Effective Mitigation of Cognitive Load in Complex Mixed Reality Tasks

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Abstract: Little work has been undertaken to investigate the effects of a high cognitive load in Mixed Reality (MR) headsets or successful mitigation techniques to reduce its related cognitive burden, especially compared to strictly fully immersive VR settings. We explore the measurement and mitigation of cognitive load in MR environments through the deployment and analysis of a novel set of visual and haptic interventions aimed at optimising the user's experience and performance in complex tasks involving the use of proprioception. We conducted a study comparing fully immersive VR against pass-through enabled MR environments, employing focused blur, targeted lighting, targeted shadows, and haptic feedback to reduce cognitive load. Participants performed complex motor tasks in both environments for comparative measures, measuring cognitive load through standardized subjective scales, such as the NASA Task Load Index and Likert scales, mixed with electrodermal activity and electroencephalogram sensors. Results indicate that MR environments, augmented with tailored visual and haptic effects, demonstrate a reduction in cognitive load compared to their non-augmented states. These findings suggest that tailored visual effects within MR can offer a more conducive environment for task performance through the reduction of cognitive load.

1 INTRODUCTION

Virtual Reality (VR) and Mixed Reality (MR) show significant potential in the fields of education, healthcare, gaming, and corporate training, owing to their interactive and immersive capabilities not found in traditional 2d displays. Even with modern advances in headset capabilities, there remains challenges in managing cognitive load in these environments. (Juliano et al., 2020)

Headsets allow users to engage with digital environments in ways traditional media have not been capable of, offering quantifiable benefits in task performance and cognitive learning. (White et al., 2024).

Despite the potential of these technologies, the cognitive load they impose on users, especially during complex tasks, remains an important factor that can influence performance, retention, and engagement. Research undertaken in this domain space, primarily looking at fully enclosed VR environments, has explored the impacts of cognitive load on user experiences. (Belani et al., 2023)(Schrader and Bastiaens, 2012)

However, while much research has explored the cognitive impacts of fully immersive VR(Gabriel et al., 2018)(Dan and Reiner, 2017), there remains a notable gap in understanding how MR environments, leveraging new technologies such as full colour pass-through, cable-free usage, and recent software improvements, affect cognitive load. Especially in tasks requiring complex decision-making and motor coordination. In addition, there's been a distinct lack of approaches within MR research into how to measure both quantitative and qualitative methods to integrate effective mitigation strategies that reduce cognitive load and its associated cognitive burden. (Slater et al., 2022).

Cognitive load theory describes the term cognitive load. It suggests that the human brain is limited in its working memory capacity, with cognitive load referring to the mental effort required to process information, with excessive cognitive load impairing learning and task performance. (Orru and Longo, 2019) This is pertinent in VR and MR environments in which users generally process large amounts of visual, auditory and haptic information simultaneously, often over-

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whelming sensory input, hindering task performance and learning. (Armougum et al., 2019) (Rebenitsch and Owen, 2016)

Cognitive load is likely to be a consistent factor to address in headset environments as users continue to expand into increasingly complex and mentally demanding tasks in VR and MR, such as corporate training, education (Merchant et al., 2014), military and medical simulations (Qiu et al., 2022) and more ubiquitously data visualisation (Olshannikova et al., 2015), which requires processing increasingly complex forms of information and, therefore, puts further strain on user cognitive resources.

The interactive nature of VR/MR environments, whilst beneficial for presence and engagement, inherently introduce challenges by presenting users a high volume of sensory input to manage simultaneously. If this is not mitigated, cognitive overload will continue to impair performance, learning, and decision making in future applications.

We aim to address these challenges through the introduction of visual and haptic effects aimed at reducing cognitive load and, therefore, improving task performance. This experimental design represents a novel contribution to the field, comparing both MR and VR environments while exploring the effectiveness of multimodal sensory interventions in real-time mixed and virtual reality scenarios.

This research presents an innovative approach to addressing the persistent issue of cognitive overload in MR environments in an attempt to provide insight and methods that future development in VR and MR applications can leverage to aid in the development of immersive interfaces and user-centered applications.

2 RELATED WORKS

Here we review the current landscape of VR and MR respectively, looking into recent advancements in both hardware and software as well as recent innovations in assessing cognitive load and presence, identifying gaps in current VR/MR research.

Virtual and Mixed Reality: Modern innovations in headset development have started to reach a wider and more receptive market, bolstered by recent advances in headsets such as the Meta Quest Pro and Meta Quest 3. Mixed reality headsets have begun to gain popularity, market share, and general traction within the industry, as well as seeing new major competitors in the domain space, such as Apple with the launch of their flagship mixed reality headset, the Apple Vision Pro.

With these innovations, there have arisen new opportunities for expanding prior VR research into MR. Improvements in field of view, display latency, and resolution of headsets, paired with new software development kits for MR development from Meta, Apple, and Unity, have led to a breakthrough point for many in the industry, with previous limitations from headsets in terms of compute power, camera resolution, and bulky form factors of headsets seeing significant improvements.

Cognitive Load: This leap has revealed a gap in understanding the cognitive implications of using MR in complex motor tasks. Excessive cognitive load in these environments is a reoccurring issue, shown to be found in strictly VR environments through work by Juliano et al. (Juliano et al., 2020). Differing techniques have shown promise in measuring cognitive load in VR. Work from Dan et al (Dan and Reiner, 2017) investigates electroencephalogram (EEG) measures of cognitive load within VR, calculating cognitive load as the ratio of the average power of frontal theta and parietal alpha events in the occipital and temporal lobes.

