IMPROVING SENSE-MAKING FOR CONSTRUCTION PLANNING TASKS USING VISUAL AND HAPTIC STIMULI IN VIRTUAL REALITY ENVIRONMENTS

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ABSTRACT: *Design documents, drawings, and specifications are visual representations that are fundamental and prevalent in today's construction engineering practice. Construction specialties (e.g., structural, mechanical) rely on these visual representations to express and draw meaning during collaborations. Construction engineering and management (CEM) students must acquire the knowledge, skills, and abilities — a key example of which is perceptual competence —for interpreting visual representations to facilitate efficient task execution, such as planning. Empowering learners with new technology using robust real-world immersion and interactive features is a significant step towards this target. The presented research explores new human-machine interactions to determine the best way for CEM students to learn through the combined senses of sight and touch. The approach merges visual and haptic interactions within an immersive environment to enhance perception and reasoning skills. The research demonstrates how CEM learners interact with and interpret the meanings of information within a planning task. It explores how VR and haptic technology augment the ability to recognize meanings — a new type of representational competency — for improved interpretation of information related to components with respect to engineering disciplines and sub-systems in a CEM, and investigates learners' problem-solving ability by using perception-rich enhanced virtual reality (VR) and haptic affordances.*

KEYWORDS: *haptic cues, human-computer-interaction, design interpretations*

1. INTRODUCTION

To satisfy the educational needs of STEM learners and foster essential 21st-century skills, such as critical thinking, reasoning, problem-solving, collaboration, and communication, educators must integrate innovative technology into the learning process (NSF, 2020). To address these requirements, human-computer interaction (HCI) offers viable solutions to augment human senses and enrich sensory input, including vision, hearing, smell, and touch (Manchanda et al., 2017).

The sense of touch or haptics is one of the most informative human senses. This sense includes both cutaneous and kinesthetic sensations. Embracing haptics opens up new possibilities to expand human capabilities, such as improving manual dexterity and enhancing sensory perception (Chryssa & Julie-Ann, 2020). This research takes advantage of the HCI affordances and explores the use of haptic technology in learning for Construction Engineering and Management (CEM) students.

Fundamentally, to explore the use of haptics in CEM learning, the presented approach draws on an individual's spatial-temporal cognitive ability (STCA) (Mutis, 2018a). Spatial-temporal ability allows learners to effectively manage and comprehend significant amounts of spatial (how design components are related to one another in the 3D space) and temporal (the logic in a process, such as the order, sequences, and hierarchies of the resources within a construction task) information (Mutis, 2018a). Limited or no ability to process spatial and temporal information (i.e., lack of spatial and temporal cognitive ability hinders the understanding of designs and management of the varying local conditions (e.g., unplanned conditions) (P. Antonenko & I. Mutis, 2017; P. D. Antonenko & I. Mutis, 2017; Mutis, 2014, 2015; Mutis, 2018b). The ability helps learners to conceptualize three-dimensional relationships between objects in space and mentally manipulate them as sequential transformations over time.

The STCA cognitive ability allows the CEM learners to recognize meanings and facilitates coupling observed representation to the given contexts – a new representational competency. The coupling abilities (spatial and temporal) significantly benefit the decision-making process. Individual spatial-temporal abilities are associated with high cognitive reasoning that defines the cognitive-processing chain — from basic visual attention to higher-level reasoning, such as an interaction between organizing, performing, and supervising the effectiveness of a plan (Mutis, 2018a). For instance, planning is a highly cognitively demanding task where STCA plays a pivotal role. Planning is critical as the learner couples observed representation in a given context to organize, perform, and supervise the effectiveness of a plan while interpreting information from engineering designs. Effective STCA training enables individuals to instantly identify concepts, events, and patterns for comprehension and projection,

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streamlining actions, solutions, and implementations in planning.

The presented approach explores the uses of haptic technology to augment cognitive capabilities, in particular the STCA. The STCA augmentation effect is from the cognitive load reduction by using a new sensing channel (haptics) in the cognitive process by liberating mental resources for other cognitive tasks (Sweller, 1988; Sweller et al., 2019), potentially enhancing spatial and temporal processes that are fundamental in problem-solving tasks. The assumption is that learners can rely on their haptic sense to reduce efforts of converting cognitive processes into physical actions— alleviating the burden of effort for processing spatial (e.g., spatial configurations of design components in the 3D space) and temporal (e.g., the logical sequence of design components for their assembly) information. The use of new senses (haptics) is a form of increasing the impact of embodied intervention in the cognitive process by, for instance, facilitating tracking information and gaining object rotations to feel and comprehend spatial relations more accurately (Tran et al., 2017).

