Assessing the Effects of Sensory Modality Conditions on Object Retention across Virtual Reality and Projected Surface Display Environments

LUCAS SIQUEIRA RODRIGUES, HU Berlin, Germany
TIMO TORSTEN SCHMIDT, FU Berlin, Germany
JOHN NYAKATURA, HU Berlin, Germany
STEFAN ZACHOW, Zuse Institute Berlin, Germany
JOHANN HABAKUK ISRAEL, HTW Berlin, Germany
THOMAS KOSCH, HU Berlin, Germany

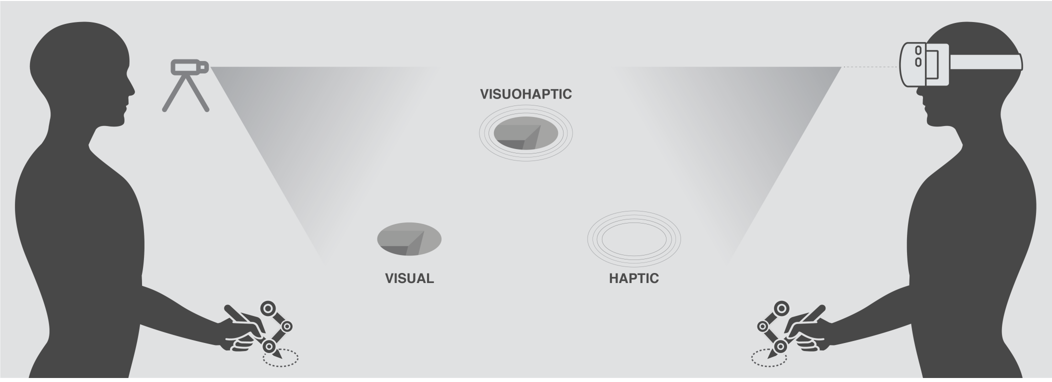

Figure 1. This paper evaluates the interaction between display environment and sensory modality encoding conditions on object memorization. We compared visual, haptic, and visuohaptic modalities across VR and projected surface environments. The visuohaptic sensory modality and the projected surface display environment produced the lowest error rates and response times.

Haptic feedback reportedly enhances human interaction with 3D data, particularly improving the retention of mental representations of digital objects in immersive settings. However, the effectiveness of visuohaptic integration in promoting object retention across different display environments remains underexplored. Our study extends previous research on the retention effects of haptics from virtual reality to a projected surface display to assess whether earlier findings generalize to 2D environments. Participants performed a delayed match-to-sample task incorporating visual, haptic, and visuohaptic sensory feedback within a projected surface display environment. We compared error rates and response times across these sensory modalities and display environments. Our results reveal that visuohaptic integration significantly enhances object retention

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Authors' Contact Information: Lucas Siqueira Rodrigues, lucas.siqueira.rodrigues@hu-berlin.de, HU Berlin, Berlin, Germany; Timo Torsten Schmidt, timo.t.schmidt@fu-berlin.de, FU Berlin, Berlin, Germany; John Nyakatura, john.nyakatura@hu-berlin.de, HU Berlin, Berlin, Germany; Stefan Zachow, zachow@zib.de, Zuse Institute Berlin, Berlin, Germany; Johann Habakuk Israel, israel@htw-berlin.de, HTW Berlin, Berlin, Germany; Thomas Kosch, thomas.kosch@hu-berlin.de, HU Berlin, Berlin, Germany.

ACM 2573-0142/2024/12-ART537
https://doi.org/10.1145/3698137

on projected surfaces, benefiting task performance across display environments. Our findings suggest that haptics can improve object retention without requiring fully immersive setups, offering insights for the design of interactive systems that assist professionals who rely on precise mental representations of digital objects.

CCS Concepts: • **Human-centered computing** → **Human computer interaction (HCI)**.

Additional Key Words and Phrases: Haptics, Visuohaptic Integration, Memory Retention, Feedback, Data Analysis, Data Exploration, Human-Computer Interaction

ACM Reference Format:
Lucas Siqueira Rodrigues, Timo Torsten Schmidt, John Nyakatura, Stefan Zachow, Johann Habakuk Israel, and Thomas Kosch. 2024. Assessing the Effects of Sensory Modality Conditions on Object Retention across Virtual Reality and Projected Surface Display Environments. *Proc. ACM Hum.-Comput. Interact.* 8, ISS, Article 537 (December 2024), 28 pages. https://doi.org/10.1145/3698137

1 Introduction

Haptics, the use of technology to simulate the proprioceptive and cutaneous sensations of touching physical objects, has been widely explored as a means to improve Human-Computer Interaction (HCI) [47]. The integration of touch into multimodal interfaces has led to important advancements in HCI as haptics generally improves user experience, enhancing precision, accessibility, and presence [111]. The benefits of haptic integration are particularly well-documented within the context of Virtual Reality (VR) systems, as immersion provides a natural three-dimensional environment where coherent haptic feedback can enhance visual cues of spatial arrangement and depth [58, 136]. Previous research has extensively examined the effects of other forms of multimodal interaction, such as audiovisual exploration [97, 127], but the combination of visual and haptic feedback merits further investigation due to the natural synergy between these senses in object exploration [43, 74, 90]. The interplay between haptics and VR is widely leveraged in haptic data visualization, as immersive environments enable users to perceive touch sensations in coherence with visual information, facilitating the perception and understanding of complex spatial relationships and dimensions of digital objects [113]. Although early haptics research focused on the effects of haptics in 2D environments, the development of VR into commercially available technology has shifted the study of haptics away from desktop displays, and limited attention has been given to comparing the effects of display environment on the efficiency of haptic feedback.

Despite the advantages of VR as a natural environment for haptic integration, there are important drawbacks to limiting the study of haptics to immersive systems. In terms of real-world impact, haptic research focusing solely on immersive data visualization forgoes the ability to generalize its findings to the majority of professional settings, where 2D displays are predominantly used [85]. Although VR has recently made large strides toward user adoption, the technology is yet to become as ubiquitous in data visualization as 2D desktop interfaces [82]. Therefore, research would benefit from assessing the applicability of haptic enhancements across different display environment conditions to ensure that the benefits of haptics are accessible to the majority of users. Although previous research separately compared the effects of display environments and haptic integration, the literature has a gap in understanding how these factors and their effects interact with user performance. Specifically, there is limited knowledge of how display environment and haptic integration collectively influence the retention of object representations, a critical aspect of cognitive performance in HCI.

Previous research showed that immersive environments alone did not improve memory retention and negatively impacted performance compared to non-immersive environments [73]. On the other hand, a recent study has demonstrated that integrating haptic feedback into immersive object visualization can improve performance on memory retention tasks [130]. The current study replicates this VR experiment and extends it to a 2D projected surface environment to enable a direct comparison between the two display conditions. Assessing whether the retention benefits of visuohaptic integration can be generalized to more widely used 2D display environments is important, as such findings could make these enhancements accessible to a broader range of professionals who typically interact with digital objects in non-immersive settings. In this study, we have investigated the impact of display environments with different levels of immersion (i.e., VR and projected surface) and sensory modalities (i.e., haptic, visual, and visuohaptic) on the retention of digital objects. We conducted a user behavioral study to compare the effects of VR and projected surface setups on error rates and response times across sensory modalities. Our experiment employed a Delayed Match-to-Sample (DMTS) task, which is a cognitive evaluation tool that involves presenting a sample stimulus for participant encoding, followed by a delay where the encoded stimulus disappears to prompt participants to retain its mental representation [28, 102]. The DMTS' learning phase presented stimuli of visual, haptic, or visuohaptic sensory modality conditions, followed by a delay. Next, participants performed a two-alternative forced choice (2AFC) task, identifying the retained sample next to a foil distractor, a stimulus that resembled the memorized sample [12]. Our results indicate that visuohaptic integration significantly reduces error rates in the projected surface display environment. Additionally, error rate and response time in the sighted conditions of our projected surface study were found to be favorable when compared to those observed in our earlier VR experiment [130], thus replicating other research results [73]. Our findings suggest that immersive environments may not be required to obtain the benefits of haptics for the formation and retention of accurate object representations, enabling designers to make informed decisions about whether to leverage VR for this purpose. Thus, our contribution can improve the design of systems that support professionals whose workflows demand precise object retention in two-dimensional display environments.