Ahmadi et al. (Ahmadi et al., 2023) compounded these methods, combining EEG data with galvanic skin response (GSR) to record the cognitive load of users in a fully immersed VR setting.

We see more qualitative measures being used in the work of Armougum et al. (Armougum et al., 2019), measuring the impact of cognitive load through the recording of relevant factual and contextual information seen by the research participants, with a combined approach that employs the NASA Task Load Index with electrodermal activity data. The work of Armougum et al. suggests VR as a promising technique for cognitive load analysis.

Cognitive load is a term used in cognitive psychology. Early research by Fred Paas describes it as a multidimensional concept in which mental load and mental effort can be distinguished (Paas, 1992). It is a construct that refers to the amount of information our working memory can process at any given time.

Research by Sweller et al. identifies three types of cognitive load: intrinsic, germane, and extraneous (Sweller et al., 1998). Recent research demonstrates that when there is a high cognitive load in VR, there is a hindrance to learning (Juliano et al., 2020). The same research also posits that complex motor tasks in immersive VR increase cognitive load, decreasing motor performance compared to computer screen-based tasks. Consequently, where you find ways to reduce cognitive load, there is benefit in terms of memory retention (Gabriel et al., 2018), engagement (Belani et al., 2023), and presence (Slater and Wilbur, 1997).

Cognitive load is in relationship with the positive feelings of long-term memory function and the feeling of presence felt by a user (Huang et al., 2019). Moreover, it shows that lack of immersion, poor interface quality, high cognitive load, and overexerted mental effort can all be negative predictors of cognitive learning outcomes (Merchant et al., 2014). As such, evaluating cognitive load goes hand in hand with measuring presence when attempting to gain insight into improving reactions, engagement, and learning retention within an MR space.

Presence and Cognitive Load: Presence is an important concept in VR, it refers to the psychological state or perception of feeling in which a headset user feels as if they are actually "there" in the virtual or mixed environment, feeling as if you are physically present in a nonphysical world. It is a concept primarily explored through one of VR's highest cited papers by one of the areas most influential authors Mel Slater (Slater and Wilbur, 1997), further explored and evolved upon in their 2009 paper which argued that presence consists of three illusions referred to as place illusion (feeling as if you are in the location being depicted in VR), the plausibility illusion,(That events in the virtual simulations are really happening) and the illusion of ownership over the virtual body self represented by the participant (Slater, 2009). An update to that research, published in 2022 discusses mixed reality in the role of presence, stating that it is more complex than in VR due to the introduction of real-world objects.(Slater et al., 2022)

It directly mentions a need for visual software effects such as object occlusion, real world reflective light, virtual light, and shadows in order to preserve presence, which is argued to have no fundamental conceptual difference from VR. We address this gap in research through our experimental design and results. As a high feeling of virtual presence enhances a user's engagement, immersion, and learning outcomes but increases cognitive load, it is necessary to create mitigation strategies to ensure that such an increase in cognitive load does not potentially hinder learning.

There are natural human limitations to the amount of information items that we can process consciously in real time, long confirmed by historical research in the field of psychology (Miller, 1956), attempting to process items near or beyond this limit leads to an increase in cognitive strain. Reducing the amount of items in a users focus and using visual techniques to lead them towards objects in advance should, in theory, reduce the cognitive strain, and thus cognitive load that they experience.

This should improve learning outcomes and task performance through immersive environments and experiences that are cognitively manageable.

It is the researchers hypothesis that users can experience a measurable reduction in their cognitive load in MR and VR environments through the use of focused blur, targeted shadows, passthrough relighting, and general controller-based vibration haptic feedback when used in combination. It is further theorized that mixed reality is a more ideal environment to reduce cognitive load in complex tasks than fully immersive virtual reality.

Prior research into cognitive load in the VR space has led to a range of methods in order to capture and evaluate qualitative data and quantitative data, respectively, from experiments.

One of the more recent influential and cited papers in VR is that of Mahdi Azmandian's paper on Haptic Re-targeting (Azmandian et al., 2016). In this paper, valuable and insightful methods of measuring presence and engagement involve the use of VR-specific methods, such as the Witmer and Singers 21 question presence questionnaire (Witmer and Singer, 1998); as well as the recording of Likert scale responses (Likert, 1932).

Whilst the presence questionnaire is the appropriate and standard method for qualitatively measuring VR presence, the Likert scales are more appropriate to measure cognitive load and the feeling of engagement. Research into the influence of virtual presence on learning outcomes shows that higher levels of presence are associated with increased cognitive load, suggesting that as you're more immersed in the virtual environment the mental effort required to process and interact with the content also rises(Schrader and Bastiaens, 2012).

The same research also mentions that identifying strategies to keep learners' attention more on the learning materials within, and reducing cognitive load based on design without reducing virtual presence was a good area of concern for researchers, concluding that the effectiveness of strategies to reduce cognitive load without breaking virtual presence is an area for deeper research. There's also investigation into alternative methods than presence questionnaire's and Likert scales, such as using similar subjective scales such as the NASA Task Load Index (Hart, 1988) or an adapted version of the 9-point symmetrical category mental effort rating scale(Paas, 1992).

There is similarly further research on alternative methods as seen in Kim Ouwehands paper "Measuring Cognitive Load: Are There More Valid Alternatives to Likert Rating Scales?" (Ouwehand et al., 2021). However, there remains a gap in combining electrodermal, electroencephalogram, and subjective scales simultaneously in mixed reality; as such, we address this in our research through the combined approach of measuring in-software analytics, EEG and GSR for quantitative data and using the NASA-Task load index, Likert scales, and open user feedback for qualitative data tracking.

