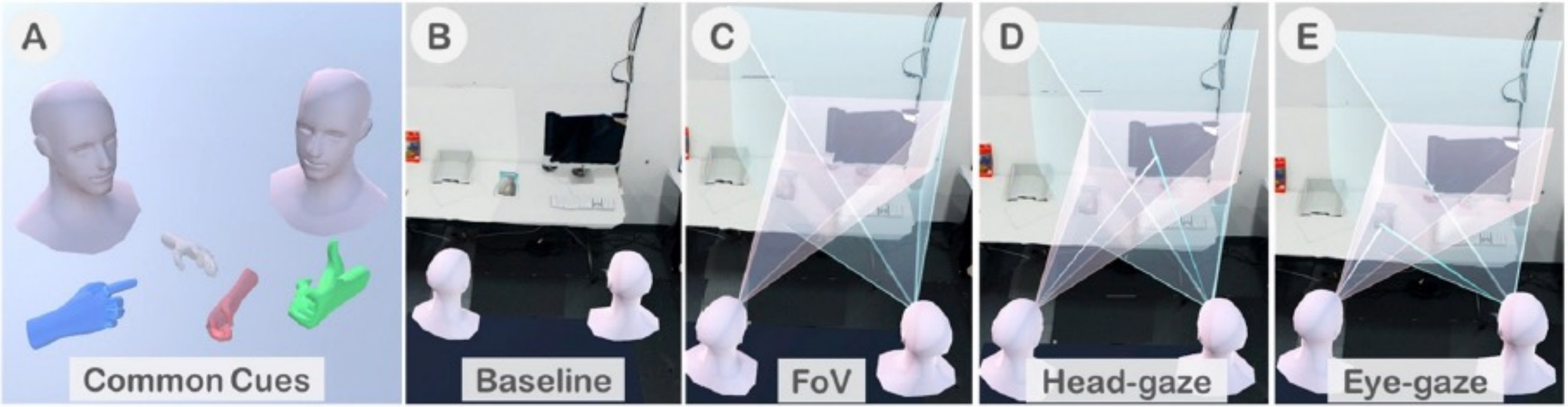
Sharing Virtual Communication Cues



- AR/VR displays
- Gesture input (Leap Motion)
- Room scale tracking
- Conditions
  - Baseline, FoV, Head-gaze, Eye-gaze

Conditions

- *Baseline*: In the Baseline condition, we showed only the head and hands of the collaborator in the scene. The head and hands were in all conditions
- *Field-of-view (FoV)*: We showed the FoV frustum of each collaborator to the other. This enabled collaborators to understand roughly where their partner was looking and what the other person could see at any point.
- *Head-gaze (FoV + Head-gaze ray)*: FoV frustum plus a ray originating from the user's head to identify the center of the FoV, which provided a more precise indication where the other collaborator was looking
- *Eye-gaze (FoV + Eye-gaze ray)*: In this cue, we showed a ray originating from the user's eye to show exactly where the user was looking at.

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Hypotheses

- H1: The Baseline condition should be the worst condition in terms of all performance metrics and behavioral observation variables.
- H2: The Head-gaze and Eye-gaze conditions provide a gaze pointer, which will enable users to perform better than the FoV only condition.
- H3: The Head-gaze and Eye-gaze will be favored more than Baseline condition. Not having a cue increase the collaborators' task load.
- H4: The Baseline condition requires more physical movement from the collaborators as they need to look at their collaborator's avatar.
- H5: The Baseline condition requires a larger distance separating the collaborators so that they could see each other's avatar.

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Task

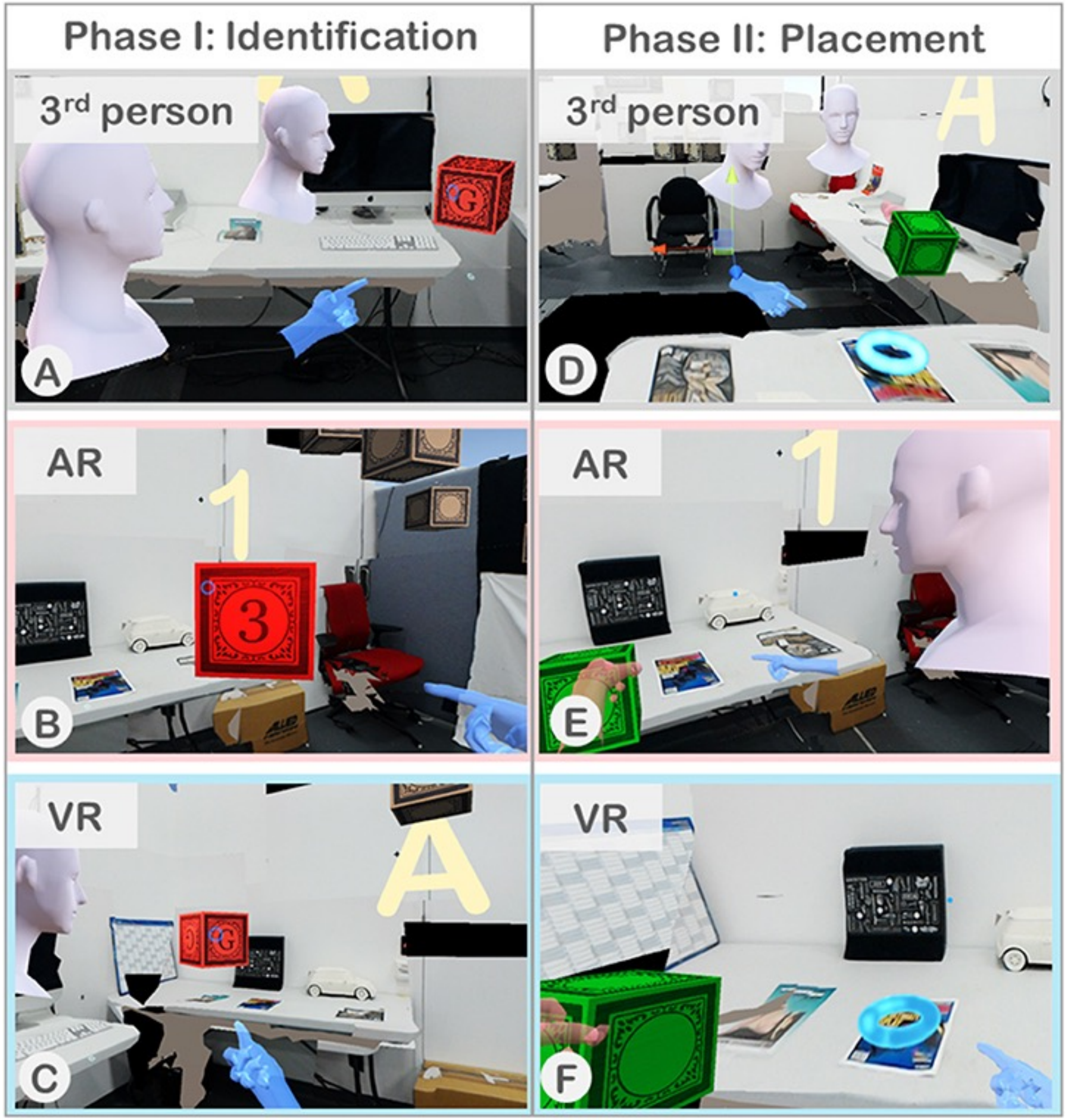
Search task

Two phases:

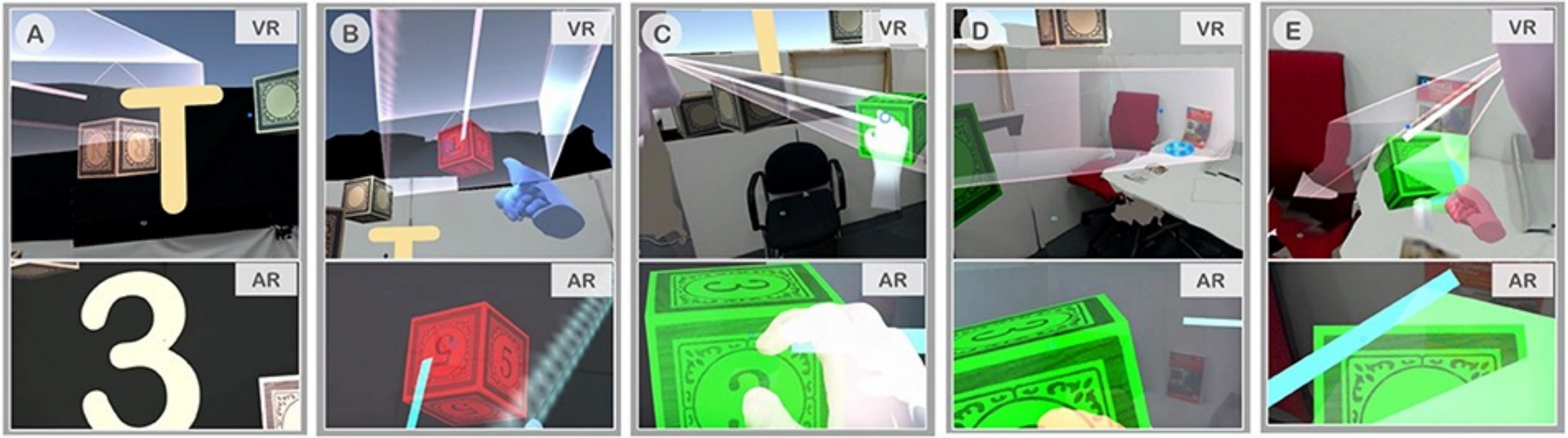
- Object identification
- Object placement

Designed to force collaboration

- Each person seeing different information



Task



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We reconstructed the environment on the AR side and shared it with the VR side for spatial reference.

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Measures

Performance Metrics

- Rate of mutual gaze (objects identified/min)
- Task completion time(seconds)

Observed Behaviours

- Number of hand gestures
- Physical movement (meters)
- Distance between collaborators (meters)

Subjective Surveys

- Usability
- Social presence
- Semi-structured interview

Measure type	Variable name	Key results
Performance metrics	• Rate of mutual gaze (objects identified/minute)	• Head-gaze and Eye-gaze had more rate of mutual gaze than Baseline
	• Task completion time (seconds)	• No significant difference
Observed behavior	• Number of hand gestures	• Head-gaze and Eye-gaze needed less hand pointing than Baseline
	• Physical movement (meters)	• Head-gaze required least physical movement in the scene
	• Distance between collaborators (meters)	• Eye-gaze condition had collaborators in closest proximity and Baseline had them most dispersed
Subjective surveys	• Usability	• Head-gaze was most easy to use and useful • Baseline and FoV were more confusing than Head-gaze
	• Social presence	• Baseline had least co-presence, others were similar • FoV had worst attention allocation ratings and Eye-gaze was best • Head-gaze had best perceived message understanding and perceived behavioral independence, baseline was worst in both
	• Semi-structured interview	• Head-gaze preferred mostly • AR users reported higher difficulty than VR users

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Data Collected

Participants

- 16 pairs = 32 people
- 9 women
- Aged 20 – 55, average 31 years
- Experience
  - No experience with VR (6), no experience AR (10), no HMD (7).