2 Related Work

2.1 VR and Task Performance

The literature provides mixed support regarding performance advantages associated with VR, as its effects might largely be task-dependent. As Bowman and McMahan state, VR is prone to improve performance in tasks involving spatial understanding as it leverages our brain's ability to exploit depth cues such as stereopsis and motion parallax to correctly understand perspective and resolve visual ambiguities [16]. More specifically, VR reportedly enhances depth perception and has been linked with improved performance on object manipulation and search tasks. Supporting this finding, Barfield et al. reported that stereoscopic rendering decreased completion time and head tracking reduced the number of errors in a psychomotor tracing task [8]. Similarly, Ellis et al. assessed the effects of motion parallax, which is supported by head tracking, and found that it lowered errors in distance judgments [38]. Additionally, McWhorter et al. reported that stereoscopy produced faster times in target acquisition tasks involving accurately grasping and releasing objects [100]. Furthermore, Pausch et al. compared the performance of VR and stationary displays on search tasks and found that immersed users were significantly faster than participants in their desktop condition [116]. Stereoscopic visualization has been abundantly assessed for its benefits in medicine, as studies have demonstrated its ability to reduce error rates in robotic-assisted surgery [34, 105], improve needle placement accuracy in neurosurgery training [67], and enhance proficiency through training [1, 119, 137]. However, previous research has also shown that stereoscopic visualization does not outperform monocular rendering for every task. For example, Murcia-López and Steed reported no difference in performance between participants using HMD and desktop systems on spatial learning in low-detail virtual environments [106]. Similarly, Teather et al. demonstrated that stereo-rendered cursors hindered technique in a 3D Fitts' law pointing experiment due to stereo cue conflicts, cursor diplopia, and depth perception challenges [139]. In a similar manner, Passmore et al. did not report an effect of stereoscopy on depth judgments in virtual reality laparoscopy simulation [115]. Moreover, Davis and Hodges reported that monoscopy yielded better performance in tasks involving plan views, whereas stereoscopy improved efficiency for perspective views [30]. In specific cases, immersion might ultimately hinder task performance. For example, Batmaz et al. found that participants were significantly faster and made fewer errors in the 2D touchscreen condition of a study on eye-hand coordination [10]. Similarly, Sousa Santos et al. reported that desktop participants outperformed their HMD counterparts in 3D navigation tasks [133]. Such low task performance of immersive systems was explained by Fink et al. as a possible consequence of the cumbersomeness and field-of-view limitations of head-mounted devices [40], while Frederiksen et al. attributed such performance inhibition to higher cognitive load [41].

2.2 Effects of Haptics in 2D Display Environments

The effects of haptics on two-dimensional display environments were widely investigated following the introduction of haptic interfaces such as the PHANToM [96]. For example, Oakley et al. explored GUI interaction using this device and found that it did not improve task completion time, while it significantly reduced errors and subjective workload measures [112]. Similarly, Sallnäs et al. reported that force feedback improved precision in a collaborative object manipulation task [125]. Moreover, Gupta et al. found shorter task completion times for force feedback in a bi-manual assembly task [49]. Studies exploring the impact of haptics on target acquisition tasks, such as the work of Wall et al., also highlighted performance benefits [142]. Indeed, in a study involving 2D medical imaging segmentation, Anderlind found that haptic feedback increases the speed of outlining target areas [5]. Similarly, Hasser et al. demonstrated that haptics lowered completion time and error rates in a targeting task [56]. Additionally, Rodrigues et al. reported that integrating haptics into image segmentation enhances the understanding of the morphology and material properties of digital objects [122]. Also, Dennerlein reported that force-feedback improved performance in steering-targeting tasks [32]. Moreover, Akamatsu et al. suggested the benefits of force-feedback in mouse-based target acquisition tasks, which was also reported by Langdom et al. [2, 84]. Finally, Cockburn et al. reported similar effects in this task leveraging vibrotactile feedback on a mouse [23]. Apart from that, the effects of vibrotactile feedback have also been largely investigated. Although this technology is often leveraged for its benefits in touchscreen input [62] and alerts [51], research has demonstrated the benefits of vibrotactile haptics on spatial awareness [22, 118], navigation [29], tracing tasks [143], and conveying semantic [65] and object [94] information. Therefore, as multiple benefits of haptic integration have been found in desktop environments, such findings indicate that an investigation on the transposition of haptic effects found in immersive environments into two-dimensional counterparts might be worthwhile.

2.3 Relationship Between VR and Haptics

Research assessing effect interactions between haptics and VR components (e.g. stereoscopy and head tracking) has yielded mixed results, indicating that the efficiency of visuohaptic integration in immersive environments might be task-specific. For example, Brickler et al. examined the effects of stereoscopic viewing and haptics on fine motor perception-action coordination, and they found that stereoscopy did not affect completion time but improved movement efficiency in the presence of haptic feedback [18]. Meanwhile, Wall et al. assessed these factors in a 3D target acquisition task and reported that force feedback coupled with stereoscopic cues improved spatial accuracy and task completion time [141]. Moreover, Hirose et al. controlled stereoscopy and force-feedback in an object manipulation task and found lower error and completion time for both stereoscopic and haptic conditions but no interaction between these two factors [60], while Richard et al. found similar effects in a task involving tracking and grasping of virtual objects [120]. On the other hand, Boritz and Booth assessed the same factors in a target-reaching task and reported that stereo viewing improved performance while head tracking did not have an effect [13]. Similarly, McKnight et al. controlled force-feedback and stereoscopy and measured completion time and accuracy on an object manipulation task, finding that stereoscopy had no significant benefit on either variable [99]. In a similar fashion, Passmore et al. also reported that stereoscopy did not have an effect on the efficiency of haptic feedback in a path-following task [114]. Furthermore, previous work reported a negative relationship between immersive display environments and haptics, as multimodality in virtual reality can sometimes lead to sensory overload, hampering task performance to the point where users might express a preference for simpler environments [95].

The differences between immersive and traditional displays on haptic efficiency have also been assessed from the perspective of sensory displacement, which is virtually inevitable in haptics-augmented applications that do not track user position. Demonstrating the importance of visuohaptic collocation, Arsenault and Ware manipulated head-tracking to measure the effects of eye-hand coordination with force-feedback and stated that visually accurate spatial perspective of haptic cues improves performance on a Fitts' tapping task [6]. Similarly, Ware and Rose found that the co-location of haptic and visual signals in a virtual workspace improved performance in tasks involving object rotation [144]. Additionally, Brickler et al. reported on a near-field pick-and-place task and revealed that visuo-proprioceptive co-location has significant effects on task efficiency [17]. These findings are also supported by Bouguila et al., who suggested that improvement of depth perception was the main benefit of coupling haptics and stereopsis in virtual environments [15]. On the other hand, researchers such as Williams et al. indicated that the effect of collocation on haptic efficiency might not always be present and depend on tasks and stimuli [146]. Similarly, Graham and Mackenzie reported that there was no advantage of a collocated display over a traditional interface held to one side of the body in translational positioning tasks involving stimuli with limited depth variation [46]. In summary, while the literature generally indicates that visuohaptic collocation impacts task performance, this effect might be limited to certain circumstances.

2.4 Effects of VR on Retention

Previous research investigating the effects of VR on retention has produced contrasting results. For example, studies conducted by Krokos et al. and Buttissi et al. reported improved retention of virtual objects in comparison with desktop and touchscreen displays [19, 78]. However, Sun et al. found limited applicability of this effect, as they assessed the impacts of VR and Desktop environments on participants with different spatial abilities and found that their VR condition only improved retention for participants with low spatial ability [135]. Other studies also reported that immersion did not affect memory retention. For example, in a study comparing the utility of head-mounted displays and desktop screens for spatial understanding, Hattab et al. did not find a significant effect of immersion on retention [57]. Similarly, Kargut et al. compared different levels of immersion and reported that immersive conditions did not improve spatial learning [73]. More contrastingly, the literature also reports on the negative effects of VR on retention. Such a detrimental impact might be due to increased cognitive load, which is supported by the findings reported by Juliano et al. in a study that compared retention in VR and computer screens [69]. Similarly, Roettl and Terlutter compared 2D, stereoscopic 3D, and HMD VR and found the best retention in the 2D condition while the worst performance occurred in the HMD VR condition, which also resulted in the highest cognitive load [123]. Likewise, Bailey et al. added that the increased sense of presence and sensory arousal that VR promotes could potentially hinder retention [7]. It is also worthwhile to note that VR might negatively impact retention due to cybersickness, which Nesbitt et al. have found to deteriorate performance measures such as reaction time [108]. Similarly, Bos et al. indicated that immersion-related cybersickness may cause working memory shortcomings [14].

