Can the Mighty Pen Be Mightier? Investigating the Role of Haptic Senses in Multimodal Immersive Learning Environments

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Abstract: This study explores the role of motor activity and tactile perception in Multimodal Immersive Learning Environments (MILEs) within the context of handwriting. A 2x2 factorial experimental design was used to investigate the impact of the intensity of motor activity and the sensitivity of tactile perception on learning performance, measured as memory recall. Mental effort and perceived workload were monitored as the mediating variables. Participants (N=20) completed a handwriting task, that is, copying text displayed on a prompter using a tablet and a stylus. During the task, the participants used additional pressure to increase the intensity of the motor activity and/or wore gloves to reduce the sensitivity of tactile perception. Results indicate no significant effect of either manipulation on recall, mental effort, or perceived workload. This may suggest that integrating supplementary haptic feedback technologies in MILEs does not impose additional cognitive load or obstruct learning. The findings contribute to the design of MILEs by informing the effective integration of wearable sensors to support authentic practice for skill acquisition. The study can inform future research that explores the effects of haptic senses and their broader applications in other learning contexts, contributing to a deeper understanding of embodied learning and dual-coding theory.

1 INTRODUCTION

As multimodal immersive technologies mature, authentic computer-supported learning environments in education have become increasingly accessible (Di Mitri et al., 2024). These environments facilitate authentic practice, which simulates realistic contexts that reflect the way knowledge will be used in real life (Di Mitri et al., 2022; Horz, 2012). Multimodal immersive learning environments (MILEs), supported by technologies such as sensors and mixed reality, enable authentic practice by engaging all the learners' senses, akin to the realistic contexts in the real world (Specht et al., 2019; Limbu et al., 2018). Schneider et al. (Schneider et al., 2019) used virtual reality to support the authentic practice of presentation skills by simulating the audience. In addition, sensors and actuators in MILEs enable the augmentation of experience, which can be used to provide in-situ learning support (Meik et al., 2021) required for the authentic practice of complex skills. For example, Limbu et al. (Limbu et al., 2019) used sensors to augment the pen strokes with different colors to provide supplementary feedback on handwriting pressure. With the growing use of MILEs-supported authentic practice in acquiring complex skills (Taguma and Frid, 2024), questions about how multimodality affects learning emerge; for example, in computer-supported authentic practice with virtual reality, where the learning experience can be manipulated, how does the amplification or diminishing of senses, such as haptic senses, affect learning?

Related research (Giannakos and Cukurova, 2023; Lee et al., 2023; Limbu et al., 2022) argues for the efficacy of multimodal and immersive technologies to support cognitive learning theories, such as Cognitive Load Theory and embodied learning. The Cognitive Load Theory (Sweller et al., 2011) assumes that learning imposes mental effort or cognitive load. Cognitive load significantly impacts the learning process, that is, the assimilation and retention of information in long-term memory (Paul A. Kirschner and Clark, 2006). In a specific context, information from the environment is received simultaneously through the multiple senses or modalities. Processing this incoming information imposes cognitive load. The dual-coding theory (Clark and Paivio, 1991) postulates that in-

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coming verbal and imagery information through the senses is processed through distinct cognitive channels. In other words, the cognitive load imposed by the two types of contextually related incoming information does not impose or impose minimal additional mental effort during the learning process. In embodied learning, as is often the case in authentic practice, multiple senses, and motor activities are involved (Clark et al., 2019). In this case, how the physical embodiment of the learner (in the case of embodied cognition) or the inclusion of additional senses (in the context of classical cognition theories), such as haptic sense/modality, impact learning is unclear. If all non-verbal information from senses, including the haptic sense/modality, is processed through a common channel (i.e., non-verbal) sharing the working memory as Dual-coding theory postulates, do embodied learning environments lead to a loss in learning performance?