Data collection

- Objective
  - 4 (conditions) × 8 (trials per condition) × 16 pairs = 512 data points
- Subjective
  - 4 (conditions) × 32 (participants) = 128 data points.

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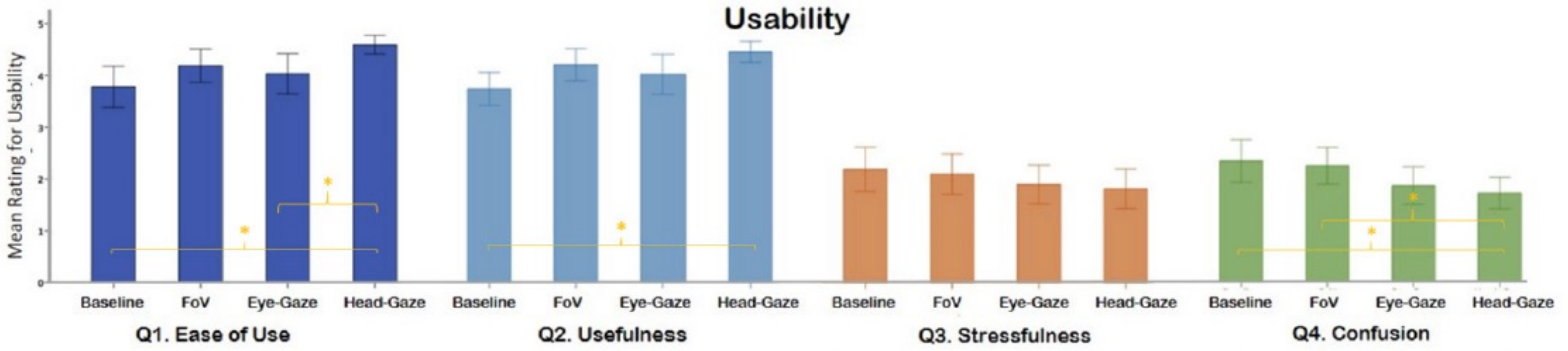

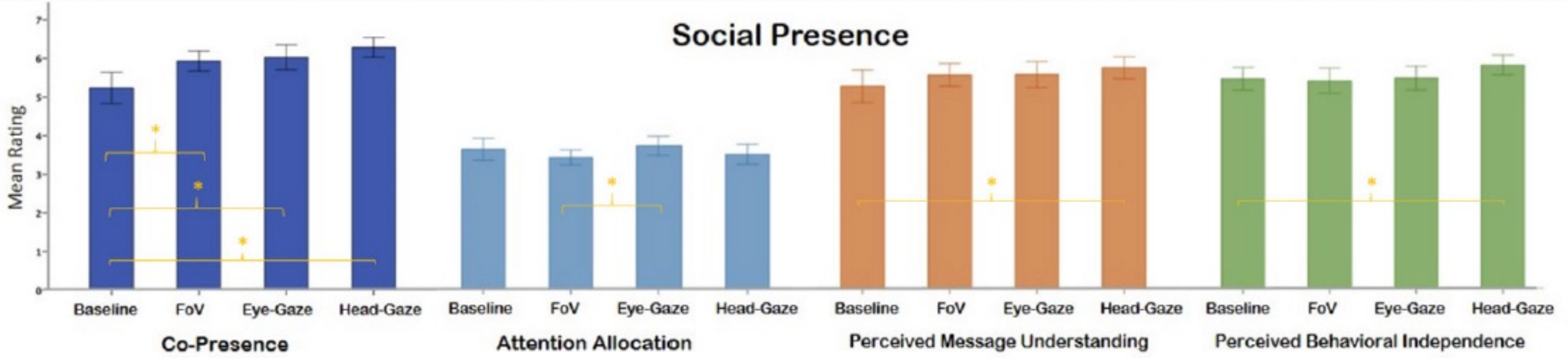

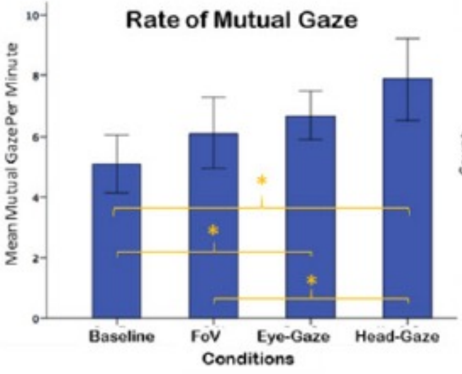

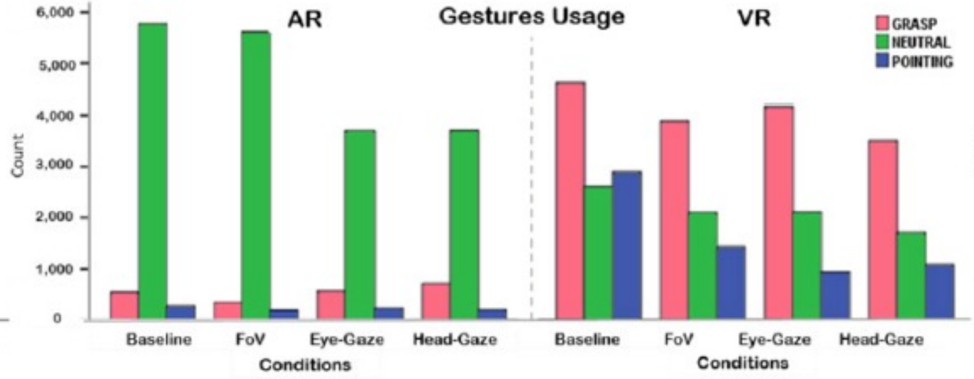

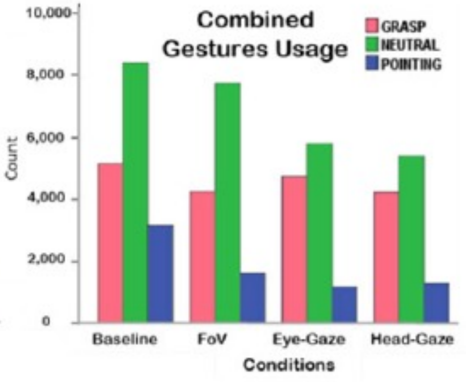

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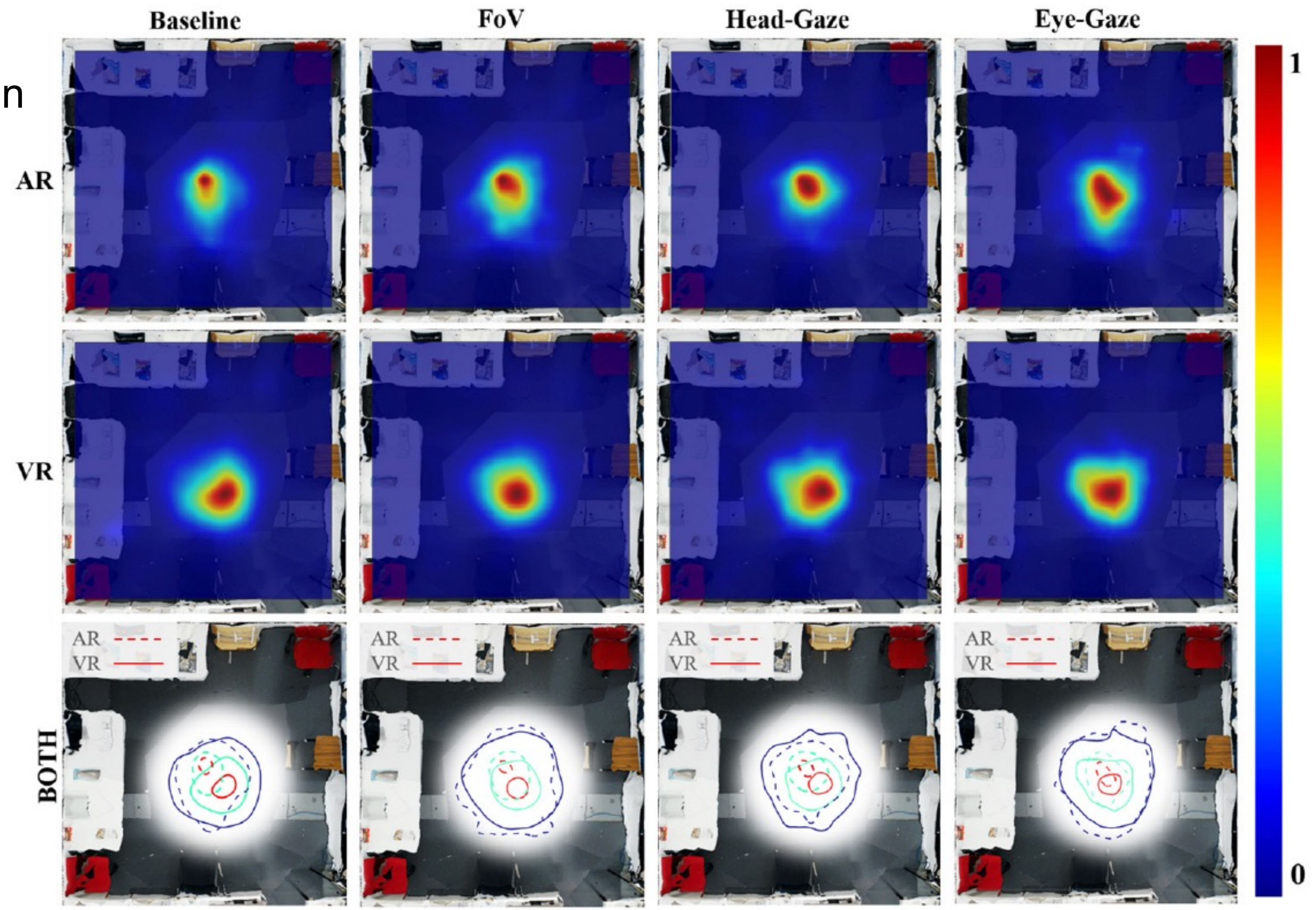
Motion Data