3 ENVIRONMENT DESIGN

Here we go over apparatus, recording measures and design of the virtual environment for our experiment.

3.1 Apparatus

We use a modern digital environment for the research, developed within the Unity 2022.3.38f1 game engine, rendered on a Meta Quest 3 headset in standalone mode (Not requiring the pairing of a desktop PC). The Quest 3's standard handheld controllers were used to facilitate interaction within the MR environment. User's have the ability to navigate the environment through locomotion based steering and teleportation based movement using the controller's thumb-sticks, with the direction of where the users head is facing corresponding to the forward direction in the environment.

3.2 Virtual Environment Aim

The experiment was designed to measure cognitive load and task performance through a motor task requiring rapid responses to visual stimuli and the use of proprioception. Within this environment, the user presses randomly illuminated targets as swiftly as possible with a number of visual or haptic interventions chosen via a toggle-able setting within the environment. This allows for controlled manipulation of task variables, allowing us to use different effect combinations in order to attempt to mitigate cognitive load experienced within the task.

3.3 Effects

To reduce extraneous cognitive load, the environment uses a variety of visual effects. Focused blur is applied to areas outside the users focal object, ensuring the illuminated target remains focused and blurring virtual objects not relevant to the task. In addition, targeted lights and shadows are used to further emphasize the active target, creating a visual contrast drawing attention to the desired focal object. Passthrough re-lighting is applied, allowing digital lighting to interact with the physical world seen by the participant, projecting light and shadows onto real world surfaces scanned via the headset. Haptic feedback, when enabled, is provided through controller vibrations when targets are pressed in an aid to reinforce user actions and helping make the experience more immersive. The combination of visual and haptic feedback aims to reduce distraction and thus cognitive load, allowing users to perform better under cognitively demanding situations.

3.4 Data Recording Measures

The Unity engine and experiment has been designed to record response times, engagement metrics and record results and interactions whilst the app is used in real time. These are stored and analyzed for comparison with different runs of the experiment in order to gleam insights into the differences in efficacy of differing effects. Electrodermal and electroencephalogram activity is recorded via PluxBiosignals 4 channel sensor kit, with separate electrodermal and electroencephalogram sensors. This is processed real time and exported post-experiment for post-processing in PluxBiosignals "Open Signal" software.

3.5 Virtual Environment

The environment itself consists of an application, booted through the Meta Quest 3's standard dashboard interface. Upon initialisation, the user is presented with 4 distinct visual objects, a wooden board, a large floating interactable red button that is connected to the board, a floating data panel displaying performance metrics and settings to the user and 3d representations of their handheld controllers.

The software settings are modified through the use of buttons on the handheld controller, allowing each individual visual effect to be toggled on or off. In addition, there is a button to swap between passthrough enabled MR mode and fully immersed VR mode. To start a run of the experiment, the user physically pressed the central red button with their controller, initiating a 5-second countdown before starting a round of the experiment.

A round consists of 30 seconds, in a round, the user in base difficulty will see 12 buttons spread around the wooden board, with 11 buttons being coloured grey to show they are in an inactive state. The remaining button becomes a singular lit up green button, this button is the target of most of our visual effects and considered the focal object. It is the aim of the user to press this green button, in which a random button out of the 11 inactive buttons will become green, and the previous green button turning to an inactive grey button, this will increase the users score by 1.

After 30 seconds are completed, the 12 buttons disappear and the user is once again presented with the familiar central red button, which can be used to begin a new round. Difficulty level, amount of buttons pressed, average response time and icons displaying what effects are active are displayed on a floating data panel to the left of the wooden board and within the eyeline of the participant. Each round generates a JSON file with the users performance metrics that is saved to the internal storage of the headset for later retrieval.

4 EXPERIMENT

This section includes details on the study design that involves participants, methodology, effects, equipment, and procedure.

Participants: In order to empirically assess the effects of cognitive load in both VR and MR, we recruited participants among students and staff from Queens University Belfast. A total of 15 participants signed up for our study. We did not provide compensation for completing the study and informed all participants that they could withdraw voluntarily at any time. The study was conducted after receiving ethical approval from the university.

Prior to the task, we asked each participant using a Likert scale questionnaire about how frequently they use VR headsets, whether or not they agree VR has a positive benefit to mankind, how knowledgeable they considered themselves in the area of VR, their age group and their gender identity.

Within the demographics of our participants, the majority of participants are in the 25-34 age group, representing 8 out of 15 participants, with the average experience score being 2.13 out of 5, indicating that most participants rarely or only sometimes use VR headsets. There is a fair gender balance of participants with 9 Male participants, 5 Female participants and one participant choosing “Prefer not to say”.

The data suggests a general sense of optimism about the effects of VR on mankind in participants and whilst perceptions do vary based on differing VR experience, knowledge levels, gender identities and age groups, no participant responded negatively to the question relating to whether they believed VR would have a positive beneficial effect on society.

Measuring Cognitive Load: This includes,

- Methods of qualitative measurement
  - **Cognitive Load :** Likert scales, NASA Task Load Index
  - **Mental Workload** : NASA-TLX
  - **Mental Effort**, **difficulty & Task comprehension** : Likert scale
  - **Overall Response and Additional Feedback** : Likert Scale Questionnaire.
- Methods of quantitative measurement
  - **Cognitive Load :** Electroencephalogram (Dan and Reiner, 2017) (Root Mean Square from frontal temporal lobe, μV). Electrodermal Activity via Galvanic Skin Response (Power Spectral Density, microsiemens/μS) (Buchwald et al., 2019).