However, integration of multiple senses has been found to significantly improve task performance in high load conditions (Marucci et al., 2021). While the use of additional senses may enhance learning in specific scenarios, Vermeulen et al. (Vermeulen et al., 2008), in contrast, also found that sensory overload often leads to an increase in mental effort for a specific modality. The design of effective MILEs necessitates an understanding of such implications of multisensory learning design. Therefore, in this paper, we investigate the association between haptic senses and learning via mental effort and perceived workload in the context of handwriting. We aim to address the following research questions:

- RQ1. **How does the sensitivity of tactile perception affect learning performance?**
- RQ2. **How does the intensity of motor activity affect learning performance?**

Haptic senses constitute multiple factors, such as tactile perception and motor activities. Tactile perception is the ability to sense and interpret incoming information through touch. First, we examine the impact of the sensitivity of tactile perception on learning (**RQ1**). Furthermore, tactile perceptions are tightly intertwined with motor activities. In an embodied learning design, all learning, regardless of whether it concerns sports or mathematics, emerges through action, which includes motor activities (Abrahamson and Lindgren, 2014). Notably, using motor activities has been shown to benefit students' performance, especially in maths (Shvarts and van Helden, 2023; Li et al., 2023). Since motor activities are indispensable to tactile perception and can impact learning, we secondly examine the impact of the intensity of motor activities on learning (**RQ2**).

In the following, we provide the background in the context of handwriting, followed by the research methods. Then, we provide the results, after which we present our discussions and conclusions.

2 BACKGROUND

In this work, we explored the association between haptic senses and learning in the context of handwriting. Handwriting remains a prevalent motor activity in educational contexts and has proven beneficial for learning. Handwriting has been found to be a predictor of literacy skills in primary grade students (Skar et al., 2022; McCarroll and Fletcher, 2017) and in Kindergarten students (Ray et al., 2022). This highlights the importance of internalizing competent handwriting fluency and is a prerequisite for all further handwriting-related learning benefits. For example, several studies (Mueller and Oppenheimer, 2014; Wrigley, 2019; Flanigan et al., 2024) found that students who took notes on laptops performed worse on conceptual questions than students who took handwritten notes. The authors argued that laptop note-takers tend to transcribe lectures verbatim, which is detrimental to learning. In contrast, handwriting necessitates processing information and reframing it in their own words, as handwriting is slower than typing, and students need to condense the incoming information. This requires more mental effort, which means the student must cognitively engage with the material. Corroborating this, Longcamp et al., (Longcamp et al., 2005) and Smoker et al., (Smoker et al., 2009) argued that the brain receives multiple signals during writing (visual, motor, and kinaesthetic), which typing does not do in the same manner. This results in increased activation in brain regions associated with language processing, working memory, and executive functions during handwriting tasks, which is beneficial for learning (Van der Weel and Van der Meer, 2024). By inference, based on the Dual-coding Theory, we can conjecture that the haptic senses during handwriting potentially allow students to expend more mental effort, which results in better assimilation and recall of information.

2.1 Handwriting and Memory

Related research demonstrated that taking notes by hand – instead of typing – can lead to improved memory (Smoker et al., 2009; Bouriga and Olive, 2021; Van der Weel and Van der Meer, 2024). This may seem counterintuitive, as the higher-level cognitive processes involved in handwriting seem to place extra mental effort on working memory, inhibiting the ability to store information in short-term memory (Peverly, 2006). Working memory holds a limited amount of information during the assimilation and recall of information in the learning process (Baddeley, 1990), and requiring a student to hold more information than possible at any given time can lead to cognitive overload. While handwriting demands more mental effort during the assimilation process than typing, handwriting leads to better short-term and long-term recall than typing (Bouriga and Olive, 2021). Learning strategies referred to as "Desirable Difficulties" (Bjork and Bjork, 2011) slow down the learner, such as requiring them to write with their hands, forcing learners to expend more mental effort leading to deeper levels of processing, and consequently better memory (Craik and Tulving, 1975). Weel & Meer (Van der Weel and Van der Meer, 2024), and James & Engelhardt (James and Engelhardt, 2012) found that handwriting, compared to typewriting, enhances brain connectivity patterns that support learning. Similarly, Ose Askvik et al. (Ose Askvik et al., 2020) found that handwriting with a digital pen induces theta-range synchronized activity in brain areas linked to memory and learning, which supports encoding new information.