Map user x,y position over time



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Results

Predictions

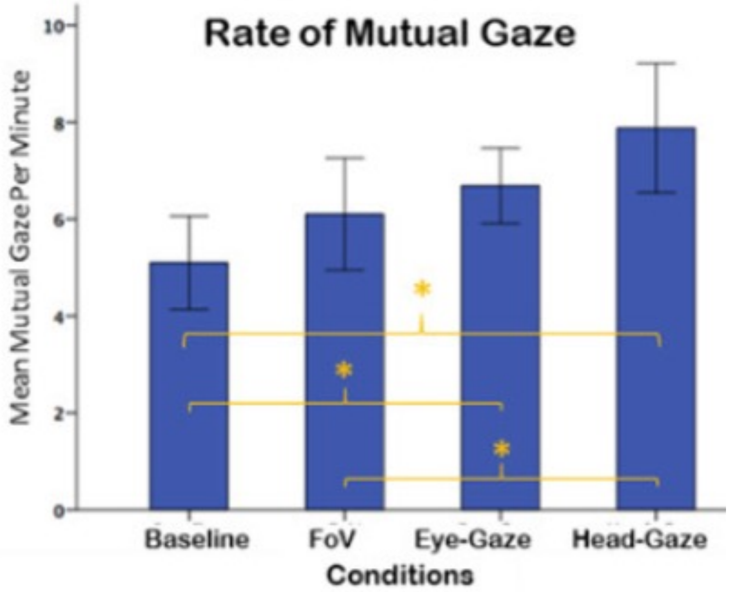
- Eye/Head pointing better than no cues
- Eye/head pointing could reduce need for pointing

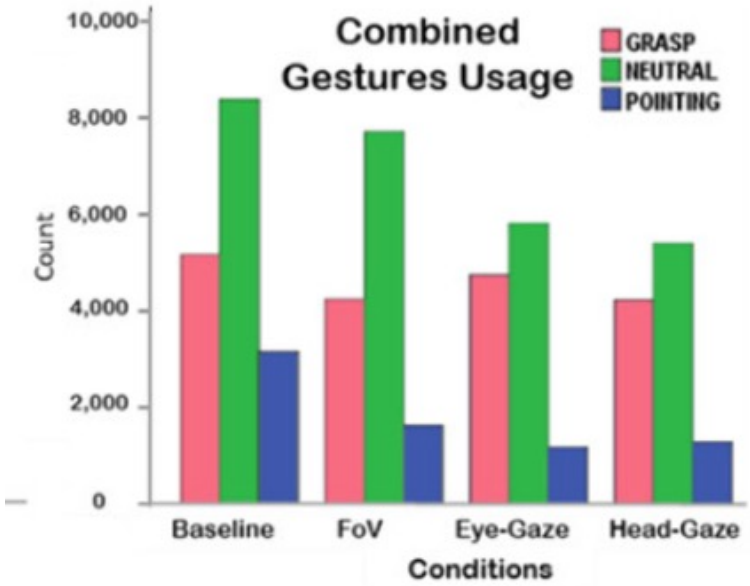
Results

- No difference in task completion time
- Head-gaze/eye-gaze great mutual gaze rate
- Using head-gaze greater ease of use than baseline
- All cues provide higher co-presence than baseline
- Pointing gestures reduced in cue conditions

But

- No difference between head-gaze and eye-gaze





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Using EEG for Adaptive VR Training

Motivation

- Making VR training systems adaptive in real-time to the trainee's cognitive load to induce best level of performance gain

Current VR training systems

- Don't adapt to user's cognitive load

Physiological measures

- Can measure cognitive load from EEG

Dey, A., Chatburn, A., & Billinghurst, M. (2019, March). Exploration of an EEG-based cognitively adaptive training system in virtual reality. In *2019 ieee conference on virtual reality and 3d user interfaces (vr)* (pp. 220-226). IEEE.

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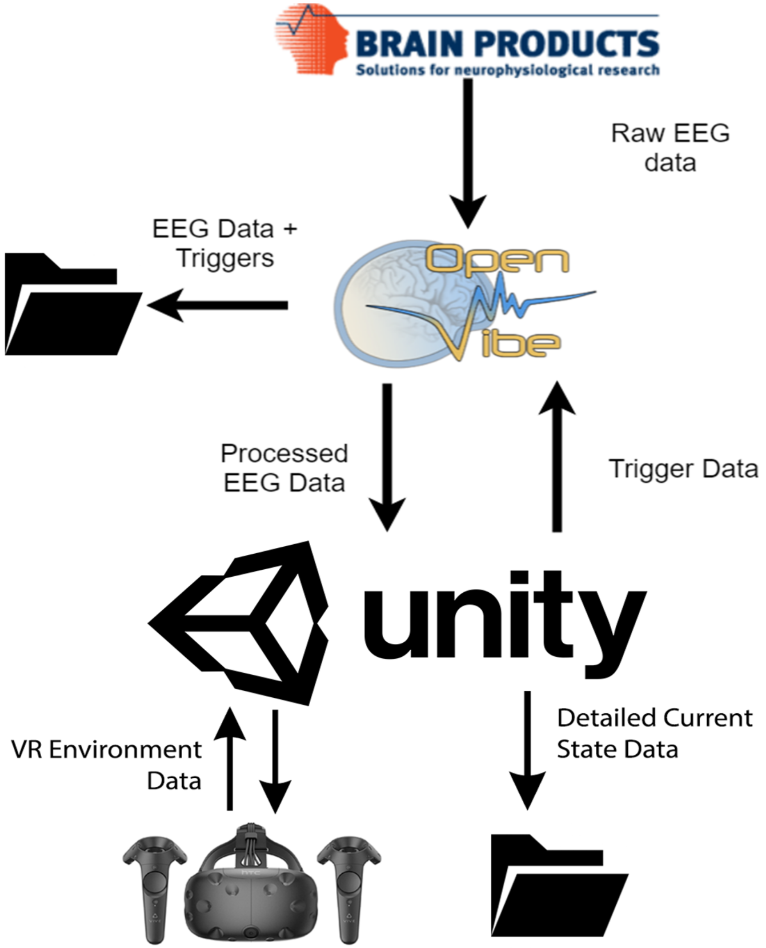
System



Oz, O1, O2, Pz, P3, and P4

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Adaption/Calibration

- Establish baseline (alpha power)
  - Two sets of n(1, 2)-back tasks to calibrate own task difficulty parameters
  - Measured alpha activity (task load) and calculated *mean* of the two tasks
  - Mean → Baseline
- In experimental task
  - load > baseline → decrease level
  - load < baseline → increase level

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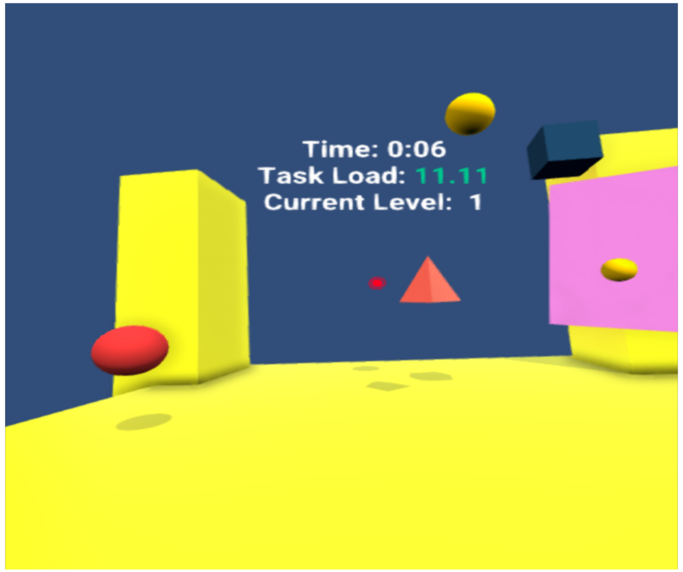
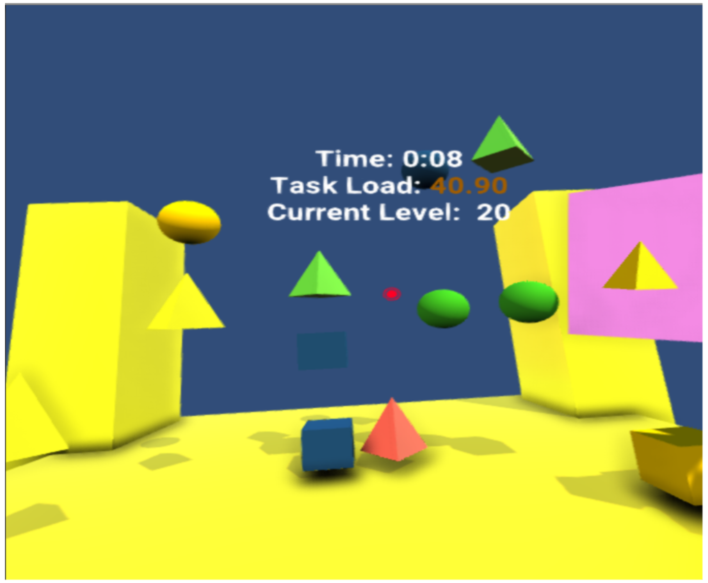
Experimental Task





Increasing levels (0 - 20)