By using perception-rich enhanced virtual reality (VR) with haptic affordances, this study addresses the following questions:

1. What aspects of haptic stimulus impact the learners' development of representational competence for better interpretation of information related to designs in a CEM? The research outlines the importance of improving *spatial-temporal skills* to facilitate high-level reasoning in complex situations.
2. What *new HCI factors*, combining visual and haptic (VH) interactions with engineering designs, enrich the perception and reasoning skills of CEM learners, leading to more accurate and efficient task execution? The solution presents *a haptic language* that implies tactile cues enhancing spatial awareness for the given context.

2. BACKGROUND

Researchers in STEM education are exploring the ways in which haptic technology can enhance the learning process, including improving student engagement, conceptual understanding, and skill acquisition. Early studies focused on developing haptic devices for enhancing spatial awareness and visualization skills (Liu et al., 2003; Williams Ii et al., 2001). Later research underlined the benefits of haptic feedback in improving interactions and spatial guidance (Jong, 2014; Takahashi et al., 2009). As demonstrated in further publications, augmenting VR with haptics increases overall task performance and the users' perceived sense of presence (Cooper et al., 2018; Kreimeier et al., 2019).

Over the years, haptic interventions in architecture, engineering, and construction (AEC) have been applied to simulate assembly tasks (Medellín-Castillo et al., 2015) and develop vocational training for construction personnel such as carpenters, plumbers, and masons (Jose et al., 2016; Ranjith et al., 2014). Current research aims to cultivate more sophisticated haptic devices and techniques for human-machine interaction in AEC, including haptic feedback for mixed reality and teleoperation (Adami et al., 2022).

In general, haptics is extensively used in engineering learning, including training, physics and chemistry simulations, robotics, and automation (Prabhakaran et al., 2022; Sanfilippo et al., 2022). Engineering education utilizes haptic interfaces to provide students with hands-on experience with virtual simulations. Likewise, vocational training with haptics provides realistic practice in handling heavy machinery and tools. Lastly, by using haptic devices on remote-controlled construction robots, operators are able to discern the properties of various objects and materials during the manipulation (Alakhawand et al., 2022). Thus, haptic technology shows promise to transform traditional learning and training methods, offering advantages such as enhanced knowledge retention, engagement, skill acquisition, safety, and accessibility (Mastrolembo Ventura et al., 2022).

Several studies have been conducted on assembly techniques, but only a few have explored the incorporation of haptics due to their relative novelty as an assistive tool in STEM learning. However, the development of haptics shows potential for enabling innovative approaches to enhance cognitive and motor skills, particularly in tasks like modeling, assembling, and teleoperation. For virtual assemblies, Yuan et al. (2008) introduced an augmented reality (AR) approach, utilizing a virtual interactive tool called VirIP and a visual assembly tree structure (VATS). This system enables assembly operators to seamlessly follow a pre-defined assembly plan/sequence without requiring sensor schemes or markers on the assembly components. Hu and Zhang (2012) presented a method leveraging a 3D game engine and software component technique to rapidly construct a reusable component library to develop virtual assembly experiments. In recent work, Li et al. (2020) proposed a framework with advanced computations such as runtime degrees of freedom (DOF) determination, disassembly directionality computation, and assembly/disassembly sequence generation. These computations efficiently integrate assembly constraint information into a virtual assembly application with minimal effort required.

Haptic technology allows the transfer of touch-based information between humans and computer interfaces (OED, 2020). Haptics can enhance the learning experience and support an environment that cultivates student engagement, motivation, and interest in the subject matter (Tytler, 2020). Haptic interaction is crucial for a sense of presence and manipulating objects in remote or virtual environments with manual dexterity (Kortum, 2008, p. 25). For example, by providing users with tactile cues, haptics makes the digital environment more interactive and informative.