The experiment investigates cognitive load and overall performance when performing a complex motor task in mixed reality; comparing it with the same environment but in fully immersive VR & then seeing how cognitive load can be reduced through visual effects applied within the environment.

Visual effects: The details include,

- Focused Blur: A real-time blurring effect able to blur specific objects so as to leave a “Focused object” un-blurred, essentially blurring everything you’re not supposed to be focusing on.
- Targeted Shadows: A real-time darkening effect, able to darken the scene with shadows apart from selected “Focused objects”, which remain unaffected by the shadows.
- Targeted Lighting: A lighting system in which the lights within the scene focus on the button required to be pressed, similar to the targeted shadows but using a virtual light system.

Non Visual Effects: This includes vibration haptic feedback, which is vibration-based controller haptics, with the ability to use custom profiles/haptics for further customisation.

Equipment: Quest 3 Headset , Development PC, Unity Engine 2022.3.30f1 , PluxBiosignals EEG Sensor, PluxBiosignals EDA Sensor, Opensignals for signal recording and post-processing.

Procedure: The task begins with the participant’s pre-study questionnaire addressed in the participants’ section prior. After this questionnaire is complete, the participant is provided with a brief training session, involving 3 practice rounds of the task in order to familiarise themselves with the controls and ensure comfortable understanding of the task and environment at hand.

After completion of the training session, the EEG and EDA sensors are attached. The EEG sensor consists of 3 electrodes, 2 of which are attached to the FP1 and FP2 locations using the international 10-20 electrode placement system, an internationally recognized method to describe and apply the location of scalp electrodes. The third electrode is placed at a location with low muscular activity and is used to filter movement-based artifacts from the output signal; this electrode is placed behind either the left or right earlobe.

The EDA sensor consists of two electrodes which were attached to the dominant hand index and middle finger of the participants. A brief signal test is performed to ensure that the electrode and device connectivity for both sensor types is valid and correct. The mode by default is in MR mode with no visual effects applied and we consider this our "Base" mode for mixed reality.

Once the settings are confirmed and sensor connectivity output checked, the participant is informed that the researcher will press the record button for the sensors, recording the sensor data to the "OpenSignals" platform, followed by which they directed to press the large red button visible within the environment to start a 30 second round of the game described as above in the environment design section "E, Virtual Environment".

Once the participants finish the round, the sensor recording is stopped and saved as 2 files, a raw .txt file output recording the raw values recorded by each sensor suite and a .h5 file recording the converted units, converted by the OpenSignals software to microvolts (μV) or microsiemens (μ S) for the EEG and EDA sensors respectively.

Following this, the participant is asked a 2 part per condition questionnaire, consisting of a 4 question Likert scale and a 6 question NASA-TLX, within the Likert scale participants are asked to rate the general difficulty of the task, the level of mental effort during the task, their confidence in understanding the objectives of the task, and whether or not they consider the task easier or harder than the base challenge for that particular environment type between MR and VR.

Initial rounds of the experiment are performed in MR mode without visual effects, followed by a round within fully immersive VR mode, similarly without visual effects. Subsequent rounds involved toggling 1 of 4 effect batches, each possible setting being tested over 2 rounds, one in MR mode and one in VR. The settings possibly chosen for toggle are the focused blur, targeted shadows and lighting, vibration haptics, and a full combination of each effect simultaneously.

In order to ensure that the order in which the conditions presented did not introduce bias within the results, the settings chosen were counterbalanced via randomized counterbalancing in order to ensure that each setting was tested in different sequences between trials. This allowed the researchers to ensure the consistency of the output data.

After the participant has completed either the full batch of available rounds, or in cases of limited participation time, any batch of rounds including both a MR and VR comparison, they are asked a final questionnaire as a simple Likert scale asking them to rate the clarity of instructions provided before the task, the perceived complexity of the game controls, the responsiveness of the virtual environment to their actions, and their overall satisfaction with the experience. The majority of the participants responded positively to all categories in this questionnaire.

5 RESULTS

This section presents the evaluation in two parts, qualitative and quantitative. The details are as follows:

Qualitative Analysis: The Qualitative data from the experiment is split into 3 categories, that being the pre-study questionnaire, the per-condition Likert scale, and the per-condition NASA-TLX.

Comparative analysis of the difference between VR and MR modes without visual effects enabled within these data revealed that participants generally found the base MR environment without visual effects to have a higher mental and physical demand compared to its fully immersive VR counterpart, indicating an increase in cognitive load within the MR mode. Participants also indicated higher levels of frustration in MR mode suggesting that mixed reality integration of real world elements adds layers of cognitive complexity to the task, this may introduce extraneous stimuli requiring additional mental effort to concentrate and increasing overall cognitive load.

The necessity for the participant to discern virtual information amongst real-world surroundings could explain the increased cognitive and emotional burden reported by participants. The mean NASA-TLX scores and the mean response scores of the Likert scale for VR and Mr modes and their comparisons can be seen in Table 1.

Comparison of the Likert scale scores show that MR mode elicits a greater feeling of general difficulty and mental effort, this is seen similarly within the data from the NASA-TLX scores.