Target selection

- number of objects, different colors
- shapes, and movement

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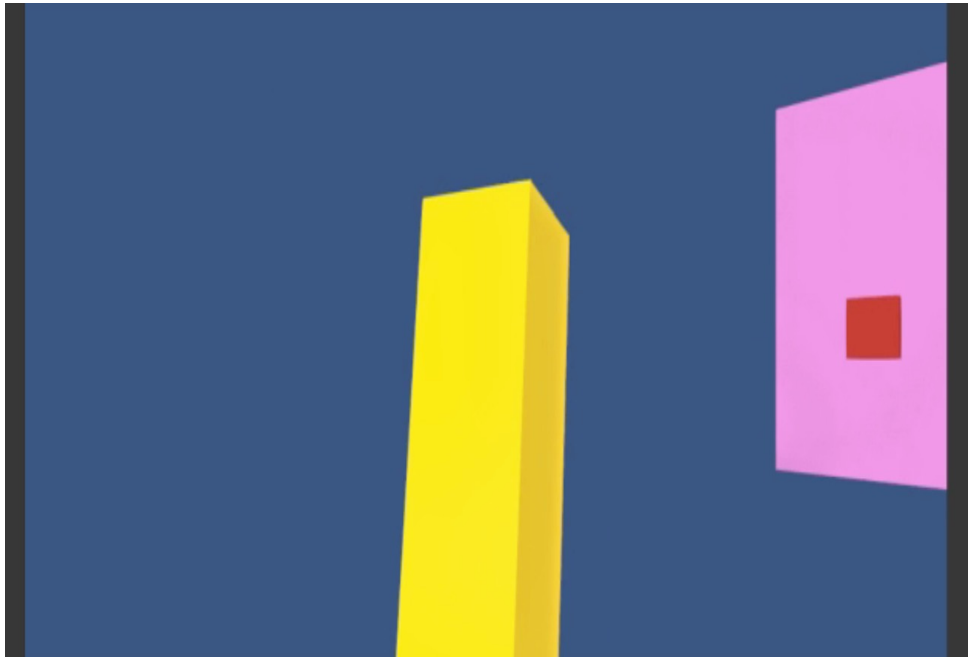
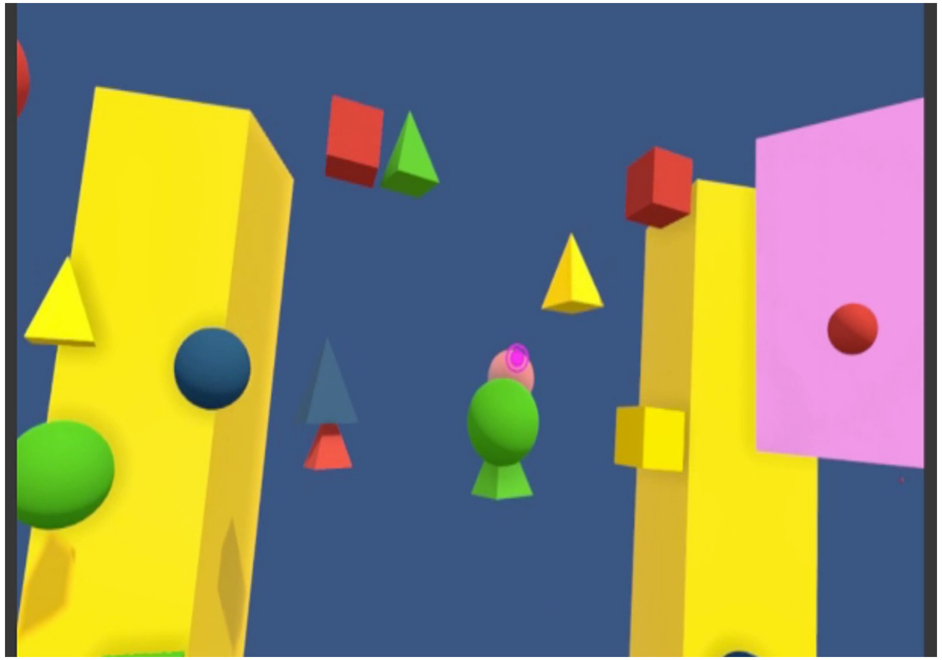
Experimental Task



Difficulty - Low



Difficulty - High

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User Study

- Participants
  - 14 subjects (6 women)
    - 20 – 41 years old, 28 years average
    - No experience with VR
- Measures
  - Response time
  - Brain activity (alpha power)

5 minutes fixed trial time

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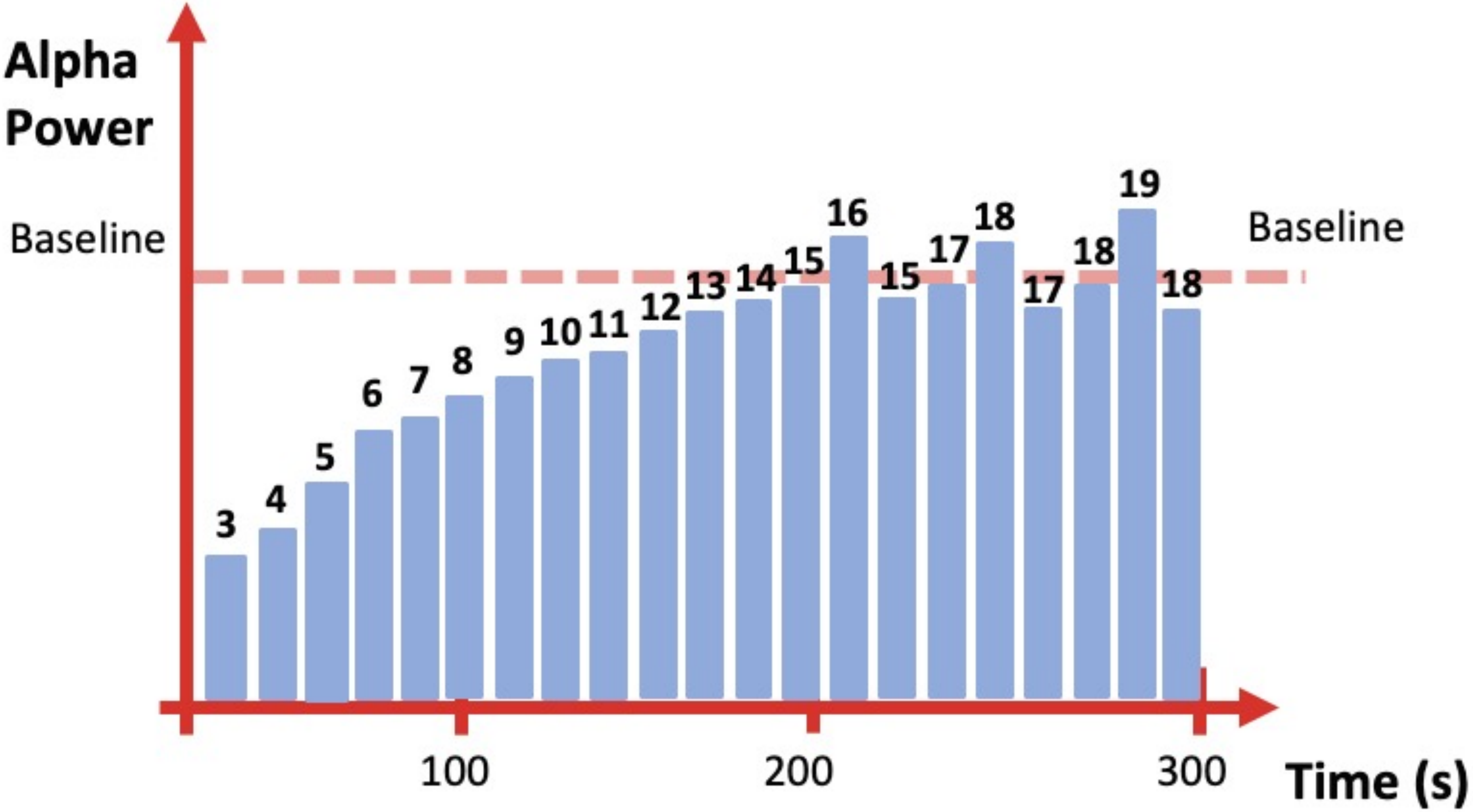
Adaption



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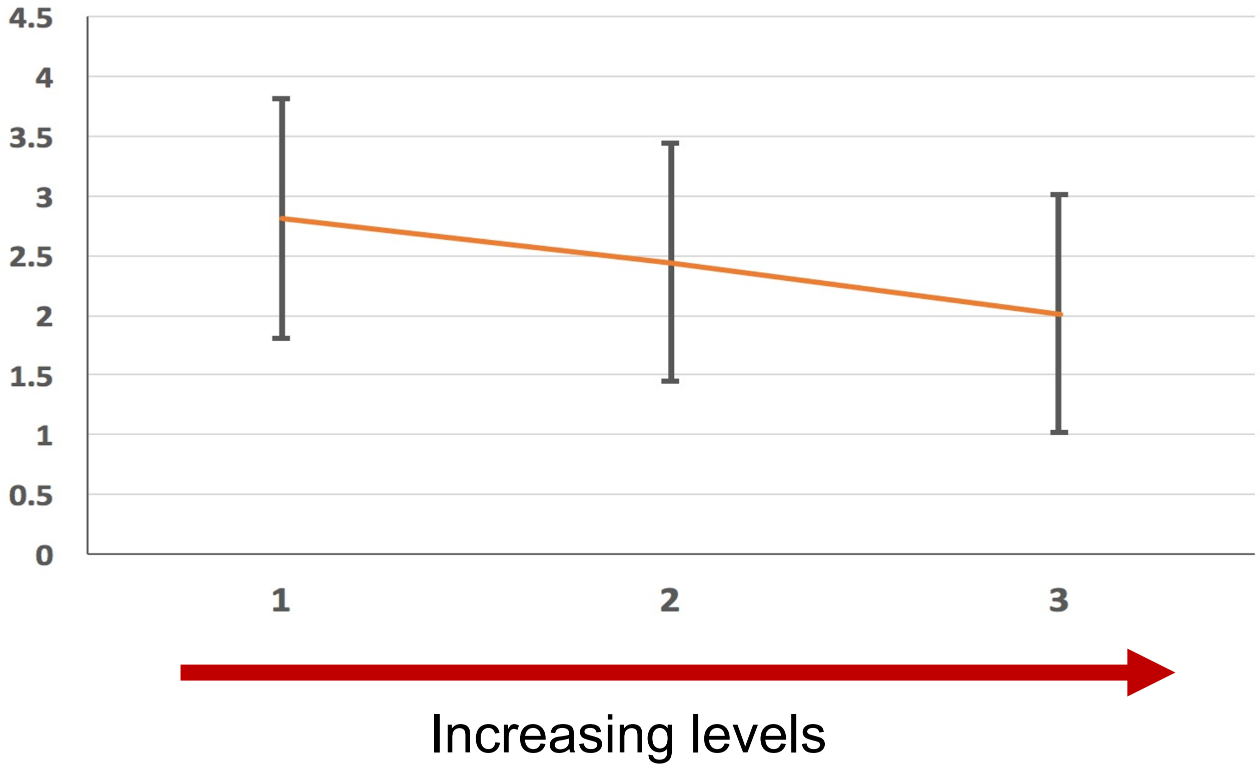
Results – Response Time



Response Time (sec.)