In the AEC discipline, there are proposed haptic interventions that aim to assist users in accomplishing an engineering task providing guidance for the decision-making process. Rahimian and Ibrahim (2011) proposed a haptic-based VR 3D sketching interface to improve novice designers' engagement with "problem-space" and "solution-space", leading to increased artifact maturity in collaborative conceptual architectural design. Following Christiand and Yoon (2011) work, haptic-path sequence guidance reduces the assembly time and the travel distance that enhances the working performance of virtual assembly tasks. Also, the availability of haptics in large immersive environments can contribute to future advances in virtual assembly planning and factory simulation (Pavlik et al., 2013). Yeh et al. (2013) suggested that multi-symbolic representations (text, digits, and colors) in haptics-enhanced virtual reality systems have the potential to help collaborative work effectively. James et al. (2019) proposed a bi-manual haptic interface for skill acquisition in surface mount device soldering. Coffey and Pierson (2022) demonstrated the effectiveness of the proposed haptic guidance system for co-navigation of non-holonomic vehicles through teleoperation. Williams et al. (2023) presented a framework for active haptic guidance in mixed reality using one or more robotic haptic proxies to influence user behavior and deliver a safer and more immersive virtual experience.

The primary focus of the mentioned studies was to improve the understanding of a process for training (e.g., the process of assembling building components). The studies have incorporated haptic guidance into the assembly processes, which helped users receive tactile feedback during the assembly tasks. However, the haptic guidance implementations fell short in providing spatial awareness and addressing high-order cognition in cognitively demanding tasks such as identification of the dependencies or hierarchy of building components for planning. While the haptic guidance aids in recognizing information about movements in training tasks through haptic feedback, the approaches do not offer a comprehensive understanding of the entire spatial context or interconnections between various building components. The presented study aims to overcome these limitations by exploring spatial-temporal cognitive abilities using visual and haptic stimuli.

Haptic feedback

Using electronic devices, we encounter multiple interactions, including sounds, flashes, and buzzing haptics (Müller, 2020). Such a combination of sensory stimuli allows the user to be fully engaged in the experience, which enriches the overall quality of the interaction. A crucial aspect of this set is haptic feedback, which draws from the psychological nature of interaction with the environment and other humans (e.g., social touch). Therefore, achieving precise replication of haptic signals in devices requires a deep comprehension of how humans perceive and attribute meaning to tactile interactions to portray their semantics accurately.

The human skin's discriminative ability arises from a dense network of cutaneous receptors allowing us to differentiate fine touch, pressure, texture, and temperature (Fulkerson, 2020). This adaptability of touch perception, known as adaptation rate, enables us to prioritize novel sensations while filtering out constant stimuli. Unlike some other senses perceived passively, haptic perception is inherently interactive and bidirectional – we actively explore and manipulate the environment to extract tactile details.

To recreate physical sensations, HCI incorporates various types of haptic technology, including force, vibrotactile, ultrasonic, thermal, and other forms of haptic feedback (Hatzfeld et al., 2015). Haptic interfaces allow users to experience tactile sensations while manipulating objects, discriminating textures, and applying forces in the virtual and physical environment.

According to the literature (Adilkhanov et al., 2022), haptics performs three primary functions such as simulation, teleoperation, and guidance. Through *simulations,* haptic feedback imitates physical interaction with the environment and its attributes to heighten the realism of learning scenarios. In *teleoperation,* the haptic interface provides a two-way communication channel between a robot and an operator, allowing the operator to perceive tactile feedback from the robotic tool (Luo et al., 2019). As part of the *guidance* process, haptics implement tactile patterns to derive directional cues to the user (Huang et al., 2019).

Guiding haptics becomes especially beneficial for facilitating the decision-making process and fostering problem-solving abilities by providing tactile cues to assist users in performing tasks or enhancing interactions in a physical and virtual environment (Bluteau et al., 2008; Feygin et al., 2002). This haptic function utilizes touch-based sensations to provide the users with real-time information, helping them make informed decisions and improving their overall performance and understanding of the context. Research suggests that using intuitive haptic guidance to assist the movement reduces errors (Mugge et al., 2016). Moreover, a partial-then-full haptic guidance strategy seems the most effective in improving learning outcomes (Teranishi et al., 2018). The most common applications of guiding haptics include vibrotactile feedback, often incorporated into commercial smartwatches for haptic notifications and alerts.

Haptic guidance can be achieved through a *haptic code* that utilizes touch-based symbols (e.g., haptic icons or "hapticons" (Enriquez & MacLean, 2003)) to instantly deliver information to the user via vibrations, pressure, or movement (Hatzfeld et al., 2015, p. 75). According to Enriquez et al. (2006), haptic code has to meet the following conditions in order to offer explicit meaning:

- *Differentiable*: All haptics must be distinct from one another when presented either alone or in any common haptic combinations.
- *Identifiable*: Once a meaning has been connected to a stimulus to form an icon, it must be simple to recall.
- *Learnable*: The associations between meanings and stimuli should be intuitive and easily remembered.