2.5 Effects of Haptics on Retention

Behavioral studies have explored the effects of visuohaptic integration on object retention. For example, Seaborn et al. examined multimodality in a pattern-matching task and established that the combination of vibrotactile feedback and vision improves retention and does not cause cognitive overload [128]. Similarly, Wijntjes and colleagues suggested that haptic cues disentangle visual ambiguities and improve shape perception accuracy [145]. Moreover, Kreimeier et al. compared the efficiency of data gloves in shape identification and found that vibrotactile feedback increased detection accuracy but decreased speed [77]. In a similar fashion, but investigating a different paradigm, Jüttner et al. described that visuohaptic exploration as prior knowledge yielded significant effects on learning speed and retention performance [70]. Similarly, Desmarais et al. investigated visuohaptic integration effects on physical object identification through cross-modality interactions, stimulus similarity, and congruence and reported that haptic and visual identification depend on shared mental representations [33]. Additionally, using a Phantom desktop and a laptop computer screen as experimental apparatus, Jones et al. assessed the impact of haptic feedback on the perception of unknown objects and found that the group that explored objects with vision and haptics was more accurate in identifying objects [68]. Finally, Kalenine et al. found that visuohaptic integration outperformed vision in the identification of physical objects [72].

2.6 The Potential of Haptics to Improve Retention

Cognitive neuroscience research enables deliberations on the potential of visuohaptic integration to improve object retention. The modality-specific processing of haptic and visual cues converges in brain regions that code abstract and modality-overarching shape representations [25, 36, 37]. In fact, behavioral studies involving object identification have demonstrated that haptics and vision have common mental representations [74, 90]. Meanwhile, studies leveraging brain imaging have revealed cerebral regions responsible for integrating sensory information from haptic and visual channels into object representations [4, 47, 64]. Additionally, researchers have found that haptics and vision possess comparable error patterns in object identification tasks due to their remarkably similar dependence on shape perception [43]. The literature on the cognitive synergy between vision and haptics strongly supports the necessity of evaluating this proposition due to its theoretical ability to generate accurate object representations. Indeed, as described by Lalanne et al., the integration of visual and haptic cues is bound to enhance the accuracy of mental representations through the creation of perceptual efficiencies such as ambiguity resolution, heightened sensory salience, and integrated object perception [83].

2.7 A Comparative Study of Visual, Haptic, and Visuohaptic Encoding on Object Retention in VR

In a previous study, we investigated how different encoding modalities — visual, haptic, and visuohaptic — affect memory retention of digital objects in VR [130]. Participants performed a DMTS task, where they memorized stimuli encoded in one of the three sensory modalities, and responded to a 2AFC task in which they identified retained samples against foil distractors that resembled memorized samples. Results indicated that visuohaptic encoding, which integrates both visual and haptic feedback, significantly lowered error rates compared to unimodal visual and haptic conditions, suggesting a cognitive advantage from the combined sensory input in terms of memory accuracy. We argued that visuohaptic integration may enhance the retention of digital objects in VR environments, adding that the combination of visual and haptic cues may form more robust mental representations, which could benefit professionals who need to memorize and manipulate digital artifacts in VR. Among the various articles discussed in this related work section, we have highlighted this previous VR study because it serves as a foundation for exploring whether findings on the comparative effects of visual, haptic, and visuohaptic encoding on memory retention can be generalized from VR to a two-dimensional display environment. Therefore, this study is frequently mentioned and compared to our projected surface experiment in the following sections.

3 Methodology

We replicated and extended our aforementioned study [130] from VR to a projected surface display environment, conducting a DMTS task using three sensory modality conditions (i.e., haptics, visual, and visuohaptic) as within factors. Additionally, we investigated display environment as a between factor (i.e., VR and projected surface display environments). Visual information was presented using a projected surface, while haptic signals were delivered through a grounded force-feedback device. To determine any performance benefits from the addition of haptic feedback and compare these effects across display environments, we measured error rates and response times. Based on the literature, we state the following hypotheses:

- **H1:** The error rate will be lower in the projected surface display environment compared to the VR display environment across all sensory modalities.
- **H2:** The response time will be shorter in the projected surface display environment compared to the VR display environment across all sensory modalities.
- **H3:** Within each display environment condition, visuohaptic encoding will result in the lowest error rates, followed by visual and haptic sensory modalities.
- **H4:** Within each display environment condition, visuohaptic encoding will result in the shortest response times, followed by visual and haptic sensory modalities.
- **H5:** There will be a significant interaction between the display environment and sensory modality conditions.

Figure 2. **Left:** a participant in our original VR study [130] exploring a stimulus using an HMD and a grounded force-feedback device. **Right:** a participant in our projected surface study performing the same task while facing the stimulus on a projected surface.

3.1 Participants

We closely matched the participation criteria used in our previous VR study, including handedness, health status, and haptic device experience [130]. In both studies, participants were reportedly free of psychiatric or neurological conditions, had normal or corrected-to-normal vision, and were right-handed. Additionally, participants declared no prior familiarity with grounded force-feedback haptic devices, and none of the participants in our projected surface experiment had taken part in our earlier VR study. As in our previous experiment, participants from the general population were recruited using online forums, provided written informed consent upon boarding, and were compensated with 30 Euros upon completing the study. Neither study assessed participant familiarity with its respective display environments. In conformity with our original study's exclusion criteria, we removed participant datasets whose average error rate exceeded 40% (more than 36 incorrect responses out of 90 trials), which is the threshold for above-chance performance at $p < .05$ using a binomial probability distribution [130]. A total of 23 participants completed the current projected surface study, but 1 dataset was excluded due to low performance and another due to a technical error that prevented full completion, leaving N=21 participants for the analyses. The average age of its participants was $\bar{x} = 31.1$ ($s = 6.34$). Eleven participants self-identified as female, nine as male, and one as non-binary. In our original study [130], participants self-identified as 50% female, 40% male, and 10% non-binary, whereas in this present study, 52.38% self-identified as female, 42.86% as male, and 4.76% as non-binary.

3.2 Procedure

Participants signed informed consent forms and provided demographic information after reading our study information sheet and agreeing with its terms. Subsequently, participants were introduced to the experimental setup and adjusted their positions for comfort. Whereas our VR experiment aligned the haptic device with the participants' right shoulders [130], our projected surface setup needed this device to be positioned further right within shoulder rotation ranges to prevent stimulus occlusion. None of the participants reported shoulder discomfort, and qualitative and quantitative results later confirmed that this change did not increase workload nor decrease performance. Similarly to our previous study [130], participants performed 9 training trials of unlimited time, equally divided between the 3 conditions. Upon completing the initial training, participants completed 90 trials, divided into 6 experimental runs containing 15 trials each. As each experimental run spanned over about 10 minutes, participants were instructed to take breaks of a self-determined length and inform the researchers when they felt adequately rested to engage with another experimental run. Participant-regulated breaks commonly spanned between one and five minutes, and their duration was later evaluated as a secondary behavioral measure of workload. Concurrently, the researchers re-calibrated the haptic device during participant pauses to ensure consistent haptic feedback throughout the study. Experimental runs contained 3 blocks of 5 trials corresponding to the three experimental conditions and were randomized in order, as in our previous study [130]. The current study maintained the previous experiment's block order to prevent further confounding factors and directly compare task performance over an equal sequence of sensory modality conditions. Figure 3 describes the experimental procedure.

3.3 Apparatus

Similarly to our previous VR study [130], we utilized a 3D Systems Touch grounded force-feedback device[1] for haptic interaction. The hardware setup included a desktop computer[2] capable of rendering graphics at 60Hz and haptics at 1000Hz. We adapted our open-source project to a 2D screen application using the same version of Unity3D (2021.3.5f1) running on Windows 10 [130]. In the

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[1] 3D Systems, Rock Hill, SC, United States.