No difference between easiest and hardest levels

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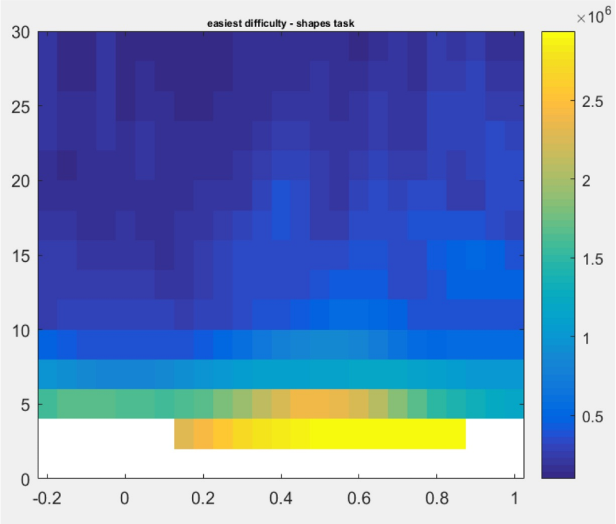
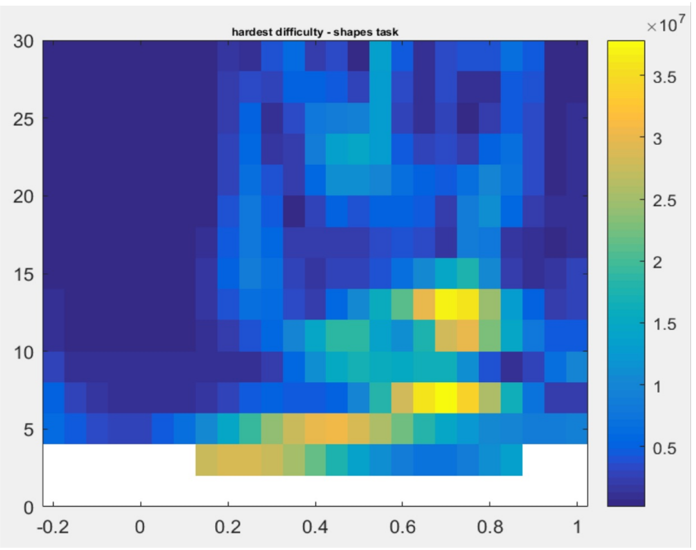
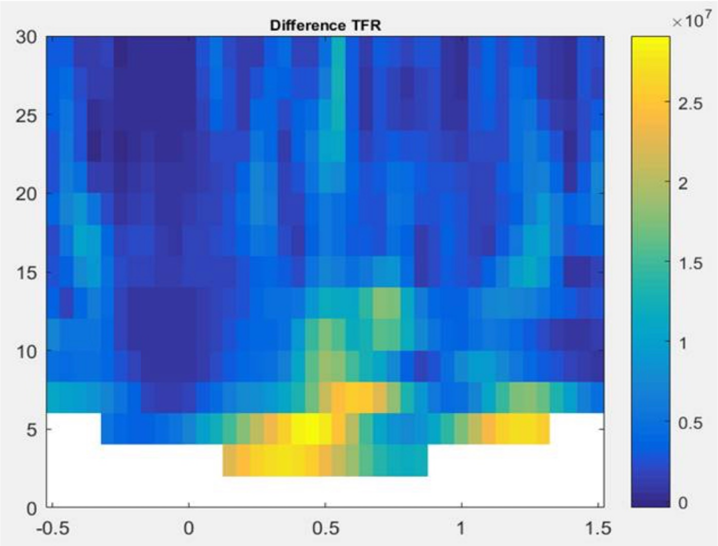
Results – Time Frequency Representation



Easiest



Hardest



Difference

Task Load

- Significant alpha synchronisation in the hardest difficulty levels of the task when compared to the easiest difficulty levels
- increased cognitive effort in higher levels to sustain performance

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Conclusions/Future Work

Conclusions

- Adaptive VR training can increase the user's cognitive load without affecting task performance
- First demo of the use of real-time EEG signals to adapt the complexity of the training stimuli in a target acquisition context

Future Work

- Significantly increase task complexity
  - Can predict user performance based on the cognitive capacity
- Using AR display
  - See real world and more distractors

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Understanding: Trust and Agents

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Many Agents require trust

- Guidance, collaboration, etc.

Would you trust an agent?

How can you measure trust?

- Subjective/Objective measures

According to AAA, **71%** of surveyed Americans are afraid to ride in a fully self-driving vehicle.

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Measuring Trust

How to reliably measure trust?

- Using physiological sensors (EEG, GSR, HRV)
- Subjective measures (STS, SMEQ, NASA-TLX)

Relationship between cognitive load (CL) and trust?

Novelty:

- Use EEG, GSR, HRV to evaluate trust at different CL
- Implemented custom VR environment with virtual agent
- Compare physiological, behavioral, subjective measures

Gupta, K., Hajika, R., Pai, Y. S., Duenser, A., Lochner, M., & Billinghurst, M. (2020, March). Measuring human trust in a virtual assistant using physiological sensing in virtual reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)* (pp. 756-765). IEEE.

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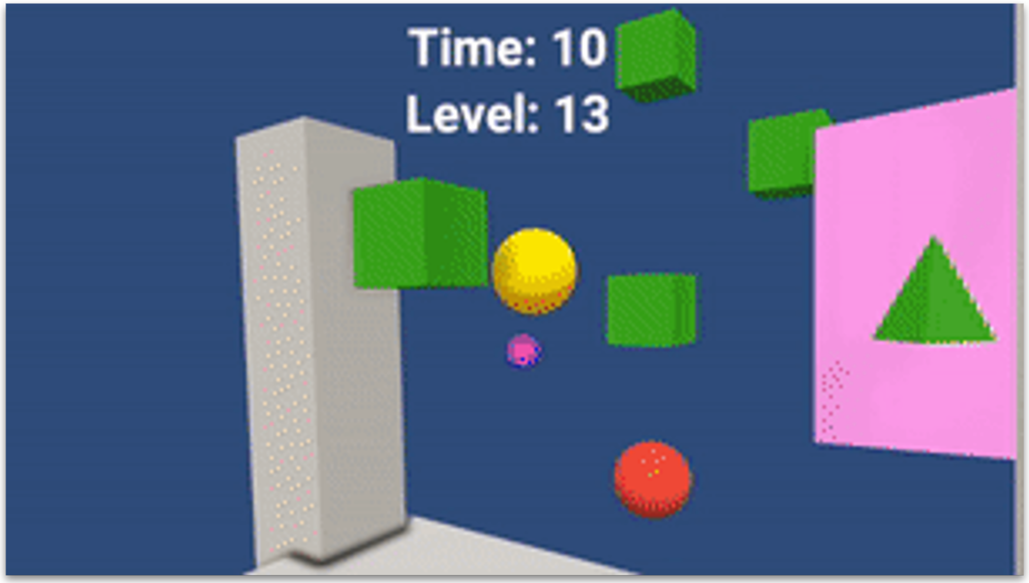
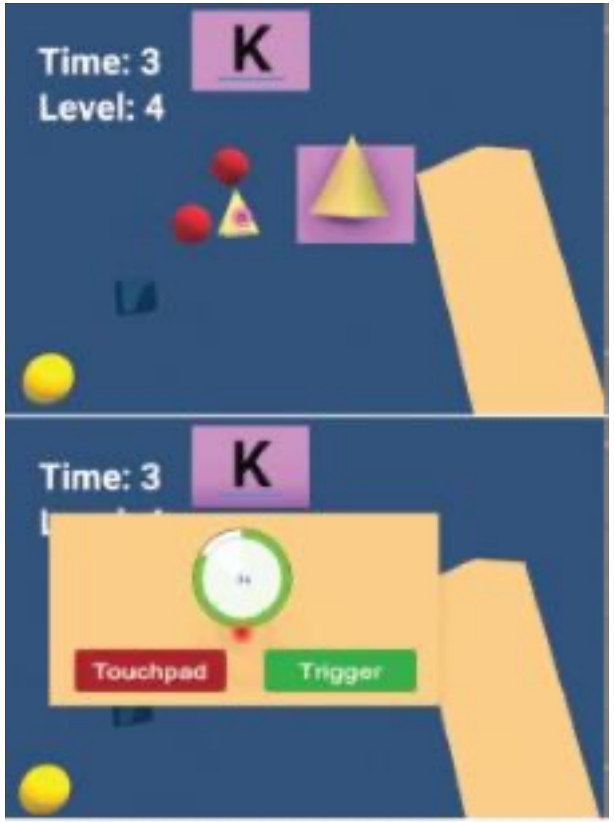
Experimental Task





Target selection + N back memory task

Agent voice guidance

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Experiment Design

Within Subject Design

- 24 subjects (12 Male), 23-35 years old
- All experienced with virtual assistant

Two factors

- Cognitive Load (Low, High)
  - Low = N-Back with N = 1
  - High = N-Back with N = 2
- Agent Accuracy (No, Low, High)
  - No = No agent
  - Low = 50% accurate
  - High = 100% accurate

	No VA	Low Accuracy VA	High Accuracy VA
Low CL	LCL-NOVA	LCL-LAVA	LCL-HAVA
High CL	HCL-NOVA	HCL-LAVA	HCL-HAVA

2 x 3 Expt Design

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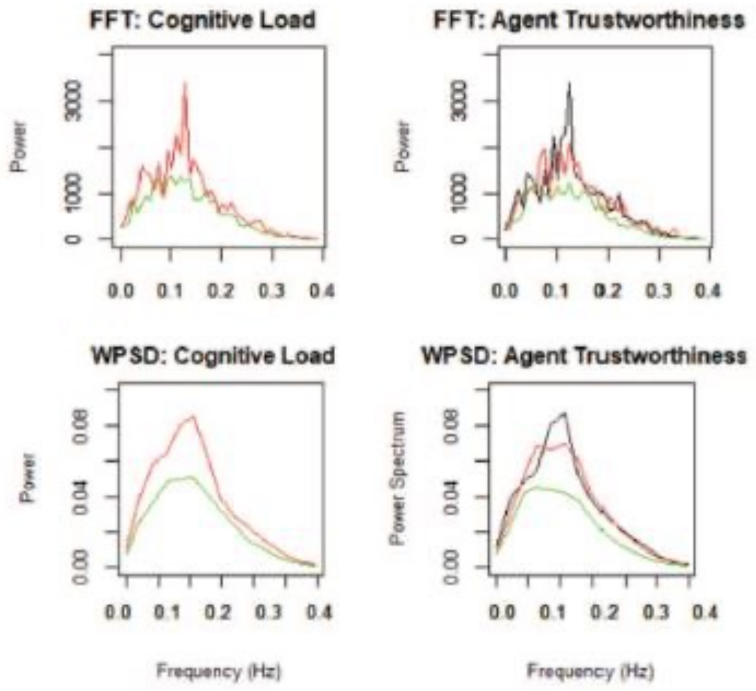
Results

Physiological Measures

- EEG sign. diff. in alpha band power level with CL
- GSR/HRV – sign. diff. in FFT mean/peak frequency



Performance

- Better with more accurate agent, no effect of CL

Subjective Measures

- Sign. diff. in STS scores with accuracy, and CL
- SMEQ had a significant effect of CL
- NASA-TLX significant effect of CL and accuracy

"I don't trust you anymore!!"