The elementary functions of the haptic code include providing notifications with neutral feedback and signals with either positive or negative meaning in response to the user's actions.

Haptic code can be applied even on a broader spectrum, e.g., for rendering abstract models or concepts as a new modality for communication. At the lowest level, haptic devices notify users of an event, their identity, or their current state or contents. A higher level of abstraction implies haptic associations that allow the users to identify interdependencies and determine a sequence of actions by assigning physical sensations to an object hierarchy. Accordingly, systematic, perceptually guided haptic design can support expressive and nuanced communication that qualifies as a new haptic language.

3. METHODOLOGY AND APPROACH

The study consists of two main phases: (1) the creation of the experimental training platform, designed to be interactive and informative; (2) experimentation, with active student participation for practical application and assessment of the learning outcomes. This comprehensive approach provides an effective and engaging program for students to develop their skills and comprehend complex building concepts in a virtual and immersive environment. The presented research is the first phase, including a case example to illustrate the approach.

Immersive virtual platform

The VR design consists of the development of a VR environment based on the detailed design of a building project (e.g., a small residential building). See Fig 1. The design was represented in a Building Information Model (BIM) with at least a Level of Detail 300. The BIM model contains rich data on engineering systems through represented objects or component assemblies, such as quantity, size, shape, location, and orientation. The design was exported as an Industry Foundation Class (IFC) file to preserve the semantic information of the building components. The exported model was then imported into Unity for two purposes. First, it acts as a reference point in the form of a translucent building, allowing the user to place building components accurately. Second, it is semantically broken down into corresponding building components to build game objects. The resulting structures were game objects created based on the standard categorization of the building into Sub-Structure and Superstructure and further classified into Structural, Architectural, and Mechanical components.

It is critical to note that the created game objects were set for true building scale, generating an immersion that represents dimensions for easy manipulation in the VR environment. Each game object had a representation that described data and text information in a structured format, involving attributes as game elements based on IFC structure. For example, each object game had data related to the activity (used for planning) in their element attributes (element descriptors). The element attributes held in addition to the planning activity information associated with unique haptic feedback, as discussed in the section below. For a logical representation in planning, game objects were nested based on a work breakdown structure (WBS)— a hierarchical tree structure subdividing the deliverables and work. The WBS disciplines will deliver the work specified in each work package—the lowest level in the WBS that represents a specific amount of work. The work package as product and deliverable has a VR object representation. The structure of these components is shown in Fig. 1.

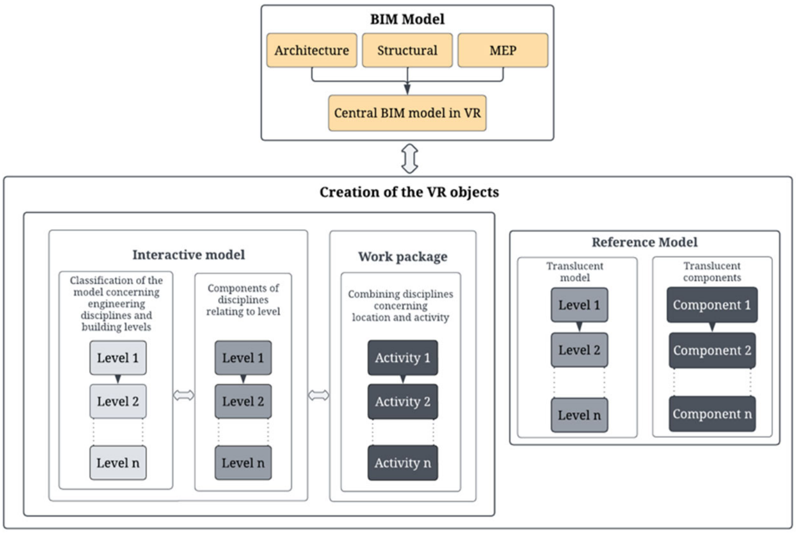


Fig. 1: Design structure of the VR platform.

Experimental Platform

Unity software integrated with a VR headset Oculus Pro and a full set of haptics devices (see 2) were used for the development. This state-of-the-art platform provides users with a fully immersive experience. An example of the visualizations is shown in Fig. 5a and Fig. 5b. They illustrate a dashboard and virtual design components where users learn virtual manipulation, featuring an informative activity pane to hold building components as activity tiles and servicing as a comprehensive reference model for planning activities to enhance the overall learning experience.