[2] Intel Core i9-9900KF CPU 3.60GHz, 32 GB RAM, NVIDIA GeForce RTX 2080 Ti

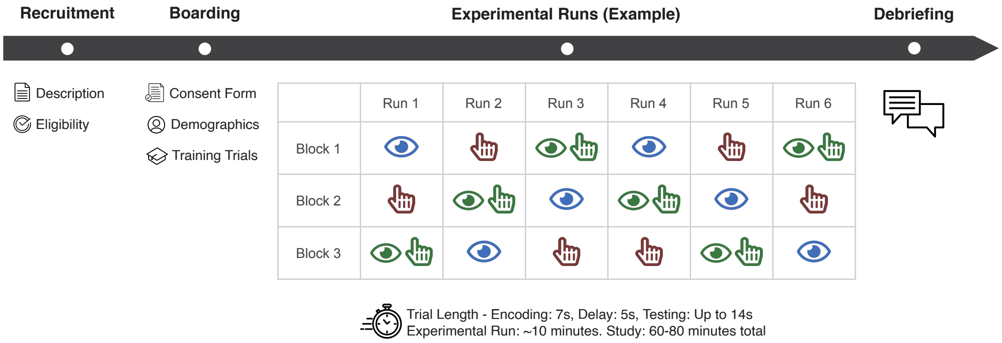

Figure 3. Experimental procedure: Similarly to our previous study [130], participants provided written consent and demographic data, were accommodated with the environmental setup, and received practical training. Participants completed 6 trial runs containing 5 trials grouped as single-condition blocks, whose order was randomized across participants. Cells with 👁 denote the unimodal visual modality, while 👆 represents the haptic-only modality, and 👆👁 represents the visuohaptic modality.

application, we replaced the VR component responsible for head tracking and stereoscopic rendering with a 2D rendering object positioned to allow the projected surface to display the scene and its components at the same perceived size as in our original VR experiment [130]. The remaining parts of the application remained unchanged to minimize confounding factors introduced by the display method. The virtual scene presenting the stimuli was visually rendered using an Epson EB X49 Projector[3]. As in our VR study [130], we used a Valve Index controller[4] for 2AFC participant answer input.

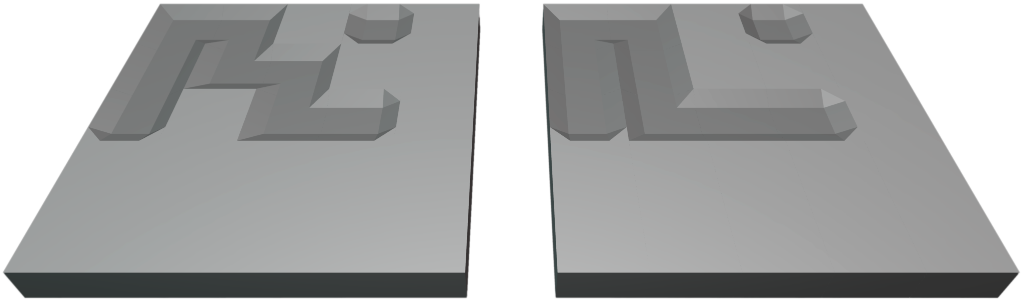

Figure 4. Example of a stimulus pair: sample **(left)** and its foil **(right)**. The 3D stimuli were created on 5×5 matrices, where 8 beveled blocks formed a path, and one beveled block was positioned outside the path. Samples and foils differ by a change to one block that belongs to either the path or the single outside block. Trials presented unique pairs of samples and foils. Stimuli in our study were identical to the ones used in our VR study [130].

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[3] Seiko Epson Corporation; Suwa, Nagano, Japan.
[4] Valve Corporation; Bellevue, WA, United States.

3.4 Stimuli

We utilized stimuli originally developed for our previous VR study [130], whose study materials were made available as an open-source repository. The projected surface environment was calibrated to present stimuli at the same perceived size as in the original VR experiment. We created a set of unique stimuli that matched the number of trials, assigned them in a randomized order across participants, and maintained our original stimulus and trial order to ensure consistency across trials and conditions [130]. As exemplified on Figure 4 (left), stimuli consisted of square surface patterns of beveled blocks on 5x5 matrices, which were inspired by previous research [21, 117] but adapted to present sensory-agnostic height modulation instead of modality-specific object information such as color and texture [81]. The stimuli were created through a self-avoiding walk algorithm [92] that connected randomized target positions as continuous 8-block paths of unrepeated cells and randomly beveled an available block in the matrix. Block designs adapted to their relative positions within paths and performed as pass-through, corner, or boundary components. Target blocks were beveled by a quarter of their height, and each external wall featured a 45° slope that enabled the probe to effortlessly enter and exit the target path. Continuous beveled paths were designed to allow for *contour following*, as suggested by Lederman et al. as a common *exploratory procedure* [86]. As our DMTS paradigm involved a 2AFC task, each sample stimulus had a matching foil stimulus, as demonstrated in Figure 4 (right). Samples and foils diverged by a single-block change to either the stimulus' path or to its single outside block. In the case of foil path alterations, the algorithm changed beveled slopes to ensure that the path would remain continuous, whereas single-cell modifications randomly moved to an available cell in the original's immediate surroundings.

3.5 Task

As described in our original study [130], we implemented a DMTS task involving three phases. First, participants encoded centrally-presented sample stimuli from visual, haptic, or visuohaptic sensory modalities for 7 seconds. This was followed by 5-second delay phases during which the stimuli were absent. Finally, participants engaged in a 2AFC task [12], where they had up to 14 seconds to distinguish retained samples from foil distractors that closely resembled the original samples. Figure 4 exemplifies the differences between sample and foil stimuli. We replicated the same intervals utilized in our earlier study to maintain consistency and avoid confounds [130], and our pilot testing confirmed that the allotted time allowed for task completion while supporting sufficient performance variability for meaningful comparison between conditions. Similarly to our previous study, participants utilized the left-hand VR controller joystick to indicate the side of the target stimulus in this 2AFC task [130]. Target positions were randomized and balanced across trials to prevent response biases. Participants received visual feedback (green thumbs-up or red thumbs-down) regarding the correctness of their responses. An inter-trial interval of 5 seconds separated each response and the start of a new trial. During the interphase delay and the inter-trial interval, the application visually and haptically nudged participants to raise the haptic device's stylus to a marked location designed to prevent the probe from revealing stimuli before new phases or trials started.

Similarly to our previous design [130], a mask covered stimuli in all sensory modality conditions in the learning and testing phases, and the stimuli could only be revealed through a circular aperture window at locations touched by participants using the probe, as exemplified in Figure 5. This sampling limitation equalized the different sensory modality conditions, as vision and touch significantly differ in encoding rate and range, with vision being significantly faster at object sampling [86, 87]. Jansson et al. stated that the visual equivalent of sampling objects through a tool-handling-type haptic interface would be to visualize an image through a small hole in a paper that covers the remaining areas [66]. As such haptic perception is typically accomplished through successive impressions [45], our design limited sight to touched areas to cause visual and haptic exploration to sample object information at the approximately same rate and range. A similar visual constraint was implemented by Loomis, Klatzky, and Lederman, who found comparable performance between unimodal visual and haptic conditions when the visual aperture matched the touched area [91]. A similar visual aperture design was later implemented by Jones et al. [68]. Additionally, this task design ensures that participants explore stimuli through similar movements under the three conditions to prevent hand movement differences from becoming a confounding factor in sighted conditions, as humans generally prioritize vision to perceive geometric features [150]. Thus, in our experiments, the visual condition allowed participants to reveal the stimulus' visual appearance at the probe location. The visuohaptic condition entailed examining stimuli characteristics through vision and touch. On the other hand, in haptic condition trials, participants obtained haptic information at touched locations but were not presented with visual cues.

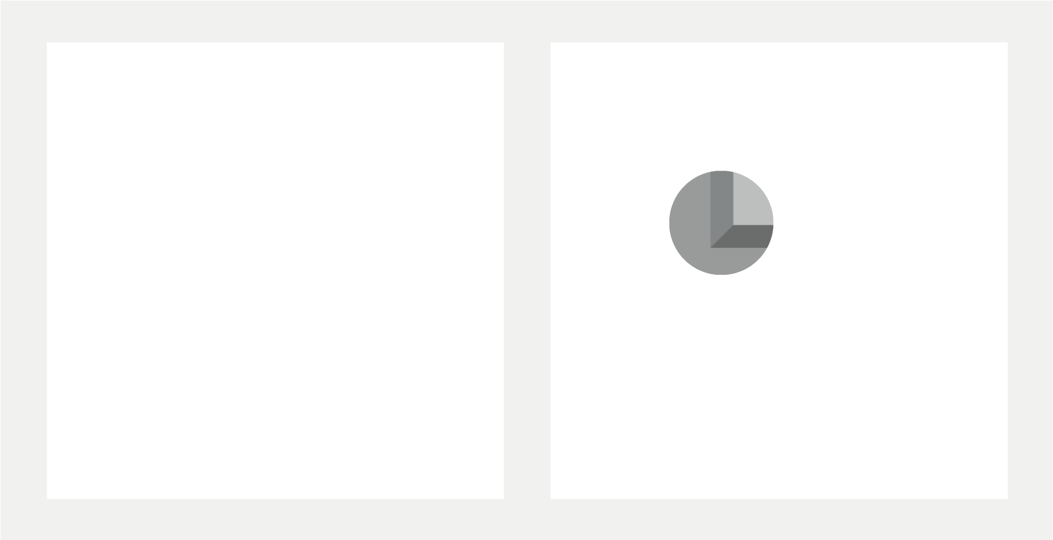

Figure 5. After memorizing a stimulus in the learning phase, a participant uses the probe to reveal the masked sample and foil stimuli through an aperture. In this 2AFC paradigm, participants indicated if the memorized sample was positioned left or right.