2.2 Multimodal Immersive Learning Technologies in Handwriting

Multimodal Immersive Learning Environments (MILEs), using sensors and actuators, are capable of supporting authentic practices (Di Mitri et al., 2022; Limbu et al., 2018). Moreover, they are capable of augmenting authentic practices by amplifying or inhibiting various stimuli in the environment. Danna and Velay (Danna and Velay, 2015) delineate boundaries between the various types of stimuli in authentic handwriting practice. According to the authors, primary stimuli are naturally present in writing, namely visual, proprioceptive feedback from the hand, etc. The supplementary stimuli, on the other hand, are consequences of applied technologies and their affordances, which can potentially benefit learning (Danna and Velay, 2015; Kiefer and Velay, 2016). Loup Escande et al., (Loup-Escande et al., 2017) and Limbu et al., (Limbu et al., 2019) have used color gradients in their applications to provide supplementary visual information about pen pressure while writing. Loup Escande et al., (Loup-Escande et al., 2017) found that the supplementary information led to an increase in mental effort, while Limbu et al., (Limbu et al., 2019) found no significant difference. It should be noted that Limbu et al., (Limbu et al., 2019) have limited participants to make definite conclusions.

In summary, handwriting benefits memory by activating multiple sensory pathways, while the additional mental effort required enhances cognitive engagement, fostering deeper learning. This encourages MILE designers to use haptic senses during learning, but it is essential to exercise caution. First, Yoshida et al., (Yoshida et al., 2015) postulate a smaller memory capacity for haptic senses than for visual senses. A complex implementation of haptic stimuli can more easily create cognitive overload. Second, while the advantages of handwriting on paper have been well studied, there is a lack of understanding of how those benefits will transfer to digital devices, such as in the case of MILEs (Kiefer and Velay, 2016). In this study, we explore the timely need to better understand the implications of haptic senses for learning to support the design of MILEs.

3 METHODOLOGY

To investigate our research questions, we designed a formative study. For this study, we defined haptic sense across two dimensions: a) the sensitivity of the tactile perception and b) the intensity of motor activity. We experimentally compared the learning performance of the four groups (see Section 3.1, Table 1) with a memory-based post-test. Additionally, we compared the mental effort and perceived workload of the groups as the mediator variables.

3.1 Experimental Design

Table 1: Four study groups (P=Pressure, G=Glove): three experimental groups (Group 1, 2 and 3) and one control group (Group 4).

Study groups		
Group	Condition	N
1	P + G	5
2	P + ¬G	6
3	¬P + G	5
4	¬P + ¬G	4

This study investigated the effect of specific haptic senses, namely, handwriting pressure and tactile perception, on learning as memory recall (Paul A. Kirschner and Clark, 2006). The experimental design used between-subjects 2x2 factorial design (see Table 1). The two treatment conditions were: 1. intensity of motor activity implemented by additional writing Pressure (P), and 2. inhibiting the sensitivity of tactile perception by use of a Glove (G). The participants of Group 1 used additional pressure while writing and used a glove (P+G). In Group 2, the participants only used additional pressure (P+¬G), Group 3 did not use additional pressure but wore gloves (¬P+G), and the participants in Control Group 4 did neither (¬P+¬G). Participants who were required to use additional pressure while writing, i.e., Group 1 and 2, were informed about the distinct audio signal that would occur to notify when pressure was below the required threshold. This audio signal was noticeably different from the auditory stimuli for the secondary task (see Section 3.5.2).

3.2 Participants

Twenty (20) participants took part in the study; twelve (12) were female, and eight (8) were male. The mean age of the sample was 22.09 (SD=2.09). The female participants were, on average, younger (M = 21.6, SD = 1.83) than the male participants (M = 23.1, SD = 2.23). The participants were university students in the Computer Science faculty and were fluent in German, as the study was conducted in German. Only right-handed students were invited to control the variation that may arise from the dominant hand.

3.3 Apparatus

A WACOM One™graphic tablet with a display and complementary stylus pen was used by the participants to copy the text displayed on the adjacent monitor (see Figure 1). The graphic tablet was connected to a PC running a custom application developed to log the pressure. It also reminded the participants in the "P" treatment group to exert more writing pressure when it was low. A gardening glove with minimal impact on the pen grip was used to reduce the sensitivity of the tactile perception for the group with the "G" treatment. A keyboard was also placed next to the participants. The participants were instructed to react to the auditory signal associated with the secondary task (see Section 3.5.2) as fast as possible by pressing the spacebar button on the keyboard.