Overall

- Trust for virtual agents can be measured using combo of physiological, performance

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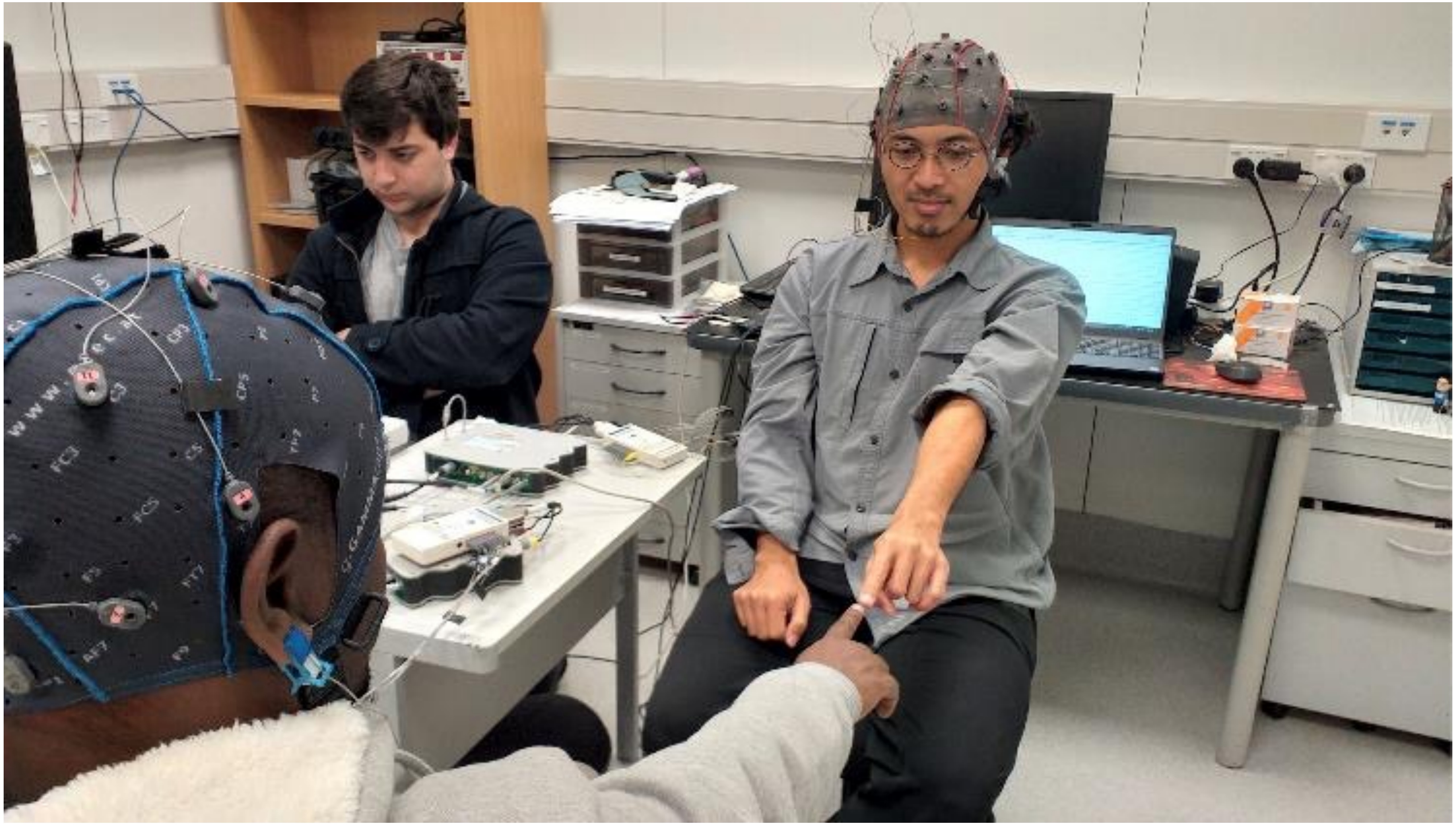
Brain Synchronization



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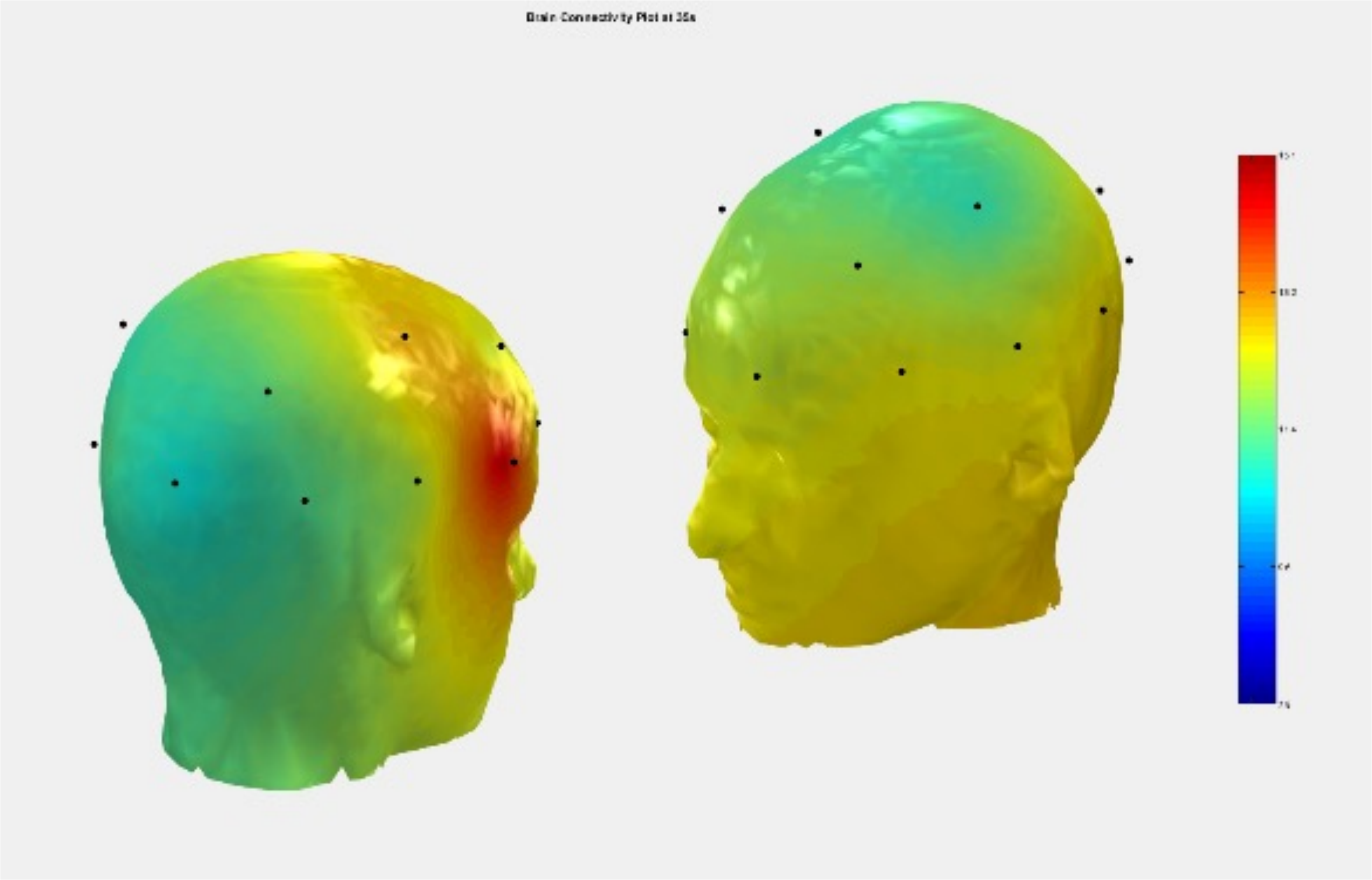
Pre-training (Finger Pointing) Session Start



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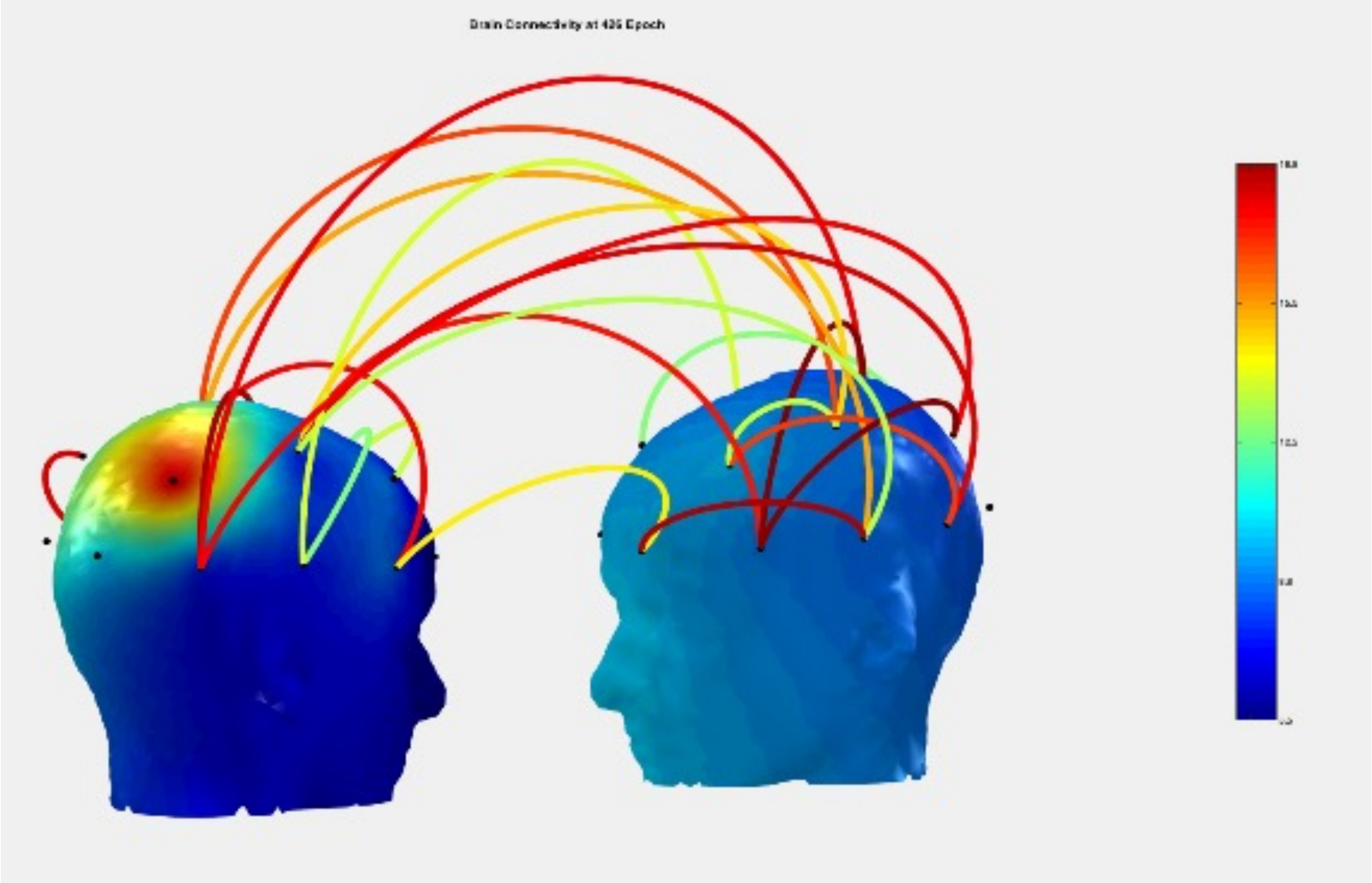
Post-Training (Finger Pointing) Session End