3.6 Independent Variables

In our studies, Sensory Modality was an independent variable that included three conditions: *Visual*, *Haptic*, and *Visuohaptic*. During *Visual* sensory modality trials, participants visually explored sample stimuli through an aperture window, as described in the Task subsection. In the *Visual* condition, haptic feedback was limited to conveying a flat surface to convey physical contact with stimuli without communicating stimulus-specific characteristics through touch. In the opposite case, trials in the *Haptic* condition conveyed object characteristics through force feedback while it did not present visual stimulus characteristics. Lastly, the *Visuohaptic* condition presented stimulus characteristics through both visual appearance and force feedback. Furthermore, we defined the variable Display Environment with the levels of *VR* and *Projected Surface* display environments. In the VR condition, participants were fully immersed in a virtual 3D environment while the projected surface display environment employed a 2D projection on a table (see Figure 2).

3.7 Dependent Variables

Error Rate and *Response Time* were measured as dependent variables. *Error Rate* was quantified as the relative number of incorrect responses, namely opting for the foil stimulus in place of the encoded target stimulus during the 2AFC task. *Response Time* was assessed as the interval between the beginning of the testing phase, i.e., the onset of target and foil stimuli, and response action, i.e., the conclusion of a lateral thumbstick movement.

3.8 Statistical Analysis

We employed various statistical tests to evaluate the differences in error rates and response times between Display Environments (VR and Projected Surface) and Sensory Modalities (Visual, Haptic, and Visuohaptic). The normality of our data was assessed using the Shapiro-Wilk test. For normally distributed data, we employed repeated measures ANOVA, applying Greenhouse-Geisser corrections when the sphericity assumption was violated. We utilized non-parametric tests, such as the Friedman test, for non-normally distributed data. To analyze the dataset containing merged output from our VR and projected surface experiments, we employed the Aligned Rank Transform (ART) ANOVA and Linear Mixed Models (LMMs) due to their robustness to non-normality and ability to handle mixed designs, as the joint analysis involved between-subjects factor (i.e., Display Environment) and a within-subjects factor (i.e., Sensory Modality). LMMs were deemed appropriate for our statistical analysis as they do not require the assumption of sphericity and can process unbalanced datasets. This was our case, as despite having the same number of participants, the projected surface experiment yielded more usable participant datasets than its VR counterpart. The LMMs computed error rates and response times as dependent variables and included the main effects of Display Environment (Projected Surface vs. VR), Sensory Modality (Visual, Haptic, Visuohaptic), and their interaction. The models included randomized intercepts to account for individual differences in participants' baseline performance and leveraged the Nelder-Mead and BFGS algorithms to handle potential convergence issues and ensure the reliability of their estimates. Model diagnostics checked for convergence, examined residuals to assess normality, and evaluated random effects to ensure they correctly captured data variability. We also performed logistic regression for error rates and Mann-Whitney U tests for response times to explore alternative analyses. Bonferroni corrections were applied when necessary to control for multiple comparisons, and effect sizes were calculated using Cohen's d or other appropriate measures.

4 Results

In addition to the data collected in our projected surface experiment, we analyzed the results from our previous VR study [130]. We analyzed the data from our projected surface study separately from the data from our original VR experiment to make a direct comparison between the two studies. Twenty-three participants completed our projected surface study, and our original VR study included the same number of participants [130]. From the initial pool of participants, those whose average error rate exceeded 40% (more than 36 incorrect responses out of 90 trials) were excluded from analysis, as this cutoff represents the minimum score required to be performing significantly above chance at $p < .05$ according to a binomial probability distribution. After applying the exclusion criteria, the final analysis included 21 participants from our projected surface study and 20 participants from the original VR experiment [130]. Data from the VR and projected surface studies were examined independently for the primary analyses, and the two datasets were merged for a separate joint analysis to examine interactions between the display environments and sensory modality conditions. All reported p-values are considered significant at the alpha level of 0.05.

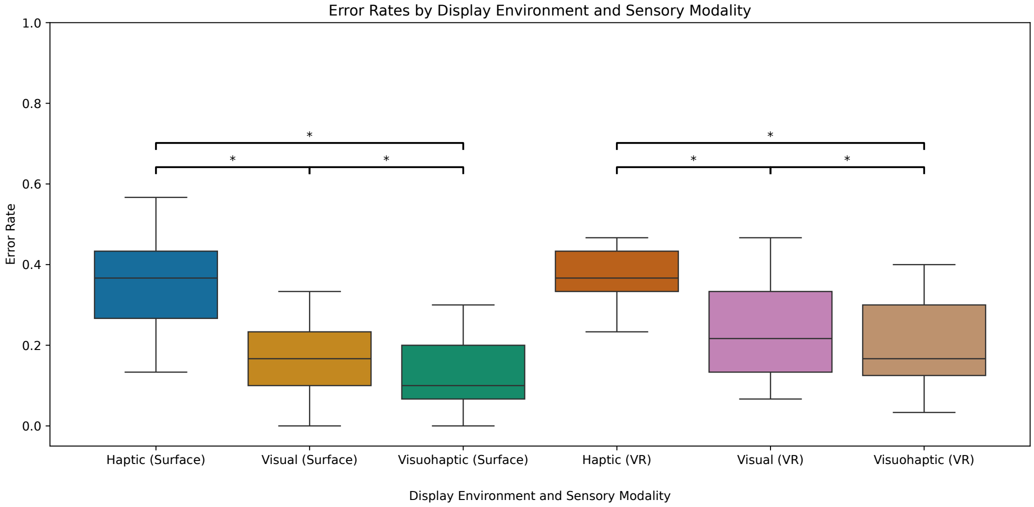

Figure 6. Error rate results for sensory modality and display environment conditions. Asterisks indicate significant differences between conditions as determined by Bonferroni-corrected post-hoc t-tests. We find significant differences between all sensory modalities in their respective display environment conditions. Trials in the visuohaptic condition resulted in the lowest error rate.

4.1 Error Rate

As reported in our previous article [130], the error rate in the original VR study was normally distributed, as indicated by a Shapiro-Wilk test ($p > .05$). Consequently, a repeated measures ANOVA was performed, which revealed a significant main effect for the sensory modality conditions, $F(2, 38) = 30.59, p < .001$. Bonferroni-corrected post hoc t-tests identified significant differences between haptic and visual conditions, $t(19) = -4.73, p < .001, d = -1.27$, haptic and visuohaptic conditions, $t(19) = -6.75, p < .001, d = -1.93$, and visual and visuohaptic conditions, $t(19) = -3.3, p = .011, d = -0.41$. The highest error rate was observed in the haptic-only condition (M = 0.37, SD = 0.06), followed by the visual condition (M = 0.24, SD = 0.13) and the visuohaptic condition (M = 0.19, SD = 0.11). Figure 6 (right) displays the mean error rate per participant in our earlier VR study [130].

In our projected surface experiment, the Shapiro-Wilk test confirmed that the error rate was normally distributed ($p > .05$). Consequently, a repeated measures ANOVA was performed, which indicated a significant main effect for our sensory modality conditions, $F(2, 40) = 78.23, p < .001$. Subsequent Bonferroni-corrected post hoc t-tests identified significant differences between haptic and visual conditions, $t(20) = 7.46, p < .001, d = 1.77$, haptic and visuohaptic conditions, $t(20) = 10.71, p < .001, d = 2.35$, and visual and visuohaptic conditions, $t(20) = 5.70, p < .001, d = 0.44$. The highest error rate was observed in the haptic-only condition (M = 0.37, SD = 0.11), followed by the visual condition (M = 0.17, SD = 0.10) and the visuohaptic condition (M = 0.13, SD = 0.08). Figure 6 (left) displays the mean error rate per participant in our study.