3.4 Procedure

Once the participants arrived, they were briefed about the study's objectives and the experimental task. They were provided with a consent form and informed that they could withdraw from the study at any point and they could ask questions throughout its duration. Once the consent form was signed, the participants received a unique identifier code. This code was used to anonymize participants' data. The study was approved by the ethics board of the university where the study was conducted.

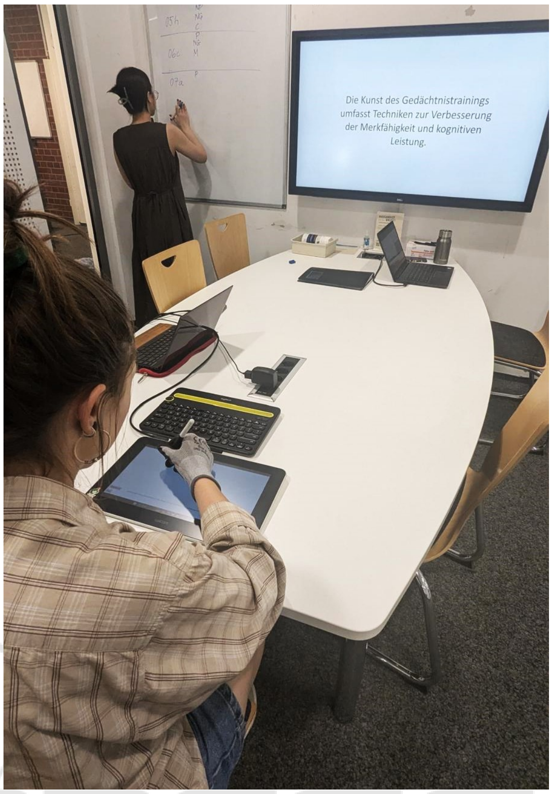

Figure 1: Experimental setup in which the teleprompter (monitor) displays text that the participants copied with a stylus pen.

First, the participants were required to familiarise themselves with the apparatus. Then, they were randomly assigned to one of the study groups. They were once again briefed about the experimental task, that is, to copy the text shown in the prompter, and the secondary task, that is, to react to the auditory stimuli by pressing a button on the keyboard with their left hand. The text for the experimental task that the participants were required to copy was displayed on the prompter sentence by sentence. Based on the treatment conditions, participants were assigned to either wear a glove, write with extra pressure, do both, or write normally (see Section 3.1).

After completing the experimental task, participants answered a multiple-choice test that checked their recall of the text displayed in the prompter. They also responded to the NASA-Task Load Index (Hart, 1986) to measure their perceived workload. The sequence in which these two tests were administered was randomized to reduce potential ordering effects (for example, the recall test might influence the perceived workload test and vice versa). The whole procedure lasted approximately 30 minutes.

3.5 Materials and Measures

3.5.1 Perceived Workload

Perceived workload, i.e., the amount of physical and mental effort invested, is measured using the Nasa-TLX instrument (Hart, 1986). The NASA-TLX evaluates perceived workload across six dimensions: *mental demand, physical demand, temporal demand, performance, effort, and frustration*. Participants rate each dimension on a scale from 0-100, reflecting the perceived intensity of each factor. A pairwise comparison between the 15 pairs from 6 dimensions is then performed in which the participant selects the most influential dimension from the two. Based on this, the individual weights for each dimension are calculated and then used to calculate the overall workload.

3.5.2 Mental Effort

Additionally, *mental effort* is also measured using the dual-task method. The dual-task paradigm is a behavioural method to estimate mental effort over time by providing a second task in addition to the primary task (such as reacting to auditory stimuli by pressing a switch, (Limbu et al., 2019)) to measure a decay in performance in the secondary (or primary) task (Esmaeili Bijarsari, 2021). As a secondary task in this study, participants responded to the auditory stimuli by pressing the spacebar key on a wireless keyboard as fast as possible. Their reaction time was logged in milli-seconds.