Comparison of the mean NASA-TLX scores be-

Table 1: Comparison of Mean Scores for BASE Mode between MR and VR

Measure	**MR Mean**	**VR Mean**	**Difference**
	Likert Scale Scores		
Q1. Difficulty	1.64	1.50	+0.14
Q2. Mental Effort	2.62	2.36	+0.26
Q3. Confidence	1.07	1.00	+0.07
Q4. Comparison	N/A	N/A	N/A
	NASA-TLX Scores		
Mental Demand	7.00	4.71	+2.29
Physical Demand	5.07	4.29	+0.78
Temporal Demand	9.36	8.79	+0.57
Performance	4.50	3.29	+1.21
Effort	7.43	6.93	+0.50
Frustration	5.64	3.14	+1.50

Table 2: Comparison of Mean Scores for FULL COMBINATION Mode between MR and VR

Measure	**MR Mean**	**VR Mean**	**Difference**
	Likert Scale Scores		
Q1. Difficulty	1.27	1.43	-0.16
Q2. Mental Effort	2.00	2.00	+0.00
Q3. Confidence	1.00	1.14	-0.14
Q4. Comparison	1.93	2.36	-0.45
	NASA-TLX Scores		
Mental Demand	3.80	4.71	-0.91
Physical Demand	4.20	4.43	-0.23
Temporal Demand	8.20	9.43	-1.23
Performance	1.93	2.79	-0.86
Effort	5.07	5.21	-0.14
Frustration	3.27	4.50	-1.23

tween VR and MR base modes shows a clear increase in mental, physical, and temporal demands, performance, effort, and levels of frustration when experiencing the task in mixed reality.

Similar trends are measured in runs including variations of all possible visual and haptic effects, this is to the notable exclusion of the full combination of effects, which is found to be overwhelming in fully immersive VR but positively mitigating cognitive load in mixed reality; however, on task runs with effects enabled, the additional question “Do you consider this task easier or harder than the base challenge” is put forward to the participant, with available answers being either 1) Much easier, 2) Easier, 3) No difference, 4) Harder and 5) Much harder. As such, when calculating the mean scores for this question, any mean score below 3 indicates a positive reduction in effort compared to no effects.

It can be seen in both comparison mean scores that the full combination of visual effects reduces the participants perception of difficulty, and by extension,

Table 3: Comparison of Mean Scores for BLUR Mode between MR and VR

Measure	**MR Mean**	**VR Mean**	**Difference**
	Likert Scale Scores		
Q1. Difficulty	1.90	1.75	+0.15
Q2. Mental Effort	2.67	2.29	+0.38
Q3. Confidence	1.00	1.00	+0.00
Q4. Comparison	2.80	2.75	+0.05
	NASA-TLX Scores		
Mental Demand	7.80	7.63	+0.17
Physical Demand	6.40	6.62	-0.22
Temporal Demand	9.70	12.00	-2.30
Performance	5.30	3.75	+1.55
Effort	8.20	7.13	+1.07
Frustration	6.60	7.13	-0.53

cognitive load within the task environment, this trend persists in both VR and MR mode indicating the effectiveness of a combined battery of visual effects in increasing focus and task performance. This can be observed in Table 2.

This is found to be the case for the majority of effects when used in isolation; however, there is a notable exception to this rule, that being that the use of the targeted blur effect in MR mode seemed to negatively affect difficulty and mental effort and thus being found to be cognitively hampering performance.

The data in Table 3 indicate that blur mode was significantly more challenging for participants in MR compared to its VR counterpart, an increased cognitive load was experienced in both NASA-TLX and Likert scale responses.

The NASA-TLX assessment reveals a surge in mental demand, physical demand, and effort, showing greater processing demand and a higher perception of physical stress. The frustration experienced by the participants more than doubled in VR (7.13), an increase of 3.99 compared to the base, relative to MR (6.60), an increase of 0.96.

MR environments inherently demand a higher cognitive load than virtual reality environments due to the need for people to continuously process and integrate information from both real and virtual worlds simultaneously (Juliano et al., 2020), within the NASA-TLX results, it is reported that the blur effect contributes to overwhelming the participant in MR mode, reducing overall performance in the task.

A breakdown of mean scores for the NASA-TLX for each individual visual effect can be seen in the chart below, an increase in effort for the blur mode is observed; however, this is mitigated when all effects are applied in combination, with the full combination of effects showing a consistent lower cognitive load in all categories reported by participants in NASA-TLX, as shown in Figure 1.

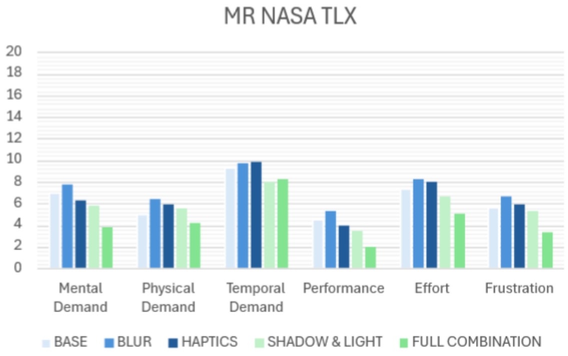


Figure 1: An illustration of MR NASA TLX.

Individual effects have different rates of efficacy in reducing cognitive load. The primary effect with the largest reduction is targeted shadow's and lighting, with a mean of 5.8, down from the base mean of 6.5. Although, a greater overall reduction is confirmed when using a full combination of each visual effect, showing the largest reduction with a mean NASA TLX score of 4.4, this trend continues within the Likert scale responses, as shown in Figure 2.