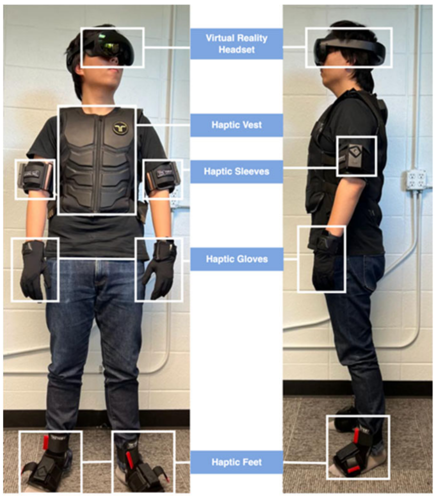


Fig. 2: Haptic devices for the VR platform.

Haptic (*vibrotactile*) code

The researchers systematically structured the haptic code as feedback for the simulation and experimentation in VR environment. The code contains the logical patterns that guide the user's manipulation of the building components through interaction augmented by haptic feedback. The code has signatures expressed as haptic icons, i.e., a haptic icon is a brief haptic stimulus associated with meanings. The haptic icons were designed to intuitively comprehend cues about a function of the object and interact (user-object effects) in the virtual environment. The code is a form of primary language wherein each icon is a constant pattern with associated semantics. The learners (users) are required to get familiarized with the code (akin to learning a primary language to operate a system) *a-priory*.

To associate semantics to the haptic code, four key perceiving haptic features play a crucial role in defining the tactile experience:

- *Intensity*. It governs the strength or magnitude of the tactile sensation delivered to the user. It determines how strong or weak the haptic feedback feels, allowing for the creation of subtle or intense tactile perceptions.
- *Sharpness*. It relates to the perceived abruptness or distinctness of the haptic sensation. It influences whether the sensation feels smooth or sudden.
- *Duration*. It refers to the length of time of the perception of haptic feedback. Short durations can convey quick events, while longer durations can simulate prolonged interactions or sustained sensations.
- *Granularity.* It is determined by the frequency of impulses and their spacing. The more granularity, the more rapid the impulses.

Manipulations with these haptic features enable prototyping and fine-tuning haptic experiences to match specific interactions and simulation scenarios, enhancing user engagement and immersion in virtual environments. The combinations of the haptic features assigned to a haptic device evolve into distinctive haptic patterns.

Haptic code (*vibrotactile*) types

The haptic code consists of two types of haptic feedback: operational and functional.

Operational

It refers to haptic feedback of the basic human-computer interaction (HCI) with the elements of the virtual environment, such as feedback on actions on the system components (to select, cancel, move, etc.). The approach includes three types of operational haptic feedback:

- *Positive* to reflect the correct actions of the user by giving soft impulses with low or medium intensity;
- *Negative* to associate the mistakes and has more even rigid impulses, medium or high intensity;
- *Neutral* to provide alerts to the user regarding updates or notifications (it is presented as a row of short impulses with gaps in between).

Functional

It refers to the feedback that gives semantics associated with activity planned in VR deployment.

Parameters of duration (D), granularity (G), intensity (I), and sharpness (S) define the functional haptic code. The combination of parameters defines features that indicate semantics. The combination can be represented in a two-dimensional matrix of *n* rows (where *n* is the number of combinations). See Fig. 3. Each row represents the distribution of values of parameters (D, G, I, S).

A VR object will have an associated haptic code combination (DGIS), representing a specific value and semantics.

Fig. 1 illustrates the approach conceptualization of the intersecting components (virtual environment, structure of VR objects, haptic (vibrotactile) code, semantics haptic feedback (as semantics), and the spatial temporal cognitive ability (while interacting with problem solving in CEM). The arrangement impacts the spatial-temporal cognitive abilities of learners, assisting them in accurately defining the sequence of activities through the integration of visual and tactile cues.