3.5.3 Immediate Recall

Recall is measured using a knowledge test. The knowledge test is administered using a multiple-choice questionnaire, which assesses the participant's ability to remember and correctly recall the information presented during the experiment. Due to the immediate administration of the test following the experiment, we regard the recall knowledge test as *immediate recall*. The knowledge test consists of 10 questions related to the content presented during the experiment that the participant was required to copy during the experiment. For each question, there were four possible choices with only one correct answer. Additionally, a control question was added to the test to ensure that the participants were not randomly filling in the questionnaire. Furthermore, participants were also instructed to skip the question if they did not know the answer rather than guessing.

4 RESULTS

The data collected as part of this study is publicly accessible (Limbu and Chounta, 2025).

Table 2: Mean and standard deviation for Immediate Recall, Perceived Workload, and Mental Effort.

Results [$\bar{x}$, sd]			
Group	Immediate Recall	Perceived Workload	Mental Effort (sec)
	Max=10	Max=100	Min-Max = 2.74-14.88
1	**7.20**, *1.64*	**57.2**, *21.0*	**5.42**, *1.18*
2	**7.17**, *1.72*	**46.8**, *16.2*	**4.55**, *1.12*
3	**8.40**, *1.52*	**40.2**, *14.2*	**8.77**, *4.07*
4	**8.25**, *1.71*	**52.0**, *13.6*	**4.77**, *2.09*

4.1 Perceived Workload

A two-way analysis of variance (ANOVA) was conducted to examine the effects of handwriting pressure (additional pressure vs. normal pressure) and glove (wearing a glove vs. no glove) on perceived workload. Levene's test for homogeneity of variances was conducted to assess the assumption of equal variances across the four groups. The result was not statistically significant, indicating that the assumption of homogeneity of variances was met [$F(3, 16) = 0.001$, $p = .999$]. Therefore, the variances can be assumed to be equal across groups. However, a relatively small sample size (N=20) across four groups means a higher probability of Type II error.

The ANOVA test showed that there was no statistically significant difference between the handwriting pressure conditions [$F(1, 16) = 0.664$, $p = .427$, $\eta^2 = 0.04$]. Similarly, the effect of wearing a glove on perceived workload was not statistically significant [$F(1, 16) = .003$, $p = .957$, $\eta^2 = 0.22$]. The interaction effect between handwriting pressure and a glove was not statistically significant [$F(1, 16) = 2.167$, $p = .160$, $\eta^2 = 0.12$], suggesting that the two conditions did not affect each other's influence on the perceived workload. While the η^2 value of 0.12 suggests a moderate effect of the handwriting pressure and wearing a glove on perceived workload, the small sample size (N=20) prohibits drawing further conclusions.

Descriptive statistics (see Table 2) showed that Group 1 (M = 57.2, SD = 21.0) perceived the biggest workload, followed by the control Group 4 (M=52, SD = 13.6).

4.2 Mental Effort

A two-way analysis of variance (ANOVA) was conducted to examine the effects of handwriting pressure (additional pressure vs. normal pressure) and glove (wearing a glove vs. no glove) on mental effort. Levene's test for homogeneity of variances was conducted to assess the assumption of equal variances across the four groups. The result was not statistically significant, indicating that the assumption of homogeneity of variances was met [F(3, 16) = 1.887, p = .172]. Therefore, the variances can be assumed to be equal across groups.

ANOVA showed that there was no statistically significant difference in the reaction time, thus the mental effort, between the handwriting pressure conditions [F(1, 16) = 3.63, p = .075, η^2 = 0.18]. However, the effect of wearing a glove on reaction time while writing was marginally significant [F(1, 16) = 4.50, p = .050, η^2 = 0.22]. The interaction effect between handwriting pressure and a glove was not statistically significant [F(1, 16) = 2.11, p = .166, η^2 = 0.12], suggesting that the two conditions did not affect each other's influence on the mental effort. While the η^2 values suggest a moderate-to-large effect of the handwriting pressure and wearing a glove on reaction time, the small sample size (N=20) prohibits drawing further conclusions.