4.2 Response Time

As reported in our earlier article [130], a Shapiro-Wilk test indicated that response times were not normally distributed ($p < .05$). Therefore, a Friedman test was applied for non-parametric testing,

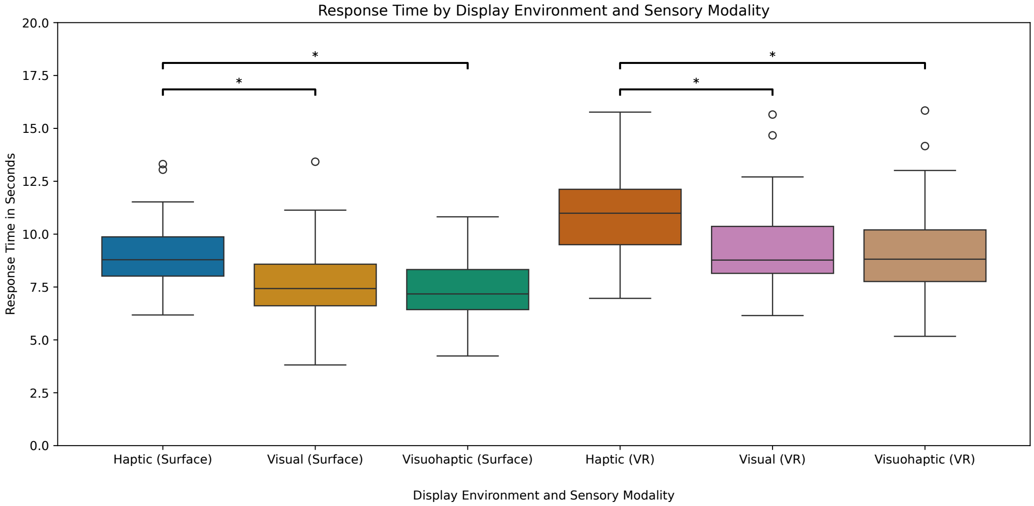

Figure 7. Averaged response time results for sensory modality and display environment conditions. Asterisks indicate significant differences between conditions as determined by Bonferroni-corrected post-hoc t-tests. We find significant differences between haptic and both visual and visuohaptic sensory modalities in their respective display environment conditions. Haptic encoding without visual cues resulted in the highest response time. The visuohaptic sensory modality resulted in the lowest response time.

which resulted in a significant main effect, $\chi^2(2) = 10.9, p = .004$. Bonferroni-corrected Wilcoxon-signed rank post hoc tests revealed significant differences between haptic and visual sensory modalities ($p = .012, d = 0.63$), and haptic and visuohaptic sensory modalities ($p = .003, d = 0.68$). No significant difference was found between visual and visuohaptic sensory modalities ($p > .05$). Haptic encoding resulted in the highest task response times (M = 11.02, SD = 2.17), followed by visual (M = 9.50, SD = 2.58) and visuohaptic sensory modalities (M = 9.39, SD = 2.57). Figure 7 (right) illustrates the response times for our earlier VR study [130].

In our projected surface study, a Shapiro-Wilk test indicated that response times in the VR group were normally distributed ($p > .05$). Consequently, a repeated measures ANOVA was conducted, revealing a significant main effect for our sensory modalities conditions, $F(2, 40) = 11.67, p < .001$. Bonferroni-corrected post hoc t-tests identified significant differences between haptic and visual sensory modalities ($t(20) = 2.81, p = .033, d = 0.74$), and haptic and visuohaptic sensory modalities ($t(20) = 4.84, p < .001, d = 1.04$). No significant difference was found between visual and visuohaptic sensory modalities ($p > .05$). Haptic encoding caused the highest task response times (M = 9.23, SD = 3.32), followed by visual (M = 7.66, SD = 7.04) and visuohaptic sensory modalities (M = 7.32, SD = 3.54). Figure 7 (left) illustrates the response times for the projected surface study.

4.3 Joint Data Analysis of Main Effects and Interactions of Display Environment and Sensory Modality

Analyzing the dataset containing merged output from both the original VR study [130] and our projected surface experiment, the Shapiro-Wilk test indicated a violation of the normality assumption for both error rates ($W = 0.965$, $p = 0.003$) and response times ($W = 0.968$, $p = 0.005$). Thus, we analyzed the data using the Aligned Rank Transform (ART) ANOVA.

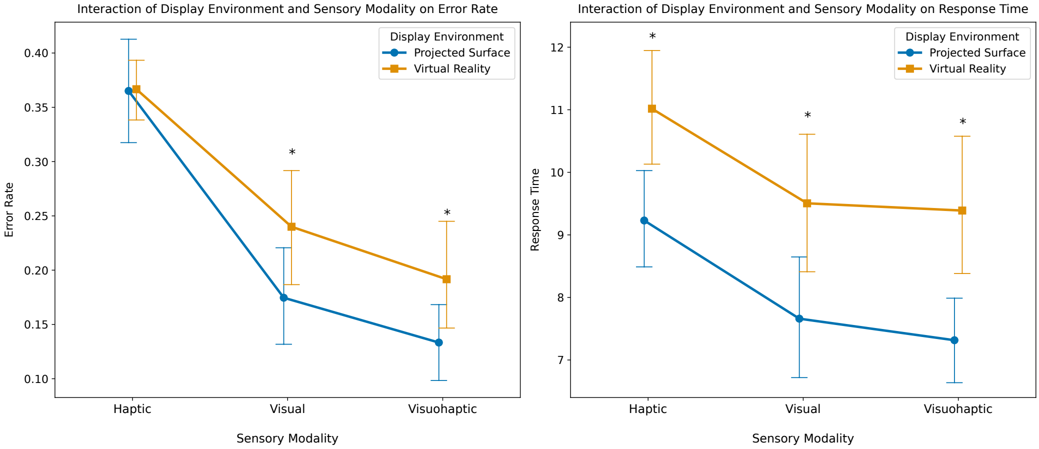

Figure 8. Error rates were significantly lower in the projected surface display environment ($F(1, 117) = 5.81$, $p = 0.02$) with significant differences between sensory modalities ($F(2, 117) = 47.76$, $p < 0.001$) . The interaction between the display environment and sensory modality was not significant ($F(2, 117) = 0.94$, $p = 0.39$). Response times were significantly faster in the *projected surface* condition ($F(1, 117) = 24.01$, $p < 0.001$), with significant differences between sensory modalities ($F(2, 117) = 10.10$, $p < 0.001$). The interaction between display environment and sensory modality for response times was not significant ($F(2, 117) = 0.08$, $p = 0.93$). Asterisks denote a significant difference between display environments.

For error rates, the ART ANOVA analysis revealed significant main effects for both display environment ($F(1, 117) = 5.81$, $p = 0.02$) and sensory modality ($F(2, 117) = 47.76$, $p < 0.001$) conditions. These results are evident in Figure 8 (left), where error rates were generally lower for the projected surface condition, and a substantial decrease in error rates from haptic to visual and further to visuohaptic sensory modalities was observed for both projected surface and VR. The interaction between display environment and sensory modality was not significant ($F(2, 117) = 0.94$, $p = 0.39$), although a consistent pattern of lower error rates in the projected surface condition involving the visual and visuohaptic sensory modalities was noteworthy.

Response time results indicated significant main effects for display environment and sensory modality. The projected surface condition significantly differed ($F(1, 117) = 24.01$, $p < 0.001$) from its VR counterpart, as evidenced in Figure 8 (right). Sensory modality also displayed a significant effect ($F(2, 117) = 10.10$, $p < 0.001$), showing a similar pattern of response time reduction from haptic to visual and further to visuohaptic for both projected surface and VR. The interaction between display environment and sensory modality was not significant ($F(2, 117) = 0.08$, $p = 0.93$), suggesting that the effect of sensory modality on response times did not significantly differ between projected surface and VR. This indicated that the consistent pattern of faster response times in the projected surface condition across all sensory modalities was due to the significant main effect of the display environment condition.

We conducted additional data analysis using Linear Mixed Models (LMMs), which revealed the main effects for Error Rates on both Visual (Coef = -0.190, $z = -8.010$, $p < .001$) and Visuohaptic (Coef = -0.232, $z = -11.319$, $p < .001$) sensory modalities with significantly lower error rates in comparison with the Haptic modality. The LMM analysis for response time reported significant main effects for visual (Coef = -1.569, $z = -3.570$, $p < .001$) and visuohaptic feedback (Coef = -1.914, $z = -6.103$, $p < .001$) as these conditions yielded significantly faster response times in comparison with the haptic modality. The display environment condition had a significant effect (Coef = 1.787, $z = 2.397$, $p = 0.017$) as VR trials had longer response times than their projected surface counterparts. We did not observe significant interaction effects for response times, as this sensory modality effect is consistent across display environment conditions.