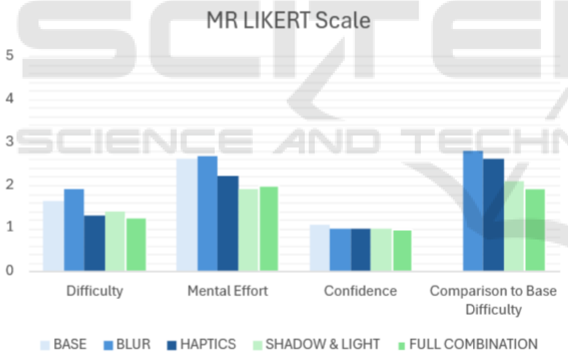


Figure 2: An illustration of MR LIKERT Scale comparison.

Likert scale data confirm a reduction in the perception of cognitive load with lower mean scores for every visual effect setting; this is in contrast to the NASA-TLX data on the targeted blur setting as it shows a positive perception of decreased cognitive load for all settings outside the base setting as well as a consistent below 3 average for the question relating to whether or not the participant found that mode easier or harder than the base task.

From this we can see clearly that the full combination of effects has a substantial reduction in the perception of difficulty and mental effort. In being asked to compare the full combination mode against the base challenge in MR, no participants responded harder or much harder, with 6 finding it easier, 5 finding it much easier and 4 finding no difference, a clear reduction in qualitative data-related cognitive load.

Delving into the comparison of the base mode to full combination of effects further can be seen in Table 4, within these data we can see in the Likert scale data a statistical reduction in difficulty, mental effort, and overall increase in confidence in objectives, as well as a significant reduction in mental demand, temporal demand, and physical demand as well as increased perception and confidence in performance, a reduction in the perception of required effort to achieve that performance and an overall general feeling of lower frustration, showing clear benefits in adopting visual focus aids and haptic feedback in MR tasks.

Table 4: Comparison of Mean Scores for MR Runs

Measure	Base	Full Combo	Difference
Likert Scale Scores			
Q1. Difficulty	1.64	1.27	+0.38
Q2. Mental Effort	2.62	2	+0.62
Q3. Confidence	1.07	1	+0.07
Q4. Comparison	N/A	1.93	N/A
NASA-TLX Scores			
Mental Demand	7	3.8	+3.2
Physical Demand	5.07	4.2	+0.87
Temporal Demand	9.36	8.2	+1.16
Performance	4.5	1.93	+2.57
Effort	7.43	5.07	+2.36
Frustration	5.64	3.27	+2.38

Quantitative Analysis: Quantitative data from the experiment consists of combined electroencephalogram and electrodermal activity sensor data, recorded in microvolts and microsiemens, respectively. Initial results show for the most part similarity to the qualitative data, with trends across the data indicating a reduced cognitive load for all effects and their combination in mixed reality.

Table 5: EEG average measures over all runs : Base vs Full Combination

Measure	Base	Full Combo	Difference
EEG (Channel 1) Measures			
MEAN (μ v)	0.08	-0.0215	+0.1015
MIN (μ v)	-35.85333333	-35.27541667	-0.5779
MAX (μ v)	35.83475	35.83375	+0.0010
STD (μ v)	13.89216667	12.93483333	+0.9573
RMS (μ v)	13.895	12.93566667	+0.9593
AREA (μv^2)	9221.771833	4584.789333	+4636.9825

The electroencephalogram data are recorded in a raw format, converted via bioplux opensignals software into microvolts, and then processed into 6 metrics. These include the mean values, the minimum, maximum, standard deviation, root mean square and the area. All are in microvolts apart from the area, being microvolts squared, as shown in Table 5.

Comparison between the mixed reality base mode and the mixed reality mode with the full combination of effects enabled shows a reduction in all metrics excluding the minimum, indicating that a reduced cognitive load was achieved for participants, with root mean squared values showing a reduction of 0.96, the mean by 0.1 and the area by 4636.

Root mean squared values are used in analysis of electroencephalogram data, they represent the magnitude or power of EEG signals; the higher the RMS, the stronger the brainwave activity, allowing for direct comparison of average signal power across the different visual and haptic conditions. As microvoltage scales and vary between individuals, root mean square values allow for the comparison of signals in a normalised manner. A reduction in these values for the full combination run in mixed reality indicates a high probability that cognitive load has been reduced.

In contrast, in regards to our EEG signals (Figure 3), the area is the combined sum of signal values of a period, a lowered area in the combined average of experiment runs suggest brain activity was weaker, less sustained or both, indicating reduced cognitive load as conditions with a lower area involved will have fewer or smaller peaks in signal over time.

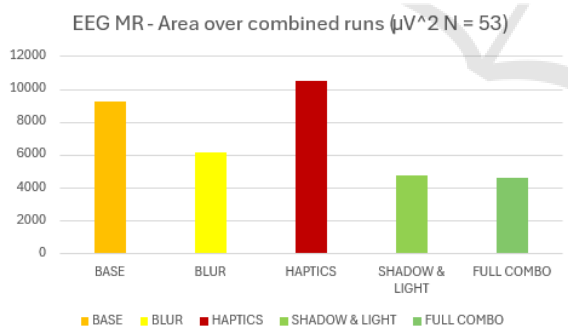


Figure 3: Area over combined runs for EEG MR ($\mu V^2, N = 53$).

We can see a reduction in area for the EEG data in all experimental conditions excluding haptics. Electroencephalogram signals oscillate between positive and negative values; our area values for haptics indicate high peaks and valleys in the oscillations of the recorded signal data, however, our mean values for haptics show a large reduction, significantly more than any comparison mode, meaning the brain activity recorded fluctuated more symmetrically around zero.