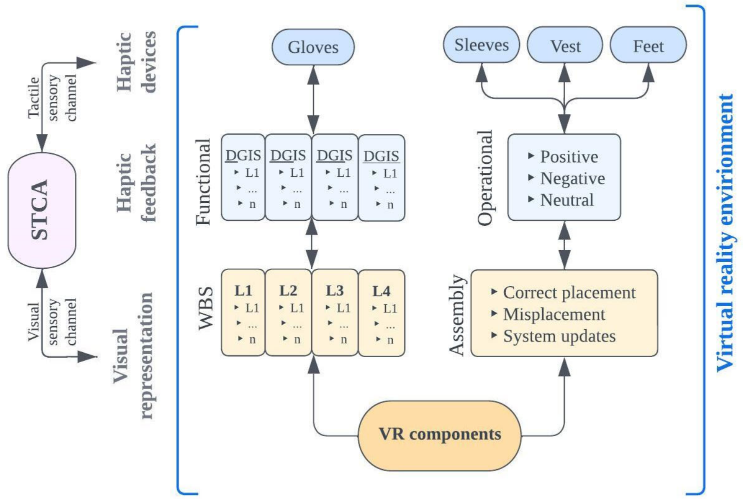


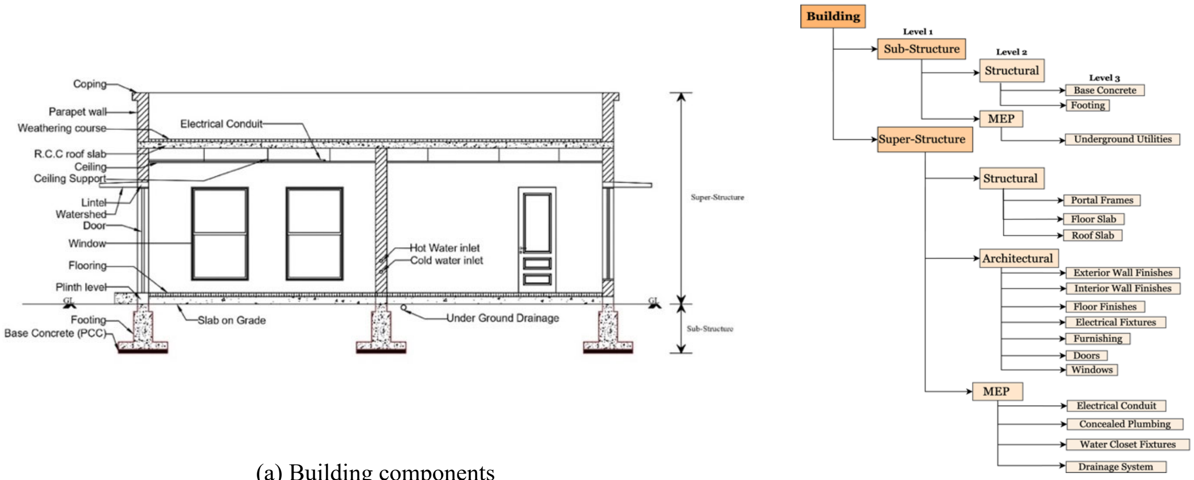
Fig. 1: Approach conceptualization.

Case Example

Learners are required to plan the construction of a small building design section in the VR environment (see Fig. 2). The user should build the plan by identifying construction work packets (associated components and activities). A work package (construction product deliverable) serves to establish a coherent and feasible subdivision of tasks within the construction project. Each packet has associations with physical areas (work zones) to cover all the components of the design.

A work breakdown structure (WBS) that incorporates the components and activities associated with the small building design (see Fig. 2a) is presented as a dashboard in the VR environment (see Fig. 5a). The WBS is used as a baseline for planning. The first milestone is set for substructure completion of the building design, and the second is set for the superstructure (see Fig. 2b). Each building component from the design is the deliverable of an activity.

The assembly sequence for each activity and packet (construction product deliverable) is based on the Finish-To-Start (FS) inference (logical relationship between two activities). A finish-to-start relationship implies that the predecessor activity needs to be finished before any subsequent actions can start.

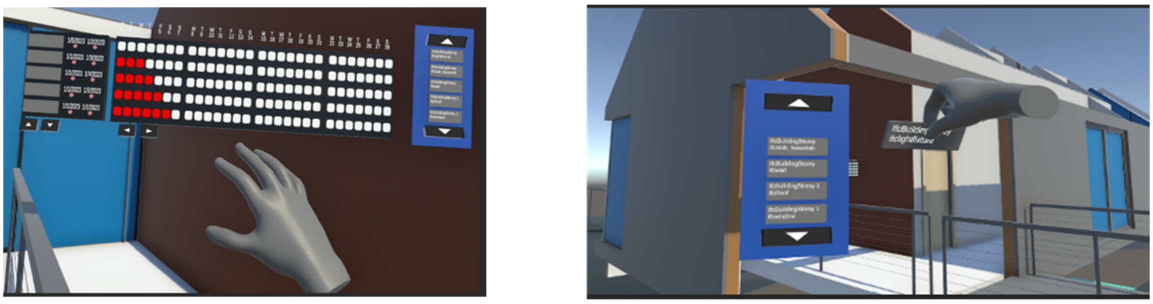


(a) Building components

(b) A breakdown of the building components in a hierarchical structure

Fig. 2: Construction product deliverables from work breakdown structure (WBS).