The logistic regression analysis revealed significant effects of the display environment on error rates for different sensory modalities. While the haptic modality ($z = -0.06$, $p = 0.954$) did not incur a significant effect, the visual ($z = -2.82$, $p = 0.005$) and visuohaptic ($z = -2.76$, $p = 0.006$) sensory modalities presented a significant reduction in error rates in the projected surface condition compared to VR. The intercept values for haptic ($z = 6.69$, $p < 0.001$), visual ($z = 14.80$, $p < 0.001$), and visuohaptic ($z = 15.97$, $p < 0.001$) sensory modalities were all highly significant, reflecting the baseline error rates for each sensory modality. As for response times, the Mann-Whitney U test analysis revealed significant differences between the VR and projected surface conditions across all sensory modalities - haptic ($U = 241769.50$, $p < 0.001$), visual ($U = 245729.50$, $p < 0.001$), and visuohaptic ($U = 248245.50$, $p < 0.001$). These results indicate consistently lower response times in the projected surface condition compared to the VR condition across all sensory modalities.

4.4 Workload Measures

NASA-TLX results for the VR and projected surface studies did not reveal significant differences in mental demand ($t = -0.166$, $p = 0.869$), temporal demand ($t = -0.620$, $p = 0.539$), effort ($t = -1.591$, $p = 0.120$), and frustration ($t = -0.084$, $p = 0.933$), but we found a significant difference in performance scores ($t = -2.786$, $p = 0.008$), with participants in the desktop condition perceiving their performance as better. We evaluated the impact of VR and projected surface display environments on the duration of participant-regulated breaks as a potential behavioral measure of fatigue and cognitive load [59]. As assumption checks revealed non-normally distributed residuals ($p < 0.001$) and unequal variances ($p = 0.043$), we employed a Mann-Whitney U test that indicated significantly longer durations in the VR condition ($U = 8281.0, p < 0.001$).

5 Discussion

We compared the performance of participants in our previous VR study and in our projected surface experiment across sensory modalities. Our findings support hypotheses H1 and H2, indicating that the projected surface display environment generally resulted in lower error rates and shorter response times across sighted sensory modalities. These results suggest that the projected surface display environment can offer effective support for the retention of digital object characteristics. Within each display environment condition, our findings supported hypotheses H3 and H4, showing that visuohaptic encoding resulted in the lowest error rates and shortest response times, followed by visual and haptic sensory modalities. This trend reinforces and extends previous results, as it demonstrates the effectiveness of visuohaptic integration in enhancing object retention regardless of the display environment. The anticipated significant interaction between display environment and sensory modality conditions (H5) was not observed, indicating that the benefits of visuohaptic integration are consistent across both VR and projected surface environments. Overall, our findings demonstrate that immersive environments are not strictly necessary to enable the formation of accurate mental representations of digital objects and that switching from VR to a 2D environment does not negatively interfere with the effects of visual, haptic, and visuohaptic sensory modalities.

5.1 Significant Main Effects of Display Environment on Error Rates and Response Times

The display environment had a significant effect on error rates and response times. Participants in the projected surface group were faster across sighted sensory modalities, and their responses were more accurate in the visual and visuohaptic conditions. Our results confirm the findings of recent research comparing memory performance between VR and 2D environments [69, 73]. These outcomes could be explained by perceptual conflicts, such as the negative effects of stereoscopy on depth perception due to cursor diplopia (double-vision) [140], distance compression [107], and vergence-accommodation conflict [61]. Accordingly, Davis and Hodges reported that monoscopy yielded better performance in tasks involving plain views, which would describe our stimulus presentation, whereas stereoscopy only improved efficiency for perspective views [30].

The observed performance gaps could be attributed to higher cognitive demand and increased visual fatigue and cybersickness reportedly associated with immersive environments [17, 54, 132]. Although our NASA-TLX results do not align with this interpretation, readers might interpret self-assessed workload results with caution as recent studies potentially indicate that this questionnaire might be susceptible to biases that could limit its measurement of cognitive workload [75, 110]. Thus, participants might have alleviated negative feedback on the original VR experimental setup in attempts to produce socially desirable responses [76]. Additionally, as participants in our projected surface study did not take part in the original VR experiment, they lacked a comparison baseline for such an evaluation. Therefore, as the subjective perception of workload does not appear to explain quantitative results, we analyzed the length of resting periods between experimental runs, which participants determined freely before restarting experimental sessions. We evaluated self-determined break duration as an alternative behavioral measure of cognitive fatigue, as suggested by Henning et al. [59]. Our analysis showed a significantly heightened duration of breaks in the VR condition, which might indicate higher levels of cognitive fatigue in this condition. The experimental protocols of both studies included resting periods between trial sets as a standard measure to prevent fatigue and its performance effects. It is interesting to note that previous research indicated that short breaks might solely decrease visual fatigue for 2D display users, while counter-intuitively inducing subjective symptoms of visual discomfort for HMD participants [48]. Research has established that VR usage incurs post-usage symptoms such as motion sickness [134], sensorimotor incoordination [55], and vestibulo-ocular reflex modification [35]. VR users might experience these symptoms as the central nervous system adapts to VR by re-weighting vestibular sensory information and visual vection during sensory integration, which enables cybersickness reduction during VR exposure but impacts vestibular sensory processing after immersion [44].

A potential account for slower responses in the VR condition could be HMD field-of-view limitations and associated head rotation time costs [20]. Our earlier VR experiment did not leverage head-tracking data [130], but it is clear that lateral head movements were necessary to fully explore samples and foils during the testing phase. Although the Valve Index's HMD has a field-of-view that nears the human capacity (130° vs 135°), head movements were necessary during the testing phase to examine stimulus areas closer to the edges of peripheral vision, which would explain the consistently increased response time across sensory modalities in the VR experiment. This conclusion would be supported by the findings of Bassano et al., who reported that stimulus detection performance in far peripheral areas was only comparable to near or mid-peripheral vision if participants were allowed more time for head rotation [9]. Regarding the negative impact of HMD field-of-view on error rates, Bassano et al. reported that the additional workload caused by head rotation does not prevent memorization [9]. Given the fact that most of our participants responded before the task's time limit, it is plausible that head rotation could have affected response times while not impacting error rates.

The disparity in the familiarity that participants in the two studies might have had with their respective VR and 2D environments might also explain the response time gap between these experiments. Although VR adoption has surged in past years [63], users are generally more familiar with two-dimensional environments [85]. This greater familiarity with 2D displays may translate into the reported self-perceived performance observed in our questionnaire, as familiarity is known to have a strong correlation with confidence in memory accuracy tasks [148]. A comparison between the NASA-TLX results of the projected surface and VR experiments demonstrated that participants in the projected surface study reported significantly higher self-assessed performance, a construct that involves participants' perceived competence and confidence. Confidence is generally negatively correlated with response time, as memory retrieval speed is one of the factors influencing participants' judgment of memory accuracy [24, 103]. Thus, participants in the projected surface environment needed less exploration time to confidently respond to our 2AFC task than their VR counterparts. Previous research has established that lack of prior experience with VR negatively affects self-evaluation of performance and pragmatic quality components such as efficiency and effectiveness [42, 124]. Makransky et al. linked unfamiliarity with VR to higher cognitive load and lower performance in immersive experiences [93]. Longitudinal studies have demonstrated that perceived and measured performance in VR improves as participants become familiar with the technology over extended exposure to immersive environments [3, 52, 104]. As our original VR study did not include a formal assessment of prior VR experience [130], we cannot make a categorical statement about the impact of unfamiliarity on performance, but it is important to highlight the role that this factor might have played on participant efficiency.