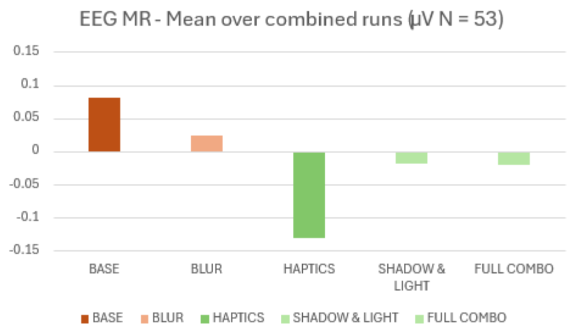
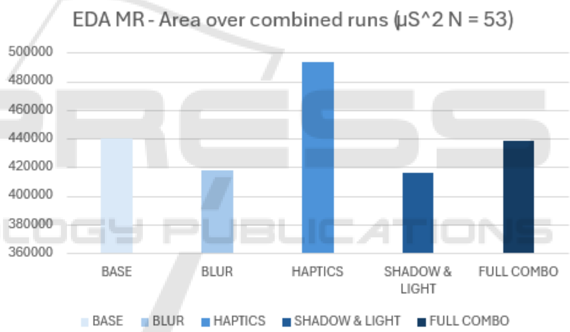
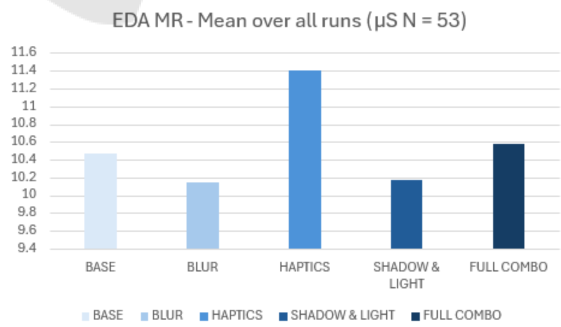


Figure 4: Mean over combined runs for EEG MR ($\mu V, N = 53$).

Haptic feedback (Figure 4) may produce short, quick bursts of neural activity due to the cognitive processing of physical vibrations felt, these bursts could contribute to the increasing total area measured while keeping the mean low. We can also see from the mean values that all experiments that use individual or combined visual and haptic effects result in reduced brain activity and signal amplitude.



(a) Area over combined runs for EDA MR ($\mu S^2, N = 53$).



(b) Mean over all runs for EDA MR ($\mu S, N = 53$).

Figure 5: EDA MR measurements shown as (top) Area and (bottom) Mean over all runs.

In essence, the low mean with high area suggests that the haptic feedback generates neural activity that is found to be energetically intense, but not a high continuous cognitive effort, if this is the case, we would expect to see higher mean and average within the EDA data for haptic interventions, as the EDA sensor records the participants' physiological response, we can see in the Figures 5a and 5b the EDA data recorded that this is indeed the case.

There is a contrast between the lower mean EEG found for the haptics condition in MR and its EDA counterpart, suggesting that whilst the brain's cognitive response (EEG) may have been lower, the body's physiological response was heightened, this indicates that vibration haptics provide participants with a more engaging or stimulating on a sensory level without being additionally cognitively demanding, indicating potential benefits for increased presence and engagement within mixed reality environments. These results are also found similarly in the root mean square values over all combined runs in both EDA and EEG data for mixed reality. All in all, the trends (Figures 6, and 7) are clear, consistent throughout the recording measures, and suggest that sensible focus enhancing effects in mixed reality can mitigate cognitive load and burden, resulting in enhanced performance in mixed reality tasks.

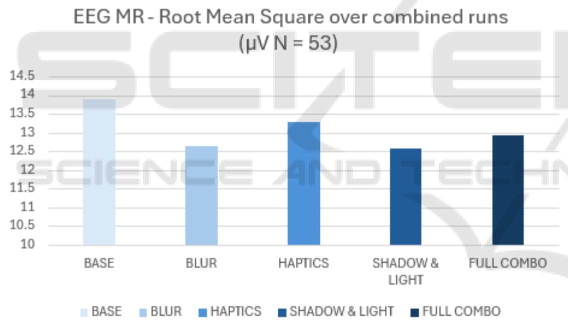


Figure 6: Root Mean Square over combined runs for EEG MR ($\mu V, N = 53$).

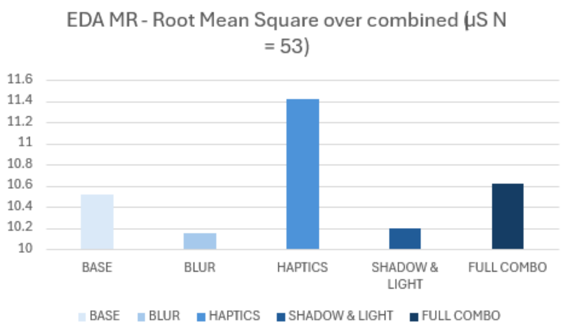


Figure 7: Root Mean Square over combined runs for EDA MR ($\mu S, N = 53$).

Earlier trends found in the qualitative data are once again asserted in the quantitative, the full combination of visual and haptic effects reduce cognitive load more than any singular individual effect with reductions consistently below cognitive load experienced within a base non-augmented mode, although whereas in the qualitative data the blur effect was subjectively experienced by participants as being cognitively overbearing, the quantitative data show it does reduce cognitive load compared to the base modes albeit at a reduced rate compared to shadow and light, haptics, and the full combination of effects.