Descriptive statistics (see Table 2) showed that Control Group 3 (M = 8.77, SD = 4.07) had the longest reaction time. However, the large SD of 4.07 is caused by an outlier, with one of the participants taking 14.88 ms, which is drastically different from the other participants in the group. Group 2, which applied additional handwriting pressure but did not wear a glove, had the shortest mean reaction time (M=4.55, SD = 1.12).

4.3 Mediation Analysis

Mediation analysis was conducted using bootstrapped estimates with 5000 draws to examine whether mental effort, and perceived workload (mediating variables), mediated the relationship between the group (independent variable) and recall results (dependent variable) in a sample of 20 participants. Group 4 *(¬P+¬G)* was treated as the reference group. The analysis was conducted using structural equation modeling (SEM) with the maximum likelihood estimator in *lavaan* in Rstudio™.

Model Specification. The following relationships were tested

- *a* paths: The effects of Group on the mediator (Mental Effort or Perceived Workload).
- *b* paths: The effect of the mediator on Recall.
- *c* paths: The direct effects of group assignment on Recall, controlling for the mediator.
- Indirect effects (*a***b*): The mediated effects of group assignment on Recall via the mediator.
- Total effects: The overall effects of Group on Recall (direct + indirect effects)

4.3.1 Mental Effort

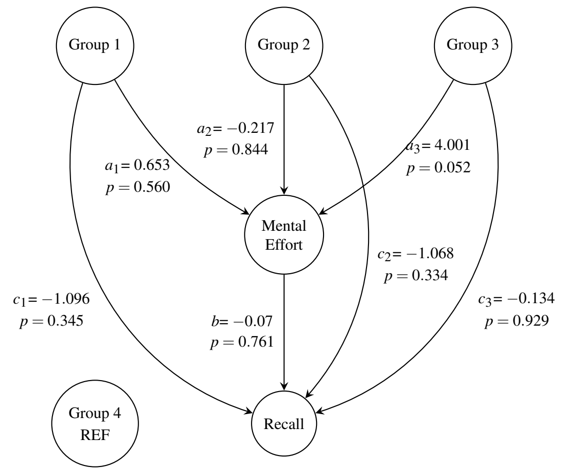

Figure 2: Path-diagram with Mental Effort as mediating variable.

Table 3: Effects of treatment (group) on Recall via Mental Effort.

Mediation analysis on Mental Effort			
Group	Estimate	Significance	95% Confidence Interval
Direct Effects			
1	-1.096	.345	[-3.427, 1.167]
2	-1.068	.334	[-3.233, 1.087]
3	-0.134	.929	[-3.198, 2.465]
Indirect Effects			
1	0.046	.904	[-0.420, 1.137]
2	-0.015	.957	[-0.646, 0.549]
3	0.284	.787	[-1.086, 2.745]
Total Effects			
1	-1.050	.344	[-3.167, 1.250]
2	-1.083	.321	[-3.225, 1.111]
3	0.150	.891	[-1.833, 2.533]

The direct effects of the three groups (1,2,3) on recall were not statistically significant compared to the control (group 4). Similarly, the indirect effects of the three groups on recall via mental effort were not significant. The total effects of the groups on recall were also not statistically significant (see Table 3). The mediation analysis indicates that the mental effort did not significantly mediate the relationship between the three groups (various treatments) and recall (memory). None of the indirect or direct effects reached statistical significance, suggesting that the differences in group treatments (relative to Group 4) did not significantly impact recall either directly or indirectly via the mental effort.

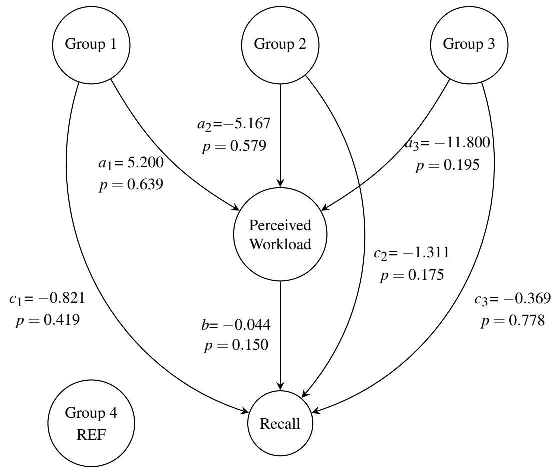

Figure 3: Path-diagram with Perceived Workload as a mediating variable.