After the user selects the packet from the dashboard in the virtual environment (see Fig. 5a), the next step is to select, drag, and drop the design component (deliverable) of the small building on a virtual layout by performing a virtual walkthrough (see Fig. 5b).



(a) A dashboard servicing as a reference model to visualize WBS packages for conceptual planning.

(b) Snapshot of the mapping between the work package and the reference model (virtual layout of the building).

Fig. 5: Interactive haptic activity for a planning task in the VR environment.

The order of activities corresponds to the deliverable sequence, and each deliverable has an associated location in the virtual layout. The assumption for the case example is that the presented activities depend on the completion of others before they can begin (FS precedence). Planning these activities takes the dependencies (precedents) into account by arranging activities in a logical sequence. The arrangement of all deliverables is the planning of the construction section of a small building design in the VR environment.

The users need to locate (by dragging and dropping) all the deliverables of the building section in the virtual layout space during the virtual walkthrough. By completing all the packets in the dashboard, the user can complete the planning of the building.

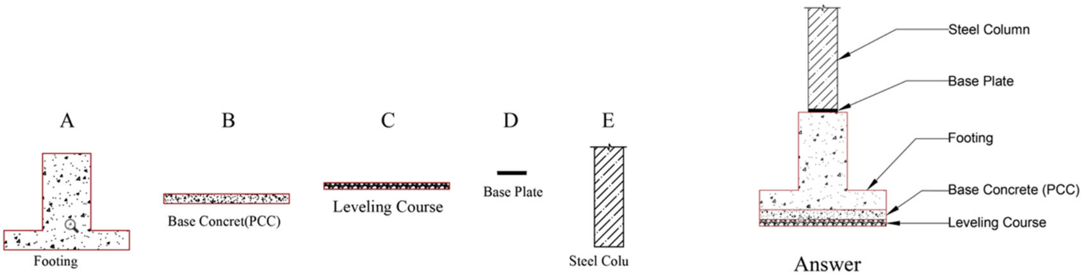
Haptic feedback is an interactive feature that responds to the actions of the users within the VR environment — i.e., certain actions generate a type of haptic feedback with associated code (meaning). When the user drags and drops a deliverable on its selected location, there are two potential haptic feedback: functional and operational. Thus, *operational* and *functional* haptics complement each other to assist with the understanding of the semantics and ensure proper placement of the system components. Operational haptic feedback is on basic human-technology interaction, while functional haptics are systematically organized and tailored to specific semantics that indicate hierarchical structures.

For example, if the deliverable is placed correctly, operational haptic feedback (*positive operational feedback* using soft impulses with low or medium intensity) would indicate a code that will inform the user that the correct location was correctly selected. However, if it is misplaced, operational feedback with the associated code (*negative operational feedback* using rigid impulses, medium and high intensity) is given to indicate to the user the error of displacement. Another example of operational feedback is *positive* when the user reaches a designated milestone while finalizing the packets from the WBS. Otherwise, *negative* feedback is given — indicating that more selections are required for planning. *Operational* haptic (vibrotactile) is produced by the haptic sleeves, which offer feedback for component manipulations like selection and canceling, as well as the haptic vest and feet, which are responsible for delivering notifications, success signals, and failure alerts. Code examples of operational feedback are shown in Table 1.

Table 1: Operational haptic feedback code

Events	Meaning	Haptic feedback	Intensity		Duration [ms]	
Select	A component is taken	Medium intensity, medium sharpness, and short duration, two short impulses with increasing intensity	low	0.2	short	150
			medium	0.5	short	200
Cancel	A component is thrown	Medium intensity, medium sharpness, and short duration, two short impulses with decreasing intensity	medium	0.4	short	100
			low	0.2	short	150
Notification	Generating another component	Medium intensity, medium sharpness, two short impulses	medium	0.4	short	50
Error	Implementation of a component meets the constraints	High intensity, sharp vibration, medium duration	high	1.0	middle	400
Success	The component is applied	Short burst of impulse, high intensity, medium sharpness	high	0.7	short	100
			high	0.7	short	150
Epic success	A milestone is accomplished	High intensity, medium sharpness	high	0.7	Short	100
Failure	A task is failed	Five short bursts of impulse with overlay, max intensity, high sharpness	high	1.0	short	200, 250, 300