When comparing the efficacy of modes between mixed reality and fully immersive virtual reality, the full combination of visual and haptics effects shows an increased reduction in cognitive load in mixed reality compared to their VR counterpart. This is similar to the Likert scales and Nasa-TLX scores, which also show a reduction in cognitive load experienced by participants, as observed in Table 6.

Table 6: EEG average measures in Full Combination Condition: MR vs VR.

Measure	**MR Full**	**VR Full**	**Difference**
	EEG (Channel 1) Measures		
MEAN (μV)	-0.0215	0.3015	-0.3230
MIN (μV)	-35.2754	-35.8532	+0.5778
MAX (μV)	35.8338	35.8343	-0.0005
STD (μV)	12.9348	14.2459	-1.3111
RMS (μV)	12.9357	14.2543	-1.3186
AREA (μV^2)	4584.7893	12881.8604	-8297.0711

All in all, the most consistent effect in reducing cognitive load individually across all data measures recorded is the targeted shadow and lighting effects, demonstrating an effective focus effect, reducing cognitive load and thus improving task performance and outcome. Shadow and lighting when used in combination with focused blurring and haptic interventions show a marked reduction in both measurable and subjective feelings of intellectual load, mental burden and cognitive demand.

6 LIMITATIONS

Our study investigated complex mixed reality tasks involving the use of proprioception, cognitive processing and fast reactions, future work will conduct studies investigating different tasks, testing recall, interpretation and comprehension of virtual data presented within mixed reality environments. Whilst our study provides valuable insights into developing comfortable and manageable mixed reality environments, the limitations in sample size provide constraints in making generalisations out of the findings.

Further limitations come down to the sensitivity of EEG and EDA data to movement-based artifacts. Whilst the sensor set up from Plux biosignals takes measures to remove movement-based artifacts through the use of additional sensors and software-based pattern recognition in post-processing, further research could be undertaken in order to investigate how to reduce movement artifacts in VR and MR EEG or EDA signal requisition.

Future studies should broaden the range of tasks focus effects are applied to and measured within, as well as approach novel ways of inducing high focus states of person through the integration of artificial intelligence assistance, such as through Meta's voice SDK suite or take experimental measures to integrate real-world use cases into task environments in order to provide tangible benefits to work in the field. Development of a modern framework for cognitive load assessment could assist in opening new avenues of novel research, now that a variety of qualitative and quantitative measures exist with efficacy in examining cognitive load.

7 CONCLUSION AND FUTURE WORK

This work has examined the effectiveness of visual and haptic interventions as a method of reducing cognitive load in mixed reality tasks and environments. Using combined qualitative and quantitative data gathering, we measured cognitive load and effectively reduced that load in MR through the combined use of targeted blurring, directed shadows, and lighting and vibration haptics.

Investigation into the individual efficacy of singular effect based interventions show positive reductions in cognitive load for directed shadow and lighting as well as vibration haptics, indicating that these are appropriate methods in reducing the cognitive burden experienced by MR users in complex tasks. However, in isolation, the usage of targeted blurring in MR has been shown to be an area that requires further research, with results suggesting mild quantitative efficacy but with results suggesting that participants feel cognitively overwhelmed qualitatively. Results indicate that whilst mixed reality users experience a higher cognitive load comparative to fully immersive VR users, that there are means to mitigate and reduce this load with the correct software and hardware focus enhancing measures, usage of targeted shadow and lighting effects, combined with vibration based haptics and blurring of non focused objects leads to a reduced cognitive load in mixed reality proprioception tasks, leading to experiences with enhanced task performance for participants as well as offer a more comfortable and easier to engage with environment. These findings give room for further investigation. Investigations into the efficacy of visual and haptic interventions can be extended to different types of tasks such as precision based tasks, memory, engagement or retention based tasks or similar appropriate objectives.

In future work our research team expects to obtain the answer to such questions; if reductions in cognitive load are able to be replicated in other types of task, then there is benefit to improving and implementing focus-enhancing effects within a variety of potential use cases across the industry.

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APPENDIX

Table 7: Comparison of Mean Scores for SHADOW & LIGHT Mode between MR and VR.

Measure	**MR Mean**	**VR Mean**	**Difference**
Likert Scale Scores			
Q1. Difficulty	1.33	1.10	+0.23
Q2. Mental Effort	1.78	1.70	+0.08
Q3. Confidence	1.00	1.00	0.00
Q4. Comparison	1.67	1.60	+0.07
NASA-TLX Scores			
Mental Demand	5.89	5.70	+0.19
Physical Demand	5.89	5.00	+0.89
Temporal Demand	7.33	8.90	-1.57
Performance	2.78	2.30	+0.48
Effort	5.56	5.50	+0.06
Frustration	4.00	3.40	+0.60

Table 8: Comparison of Mean Scores for HAPTICS Mode between MR and VR.

Measure	**MR Mean**	**VR Mean**	**Difference**
Likert Scale Scores			
Q1. Difficulty	1.44	1.22	+0.22
Q2. Mental Effort	2.00	1.67	+0.33
Q3. Confidence	1.00	1.00	0.00
Q4. Comparison	2.22	2.11	+0.11
NASA-TLX Scores			
Mental Demand	7.11	6.22	+0.89
Physical Demand	6.44	5.11	+1.33
Temporal Demand	9.89	9.22	+0.67
Performance	4.00	2.33	+1.67
Effort	7.78	6.22	+1.56
Frustration	6.44	3.67	+2.77