5.2 Potential Confounding Factors in the Display Environment Comparison

It is important to note that the performance gap between display environments could also be partially attributed to confounding factors introduced by the change in display environments. Although our experimental design attempted to isolate the display environment as the only factor that differed between our experiments, it is possible that the display modification could have introduced uncontrolled differences that could have affected performance. For example, although we did not make any software changes to the illumination of the experimental scene, our apparatus was set in a darkened experimental room and utilized a projector capable of delivering 3,600 lumens. Thus, it is possible that the differences in brightness and contrast levels between projected surface and HMD displays could have impacted performance in sighted sensory modality conditions. It is also possible that the necessary darkness of the environment surrounding the stimulus projection could have provided participants in the projected surface condition with enhanced conditions to focus on the stimulus area. Another incidental difference regards display resolution and refresh rate. Although the VR device utilized in our original study possessed superior rendering capabilities than our projected surface, lower image fidelity might not necessarily be detrimental to task performance, as it can reduce visual complexity and enhance focus on experimental tasks [27]. On the other hand, high fidelity might counterintuitively have a negative impact on retention, as it can exert an unnecessary cognitive load on participants and disrupt their capacity to attend to experimental tasks [11, 53]. Additionally, given the simplicity of the stimuli utilized in both experiments, participants in the VR study may not have realized any perceptual advantages from the higher fidelity of their head-mounted displays. Another potential confounding factor relates to a mismatch in the emotional discomfort that the two environments may elicit. Whereas we arranged our projected surface setup to make participants feel that their performance was not directly observed by researchers, wearing head-mounted devices rendered participants in the VR study unaware of their surroundings, which may have caused some level of discomfort and affected their performance [79, 98].

5.3 Haptic Sensory Modality Produces Similar Error Rates Across Display Environment Conditions

Error rates in our projected surface study's haptic-only condition were remarkably similar to the corresponding results in our previous VR study [130]. Whereas the projected surface environment significantly lowered error rates for the visual and visuohaptic sensory modalities, the type of display environment had virtually no effect on the haptic-only condition. These results confirm previous findings indicating that visual information processing is more sensitive to differences in the immersion levels of display environments [147], whereas the absence of immersive qualities in projected surface settings did not impair participants' ability to perceive and encode haptic information effectively. The stability of the haptic-only condition's error rates across VR and projected surface environments suggests that the haptic feedback mechanism was consistent and reliable in both settings, as participants relied primarily on haptic cues to encode object representations. Our findings confirm previous research demonstrating that haptic feedback can be effectively utilized in a variety of environments while maintaining performance levels even when visual cues are altered or absent [39, 149]. The important accuracy differences between haptic-only and sighted sensory modality conditions were anticipated, given the results in our earlier VR study [130] and long-standing knowledge that humans most commonly rely on visual cues to perceive and encode objects [80, 121, 150]. As our projected surface replication maintained the exact time constraints as our original VR study's sensory modality conditions [130], it was to be expected that our study's haptic-only condition would similarly underperform, given that touch is much slower than vision for object exploration [89, 109]. This consistency implies good operationalization of sensory modality in the design of our projected surface extension study, as participants in the haptic sensory modality condition were minimally influenced by the visual differences inherent to changes in the display environment. Additionally, results for this unimodal condition provide further confirmation to support the main results, demonstrating that the lack of immersion does not negatively affect participants' ability to perceive and encode haptic information.

5.4 Implications for Designing Haptic Visualization Interfaces

Our findings have implications for the optimal design of interactive data visualization systems that leverage visuohaptic integration and its ability to promote the retention of digital object information. As our results demonstrated that haptic feedback remains effective in improving the accuracy of object representations, whether it is applied to VR or projected surfaces, designers can make informed decisions regarding the most suitable display environment for their specific contexts without relying on immersion as a necessary factor for visuohaptic visualizations. Our findings indicate that the effects of visuohaptic integration on object retention are consistent across 2D and VR display environments, and, under specific circumstances, projected surfaces may even allow for slightly better retention performance in sighted sensory modality conditions, as displayed in Figure 8. Given the fact that desktop VR and projected surface environments may have comparable hardware and implementation costs, our results enable designers to select between such displays, as each has its advantages depending on contexts and use cases. Although projected surfaces are still not as ubiquitous as other display technologies, our findings provide an initial step toward validating the effects of visuohaptic integration in two-dimensional display setups, which are widely utilized in professional office environments for interacting with digital objects. Such an implementation of haptics would efficiently leverage resources that have already been normalized in the majority of professional environments, and it could increase the adoption of haptic technology among targeted audiences. Thus, professionals whose workflows rely on precise object representations, such as surgeons [31] and paleontologists [129], may benefit from haptic-facilitated retention in more familiar 2D environments. In fact, improved retention could support these professionals in tasks that require maintenance and cognitive manipulation of object representations, such as image segmentation [126] and modeling [71]. However, it is pertinent to acknowledge that while our study extends our understanding of the retention effects of visuohaptic integration to 2D displays, further research would be necessary to exclude potential effects of display size on memory [50], as the large projected surface display employed in our study is uncommon in most professional settings. Thus, further investigation would be necessary to generalize our findings to average desktop displays. It should also be noted that the DMTS task employed in our study is suitable to investigate object retention in short-term memory [28], so additional research would be necessary to extrapolate our findings toward professional workflows requiring long-term retention of digital object characteristics. Additionally, as our projected surface experiment employed the same stimuli presented in our previous VR study [130], our findings have limited ecological validity regarding the professional activities it aims to improve, which raises the necessity of further investigation assessing reported effects with workflow-specific stimuli.

5.5 Limitations & Future Work

As we replicated our VR study [130] with the same number of participants of similar ages, gender identification, equal handedness, health status, and haptic experience, our study incurs the same generalizability limitations regarding sample size and population representation. An analogous limitation regards the stimulus type, as it was sourced from our original experiment and does not represent the wealth of features and characteristics that digital objects could communicate visually and haptically [130]. In fact, our synthesized stimuli do not encapsulate the complexity of digital objects commonly encountered in professional settings, so future work is needed to assess the applicability of our findings to real-world objects and improve their generalizability. Additionally, we must acknowledge that the significant performance improvement observed in the projected surface environment could not have occurred at the same rate if stimuli exhibited visually ambiguous characteristics that stereoscopy and motion parallax could provide. Further research replicating our display environment with stimulus materials with richer depth variety would elucidate whether the absence of depth cues in 2D displays would be compensated by haptic cues, as hypothesized by the degeneracy construct [131]. Another limitation of our display environment comparison is that our original study may not have fully leveraged VR capabilities, as it did not promote physical co-location of visual and haptic cues [130]. Since visual stimuli occupied a much larger physical space than the grounded haptic device could cover, it is possible that performance in the visuohaptic sensory modality of our VR study may have been hindered [130], as such proprioceptive inaccuracy can lead to cognitive dissonance [136]. Previous research also indicates significant effects of spatial sensory cue alignment, or lack thereof, on task performance [88, 138]. Further research replicating our display environment and implementing visuohaptic congruence in the VR display environment would provide a more equitable comparison of the two display environments. Another limitation of our display environment comparison is that neither our VR study nor our projected surface replication measured participants' familiarity with the respective displays [130]. Therefore, although we might hypothesize that a likely gap in familiarity with 2D and VR environments could partially account for the observed performance gap, we cannot concretely assess the impact of display familiarity on the reported results. Our display environment comparison is also limited to a specific form of VR that employs a head-mounted device for immersion. Although HMDs have become the most prevalent type of VR, it is important to note that our results cannot be generalized to other forms of immersion, such as CAVE systems or other environments within the reality–virtuality continuum [26, 101].

6 Conclusion

This study extends previous virtual reality research on the object retention effects of visuohaptic integration to a less immersive projected surface display environment. Our findings suggest that visuohaptic integration can substantially enhance object retention in 2D display environments, as our analysis indicated that the visuohaptic sensory modality condition produced significantly lower error rates and faster response times compared to its unimodal visual and haptic counterparts. In addition to indicating that the effects of visuohaptic integration are consistent regardless of the display environment, our results suggest that projected surfaces may yield better retention performance in sighted conditions. However, this finding requires further research to overcome potential confounds in the display environment comparison. Our contribution extends the existing literature by demonstrating that the benefits of haptic feedback in forming accurate mental representations of digital objects for improved retention may be effectively realized without immersive VR setups. The implications of these results are significant for the design of interactive systems that aim to assist professionals who rely on precise object retention in their workflows. As our findings demonstrate that improved object retention may be achieved in two-dimensional display environments, our contribution provides a strong case for the broader implementation of haptic feedback in non-immersive settings. Interface designers aiming to leverage the memory advantages of visuohaptic integration may critically consider the benefits and drawbacks of VR implementation, as immersion might not be strictly necessary to reap the enhancements of haptics for object retention.

Data Availability

The data that support the findings of this experiment, along with their corresponding data analysis scripts and software on GitHub[5].

Acknowledgments

The author acknowledges the support of the Cluster of Excellence »Matters of Activity. Image Space Material« funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany’s Excellence Strategy – EXC 2025 – 390648296.

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Received 2024-07-01; accepted 2024-09-20