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Brain Synchronization in VR

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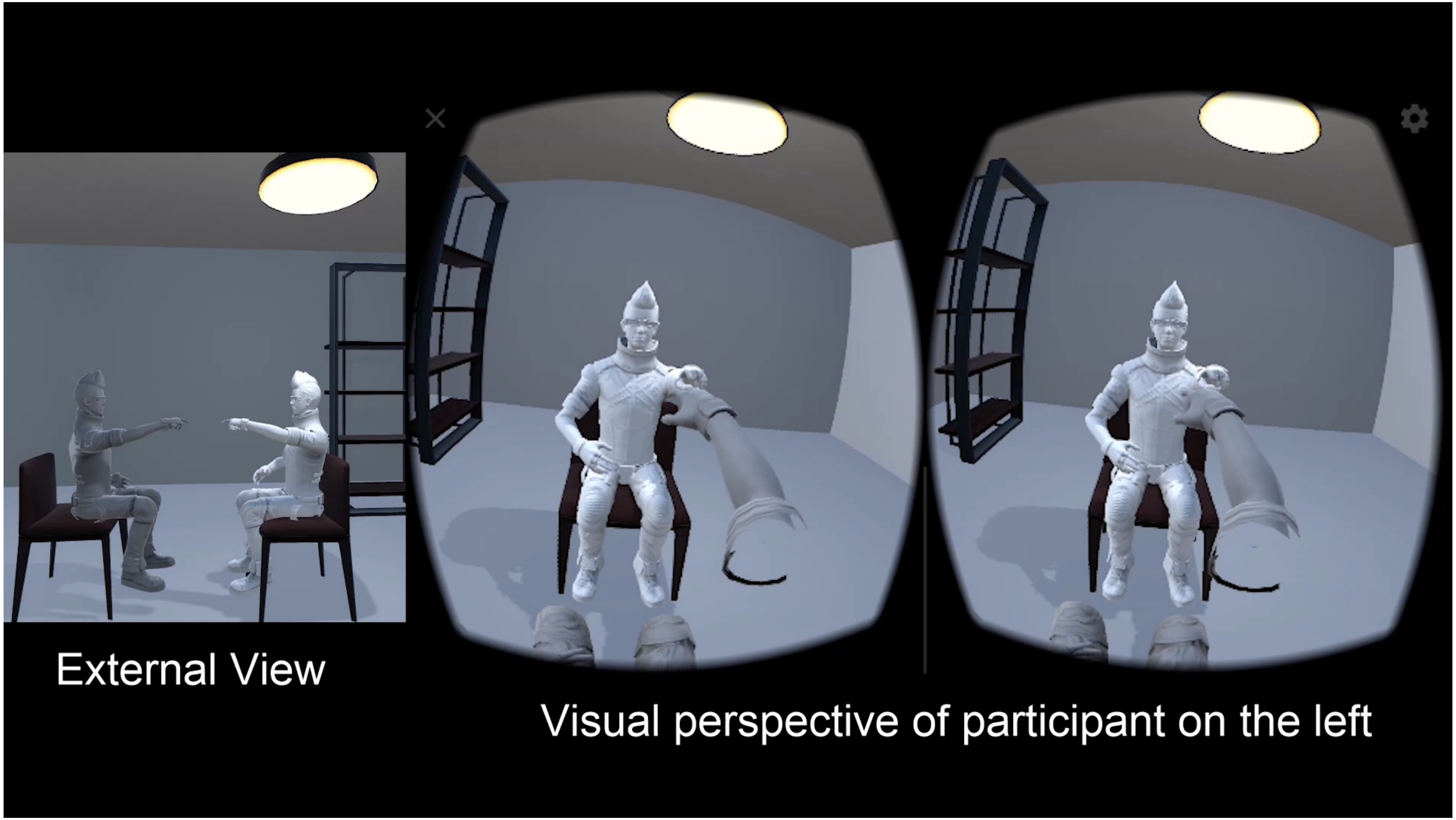

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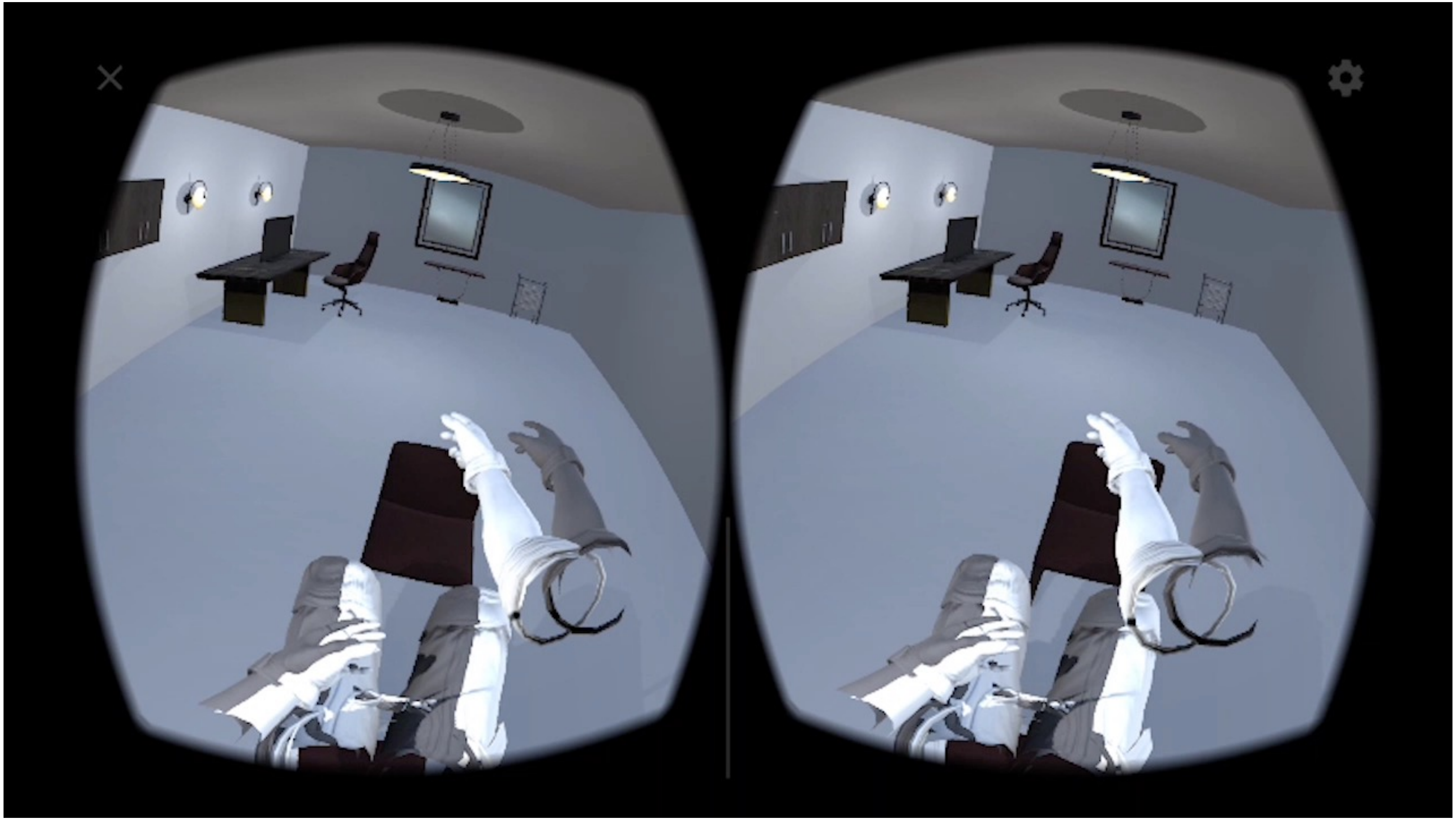

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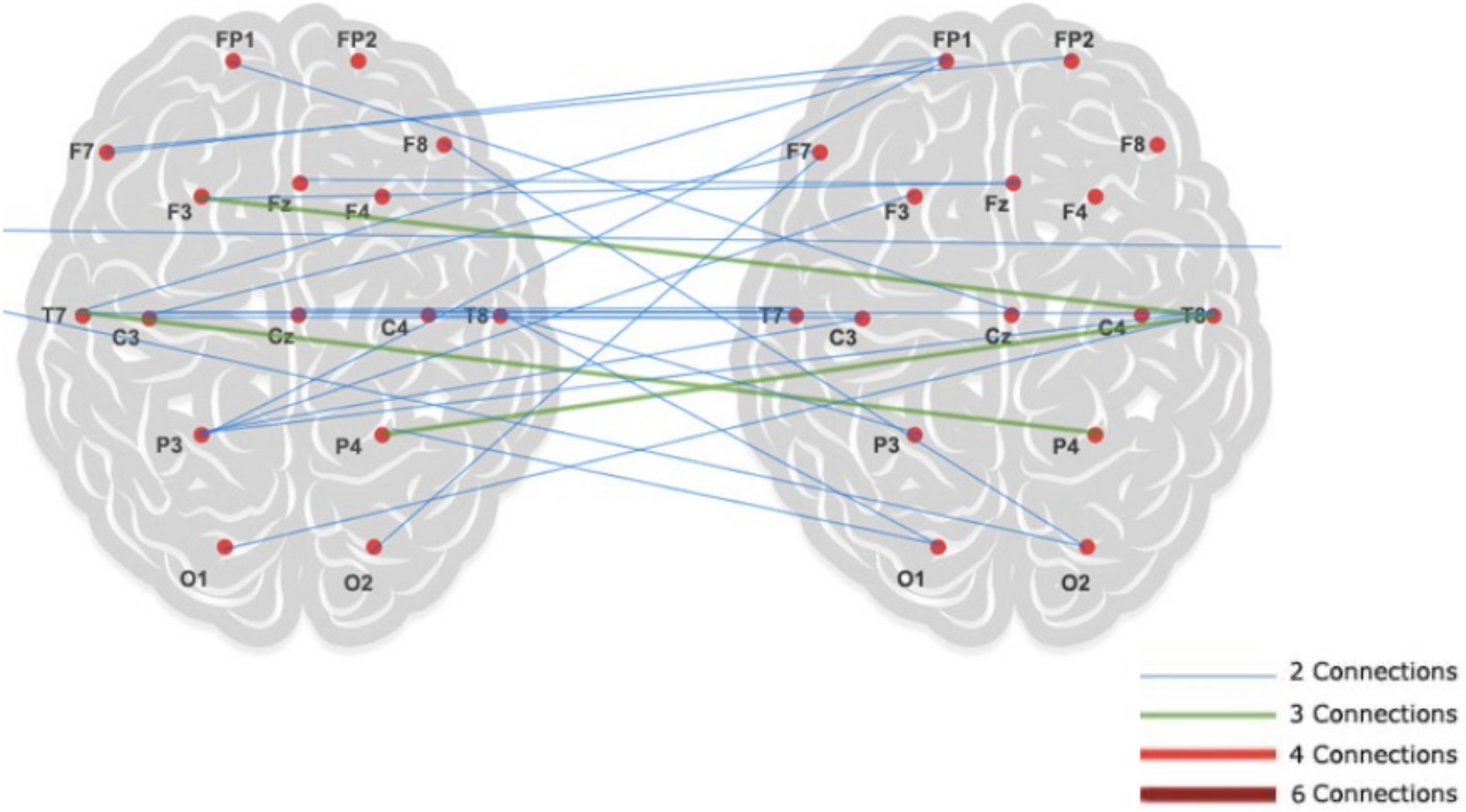
Beta Band - Pre-Training in VR FPP