Table 4: Effects of treatment (Group) on Recall via Perceived Workload.

Mediation analysis on Perceived Workload			
Group	Estimate	Significance	95% Confidence Interval
Direct Effects			
1	-0.821	.419	[-2.765, 1.269]
2	-1.311	.175	[-2.768, 1.006]
3	-0.369	.778	[-2.836, 2.414]
Indirect Effects			
1	-0.229	.716	[-1.669, 0.979]
2	00.227	.615	[-0.895, 0.994]
3	0.519	.406	[-0.585, 1.943]
Total Effects			
1	-1.050	.344	[-3.167, 1.250]
2	-1.083	.321	[-3.225, 1.111]
3	0.150	.891	[-1.833, 2.533]

4.3.2 Perceived Workload

These results indicate that the three groups (1,2,3) did not have a statistically significant effect (relative to Group 4), directly or indirectly, on recall (see Table 4). This suggests that perceived workload did not mediate the effect of group assignments on immediate recall. None of the indirect or direct effects reached statistical significance, suggesting that the differences in group treatments (relative to Group 4) did not significantly impact recall either directly or indirectly via the perceived workload.

5 DISCUSSION

The sensitivity (or depravity of tactile perception here) was enforced by requiring the participants to wear gloves during the writing process (**RQ1**). The intensity of motor activity was enforced by requiring the participants to write with additional pressure (**RQ2**). The learning performance was measured by the participant's performance on the immediate recall test. The mental effort and the perceived workload were recorded as the mediating variables. There was no significant effect of the intensity of motor activity and the sensitivity of tactile perception on the mediating variables. Furthermore, the two treatments also did not interact with each other. The mediation analysis (see Section 4.3) showed no significant direct or indirect effect of the groups on the learning performance, both via mental effort or perceived workload. Additionally, the statistically non-significant total effects of the groups showed that neither wearing gloves to deprave the tactile perception nor writing with additional pressure has any impact on the recall. However, the consistency of the total effect of perceived workload and mental effort on recall across the two models suggests that they are both constructs measuring the same or very similar variable, and/or they do not significantly contribute to the relationship between group assignment (independent) and immediate recall (dependent) in comparison to the reference group (Group 4).

The results indicate that the mental effort and/or perceived workload did not significantly differ across the two treatment conditions, nor did the treatments interact. As the learning in the context of this study was purely cognitive,i.e., assimilation and recall from memory, the finding is in line with Ray et al. (Ray et al., 2022), who only found weak evidence for the effect of psychomotor aspects on cognitive learning. The documented benefits of handwriting for memory are often associated with literacy (Skar et al., 2022; Ray et al., 2022). In the cases where benefits were observed in regards to memorization of concepts in university students (Flanigan et al., 2024; Wrigley, 2019; Mueller and Oppenheimer, 2014), the learners were cognitively engaged due to the time constraint which required them to actively process information to condense them. Consequently, the experimental task used in this study, that is, copying text shown in a prompter, might not have cognitively engaged the learner.

Further, the treatment (haptic) conditions were intended to stress the working memory through the non-verbal or imagery system of the Dual-coding model. However, the treatment is also contextually closely coupled with the information received by the verbal system (Text/words), as the experimental task uses the verbal channel in the form of printed texts. This aligns with suggestions from Danna and Velay (Danna and Velay, 2015) and potentially hints towards the integration of haptic modality in the Modality principle in Multimedia Learning (Mayer, 2005), which suggests that the use of multiple modalities results in efficient learning when the information is contextually coupled.

5.1 Theoretical and Practical Implications

As the education landscape shifts towards competency-based frameworks, multimodal immersive learning environments (MILEs) for promoting authentic practice of complex skills are becoming increasingly common. MILEs require tracking the learner's actions in the environment. This is often accomplished by using wearable sensors, which paradoxically are added on top of the actual authentic settings. For example, Mat Sanusi et al., (Mat Sanusi et al., 2021) used smartphone sensors by attaching a smartphone to the learner's body, arguably affecting the learner's authentic performance. Thus, understanding the effect of such additions on learning is of utmost importance for designing efficacious MILEs.