Functional haptic feedback provides semantics related to reasoning in problem-solving, involving analytical tasks for planning. Of particular interest is the user's understanding of the relationships between design components in the physical space. An example of a relationship is the priority for construction, assembly, or installation of the design components in the physical space. Reasoning on the relationship demands spatial and temporal cognitive abilities (STCA). The aim of *functional* haptic feedback is to assist the user's reasoning (spatial and temporal reasoning) when required. An example is providing a better comprehension or awareness of the order for construction and assembly among two or more design components—by featuring STCA— as shown in Fig. 5a and 5b.



(a) Design components (as defined in the WBS)

(b) Spatial and temporal information on the design components: an instance of relationship among components

Fig. 6: Spatial and temporal reasoning on design components (using STCA).

Functional haptic feedback informs the user which elements possess the highest priority for their construction and assembly (i.e., some design elements have higher priority than others to make their construction feasible and efficient). ga, for instance, illustrates the building components— without any spatial and temporal information. Fig. b illustrates spatial and temporal information — the relationship among the objects in the physical space, by establishing the priority and order for their construction. Haptic code will help the learner to reason on spatial and temporal information using a combination of duration (D), granularity (G), intensity (I), and sharpness (S) features. For example, a combination of values from the parameters D, I, and S will inform the order distribution in a spectrum (e.g., from the lowest to the highest value or from the highest to the lowest value). Consequently, each component on the final level has its unique haptic code (DGIS) comprising values for each parameter.

The *functional haptic* (*vibrotactile*) *feedback* is related to information on the hierarchy of construction activity sequencing. Interaction with each component is assigned with unique feedback, which allows the user to easily discriminate the components one from another based on their semantics by selecting them from the WBS of the building (Fig. 2b). Due to the perceptive haptic nature of hands, functional haptics is assigned to the haptic gloves.

4. CONCLUSION

The presented study describes an exploration of new human-machine interactions to determine the effects of learning through the combined visual and haptic modalities in VR environments. The interactions with an immersive environment involve engineering design comprehension for planning activities— framed in a problem-solving task. The study presents the technology environment using VR and real-time haptic feedback for experiencing problem-solving tasks — by complementing semantics of visualizations (e.g., 3D designs) with haptic feedback (e.g., vibrations) for a CEM task.

The approach to building a VR environment with dual interactive mode (visual and haptic) facilitates the creation of new forms of understanding problems in planning, a highly cognitively demanding task where STCA plays a pivotal role. Learners map VR visual and haptic features to domain (CEM) problems and build solutions to the planning problem. They used VR technology (headset and controllers) to engage embodied perceptuomotor information by interacting with visual and haptic representations. For example, users navigate the 3D design in VR to approach locations of interest, allowing iterations between representations and reflection while problem-solving. In future work with a higher number of testing subjects, it is expected to demonstrate that haptic feedback (haptic code) effectively informs the learners of the semantics of the components for the planning task, enabling the learner to infer conditions in a virtual scene.

The technology's pedagogical features will make design information from multiple engineering specialties readily available for haptic and visual perception in a stepwise process to learn planning tasks. The technology will facilitate learning through observation and VR movements of design components. The approach uses work packets (construction product deliverables) that would enable scenarios of learning about understanding deliverables as chunks of workload for planning—the smallest unit that can be planned and managed for construction operations. By enabling learning with a work packet focus, the approach facilitates understanding of planning by framing control into a process (set of steps for delivery) of construction (assembly). The method provides opportunities for the learner to assimilate complex simulated realities of the physical space and develop spatial-temporal cognitive ability. Spatial-temporal ability allows learners to effectively manage and comprehend significant amounts of spatial (how design components are related to one another in the 3D space) and temporal (the logic in a process, such as the order, sequences, and hierarchies of the resources within a construction task) information.

The insights collected from this study underscore the significant potential of the VR and haptic cues to enhance the learners' perception of a problem's conditions that are not visible to the learner. Further exploration of technology experimentations will allow researchers to draw conclusions on the learners' perceptual competence and problem-solving capabilities, thereby contributing to the formation of project engineers with high levels of productivity in the construction industry.

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