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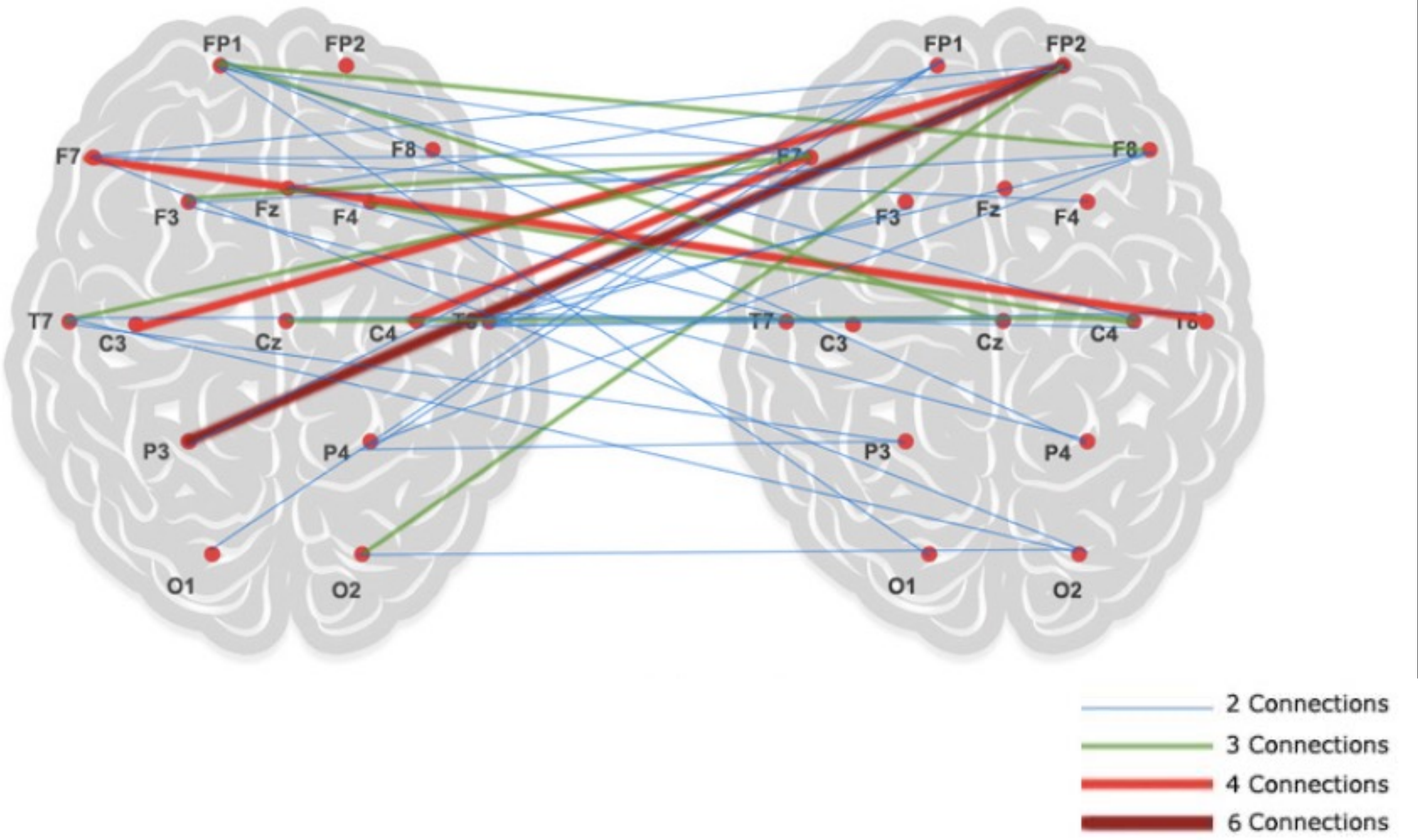
Beta Band Post-Training in FPP



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New Tools

New types of sensors

- EEG, ECG, GSR, etc

Sensors integrated into AR/VR systems

- Integrated into HMDs

Data processing and capture tools

- iMotions, etc

AR/VR Analytics tools

- Cognitive3D, etc

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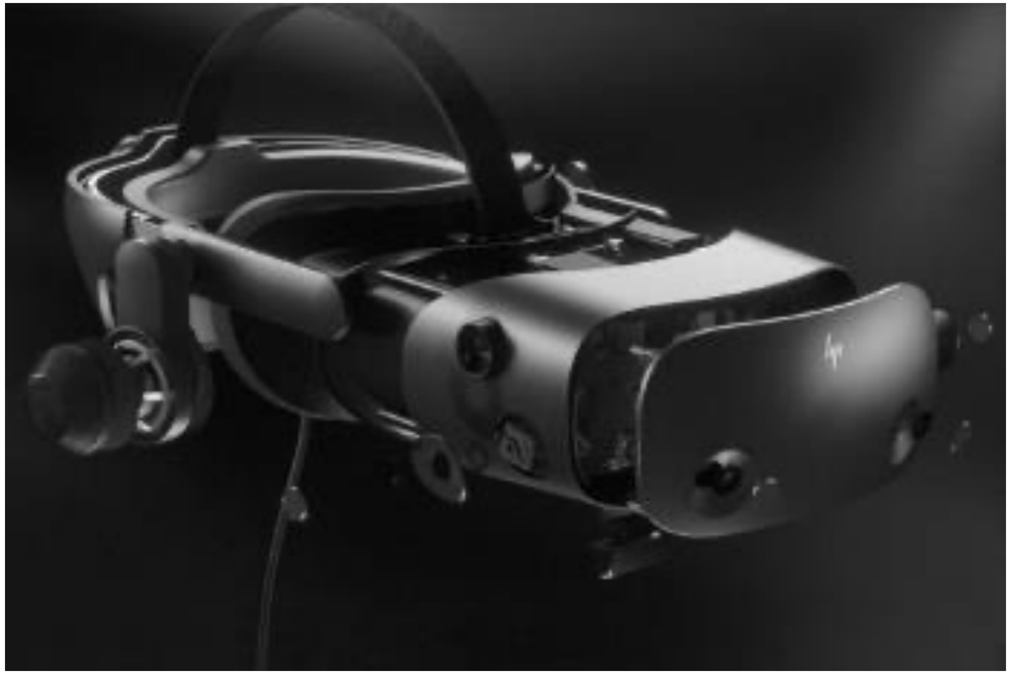
HP Reverb G2 Omnicept



Wide FOV, high resolution, best in class VR display

Eye tracking, heart rate, pupillometry, and face camera

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NextMind

EEG attachment for AR/VR HMD

9 dry EEG electrodes

https://www.next-mind.com/

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www.youtube.com/watch?v=yfzDcfQpdp0

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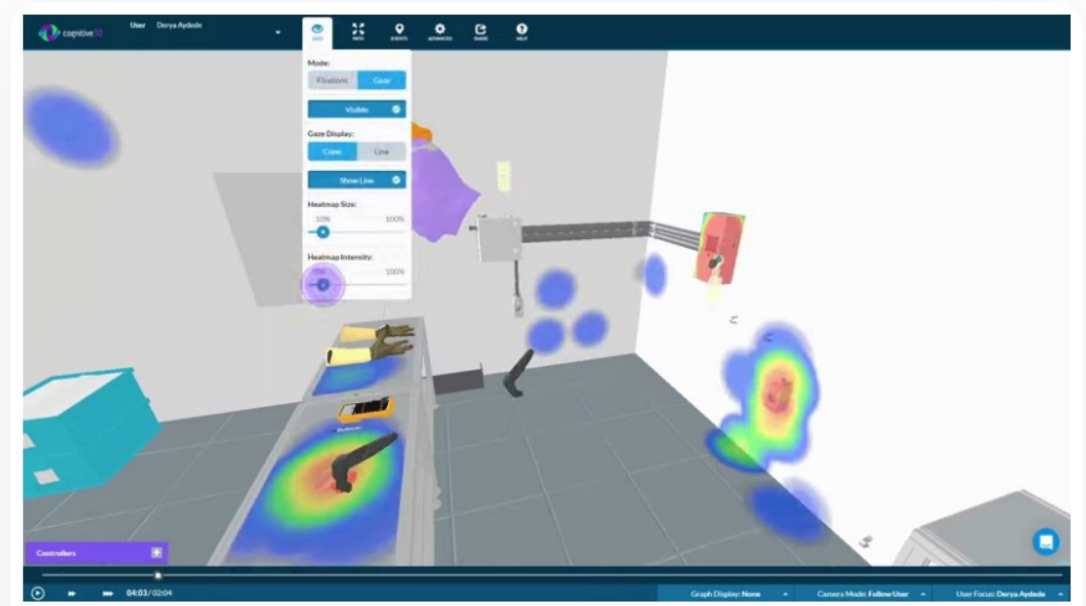
Cognitive3D



Data capture and analytics for VR

- Multiple sensory input (eye tracking, HR, EEG, body movement, etc)

https://cognitive3d.com/

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Cognitive3D Demo

https://www.youtube.com/watch?v=tlADFAGLED4

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Moving Beyond Questionnaires

Move data capture from post experiment to during experiment

- Move from performance measures to process measures

Richer types of data captured

- Physiological Cues
  - EEG, GSR, EMG, Heart rate, etc.
- Richer Behavioural Cues
  - Body motion, user positioning, etc.

Higher level understanding

- Map data to Emotion recognition, Cognitive load, etc.

Use better analysis tools

- Video analysis, conversation analysis, multi-modal analysis, etc.

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Research Opportunities

- Types of Studies
  - Need for increased user studies in collaboration
  - More use of field studies, natural user experiences
  - Use a more diverse selection of participants
- Evaluation measures
  - Need a wider range of evaluation methods
  - Establish correlations between objective and subject measures
- Better tools
  - New types of physiological sensors
  - Develop new analytics

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Conclusions

Most AR/VR user studies are limited

- Lab based, simple qualitative/quantitative measures

New opportunities for data collection

- Move from post-experiment to during experiment
- New sensors, analytics software

Many Directions for Future Research

- Data analytics
- Analysis methods
- Sensors
- Etc..

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