The study results suggest that wearing a glove and/or exerting additional effort in the form of pen pressure does not affect recall, mental effort, or perceived workload. Thus, such manipulations in MILEs may not lead to cognitive overload and, therefore, have minimal impact on learning. However, Vermulen et al., (Vermeulen et al., 2008) found that sensory overload resulted in cognitive overload when additional stimuli were presented, but the increase in the intensity of existing primary stimuli seemed to have no impact. This potential to provide additional feedback and support during authentic practice in MILEs can improve learning and acquisition of complex skills (Danna and Velay, 2015).

This may posit that wearable sensors can potentially be safely used for learning handwriting. Doug (Doug, 2019) found that the students' handwriting performance is continuously degrading, affecting their academic performance. While occupational therapy-based interventions have proven beneficial (Hoy et al., 2011), they cannot address the issue at the required scale. MILEs can contribute towards solving this problem by automating educational aspects surrounding handwriting. For example, automated systems utilizing consumer tablets have been developed to diagnose handwriting difficulties such as dysgraphia (Asselborn et al., 2020).

Similarly, Dikken et al., (Dikken et al., 2022) also developed a sensor-based application for training handwriting that provided real-time feedback on various handwriting attributes based on the teacher's expertise. Such attributes, like pen pressure and perceptual-motor abilities, directly impact handwriting itself(Dennis and Swinth, 2001), which further affects academic performance. The potential to use increasingly more invasive sensors, such as the wearable glove from SenseGlove™without adversely affecting learning, broadens the possibilities for more inclusive multisensory and seamless learning design (Specht et al., 2019). For example, such environments can cater to people with hearing loss by the use of vibration motors to provide a sense of direction in mixed-reality environments.

5.2 Limitations

The study is limited by the amount of participants (N=20). Despite the use of bootstrapping with 5000 draws, the limited number of participants divided into four groups is not sufficient to overlook this limitation.

The study was also limited by the choice to use a text excerpt for recall. This is in contrast to other studies (Smoker et al., 2009; Bouriga and Olive, 2021; Van der Weel and Van der Meer, 2024), which used an array of unrelated words to test the memory. Structured text excerpts may not necessarily overload the working memory, especially in the presence of prior knowledge. No pre-test was performed to test the presence of prior knowledge. However, the text excerpt was taken from a geology book under the pretense that the students from the computer science faculty would have minimal knowledge of the topic, if any at all. Using a text excerpt was a conscious choice to test the effects of handwriting in the absence of repetition.

The experimental treatment involved manipulating two aspects of the haptic sense, but each was only altered in one direction, even though opposite manipulations might also influence learning. For example, writing on paper is superior in terms of brain activation in comparison to writing on digital tablets (Umejima et al., 2021), conceivably due to the increased friction provided by the paper's rough texture. In this study, the tactile perception was reduced, and the writing pressure was increased. However, we did not study the effects of their corresponding reverse manipulation.

Lastly, the NASA Task Load Index (NASA TLX) questionnaire used in the study consists of only 14 categories compared to its 15 categories. One category was removed as it was irrelevant to this study. This discrepancy can impact the reliability of the instrument.

6 CONCLUSION

In this study, we experimentally investigated the effect of manipulating two attributes associated with haptic sense, namely tactile perception and motor action, on learning. Learning is defined as the assimilation and recall of information from memory. As the learning process is impacted by cognitive load, which correlates to mental effort, mental effort was observed as the mediating variable. Additionally, perceived workload, which represents both the mental and the physical effort, was also included due to the emphasis on the haptic senses. The use of gloves manipulated the tactile perception, while the motor action was manipulated using software to enforce higher pressure while writing. The results of the study showed no statistically significant effect of the treatments, individually or combined, on the learning performance via mental effort or perceived workload compared to the control. No significant effect of the treatment was observed on the mediating variables as well. The findings of this study contribute to our understanding of the design of multimodal immersive learning environments and embodied learning to enhance memory and the acquisition of complex skills. It also contributes to improving our understanding of dual-coding theory in the light of haptic senses.

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