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The Effect of Experience-Based Tangible User Interface on Cognitive Load in Design Education

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ABSTRACT

Inclusion of tangible user interfaces can facilitate learning through contextual experience, interaction with the provided information, and epistemic actions, resulting in effecting learning in design education. The goal of this study is to investigate how tangible user interface (TUI) affects design learning through the cognitive load. Extended reality-based TUI and traditional desktop-based GUI were utilized to deliver the same information to two groups of students. The NASA TLX tool was used to measure students' perceived cognitive load after receiving information through the two modalities. Contemporary design pedagogy, the potential use of XR, design cognition, today's design learners experience-oriented lifestyle were combined to provide a theoretical framework to understand how information delivery modalities affect design learning. The results reveal that the use of XR-based TUIs decreases cognitive load resulting in enhanced experience and effective learning in design studios.

KEYWORDS

Cognitive Load, Design Instructions, Extended Reality, Learning Outcome, User Interfaces

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INTRODUCTION

Design is a nonlinear process that requires a series of cognitive activities involving internal and external interpretations and representations of tangible and intangible artifacts (Akin & Weinel, 1982; Goldschmidt, 2004; Kim & Maher, 2008; Visser, 2004). Culture, background, cognitive style, available technology, experience, and exposure are among some of the influences that characterize a designer. Because of these attributes each designers are unique in their creative thinking and ideation process, synthesizing information, and constructing new knowledge (Baer, 1997; Baer & Kaufman, 2008; Gül et al., 2008; Hu-Au & Lee, 2017; Lubart, 1999; Pearsall et al., 2008; Shalley et al., 2004; Wolfradt & Pretz, 2001). To confirm effective learning design education must align with the learning preferences of the design students from this digital age. Researches have shown that efficient use of design modality and its interface are dependent on user preferences; therefore, actively contributes to successful learning. Learning and teaching in a design studio largely depend on the effective communication of design ideas, new knowledge, and the relationship between learners' preferences and instruction modality (Demirbaş & Demirkan, 2003). Because of the exponential growth of technology and high-bandwidth data sharing, types and use of digital tools as well as the modes of information delivery in design education has shifted from information age to experience age (Wadhera, 2016). Among different technologies for human-computer interactions, most commonly used is Graphical User Interfaces (GUI). Using a keyboard and mouse, computer monitor, touch screens, and tabletops fall under this category. More recently, due to the advancement of technology and wide adoption by design education and industry, Tangible User Interfaces (TUI) usage have increased noticeably (Van Krevelen & Poelman, 2007). Interactions and delivery of information through TUIs are mostly associated with presence and immersion that provides a rich experience, contextual connotation, and spatial cognition resulting in effective learning. Therefore, exploring its meaningful integration and extensive usage in design education in critical. Extended reality (XR) is a form of TUI which is a relatively new platform that incorporates the characteristics of VR (Virtual Reality), AR (Augmented Reality), and Mixed Reality (MR). VR is an immersive, simulated three-dimensional environment (Bryson, 1995), AR overlays digital (augmented) geometry in the physical environment where the task is performed (Fischer et al.), and MR anchors digital contents in the real world where users can perceive both physical and digital objects simultaneously.

Learners make a tentative interpretation of experience, elaborate and test those interpretations based on their reflections until a mental structure is formed and satisfactory structure emerges. By facilitating human memory and intelligence, extended reality-based digital modalities create constructivist learning platforms and offer multiple interpretations, mental models and experience of the built environment (C. J. Dede et al., 1996; Perkins, 1991). This experience emerges through performing an epistemic action where learners can manipulate their environment in their mind based on their reflections (prior knowledge) for successful interpretation and acquisition of new knowledge. Contextual association, interaction and active participation allow students to get engaged based on their specific character, talent, and preference; therefore, it is considered a useful method of disseminating information in design studios (Jones & Brader-Araje, 2002; Naylor & Keogh, 1999; Rovai, 2004; Soygenis, 2009). Epistemic actions, according to Kirsh and Maglio (1994) are physical actions performed in the environment to make the mental calculation easier (resulting in better spatial cognition and understanding of the environment) and change his or her computational state. They also mentioned that "certain cognitive and perceptual problems are more quickly, easily, and reliably solved by performing actions in the world than by performing computational actions in the head alone (Kirsh & Maglio, 1994, p. 513)". Tangible user interfaces (TUI) allows more epistemic actions similar to activities and interactions in extended reality (Fitzmaurice & Buxton, 1997), which reduces overall cognitive load and makes the process of interpreting and comprehending new knowledge better.

Few studies have discussed the effects of cognitive load in effective learning in design pedagogy. The focus of this study is to investigate theoretical connections between cognitive load and interface types used for information delivery in design studios. The findings of this study provide an understanding of the design students' perception of modalities and interface types for an efficient learning outcome. Additionally, it can be used as an insight for possible realignment of information delivery methods for the students of this digital age. Moreover, this understanding can be utilized in design education and practice for developing a constructivist learning environment that stimulates creativity in the design process.

DESIGN EDUCATION AND ITS NEED FOR REALIGNMENT:

Advancement of technology, today's generation Z students' learning preferences and fast-changing needs of the industry require a realignment of design education to satisfy the demand of this digital age. In one form or another, similar issues have emerged in the early restructuring efforts of the 1960s experimental college by John Dewey, Alfred Whitehead, Jean Piaget, Benjamin Bloom and more recently David Kolb (A. M. Salama, 2006). Fisher (2000), as cited in Koch (2006), mentioned, "Studio culture pedagogy originates, in part, from the 18th century and the 19th century French rationalism, which held that through the analysis of precedent and the application of reason, we could arrive at a consensus about the truth in a given situation". Originating from the Ecole des Beaux Arts, this approach of design learning and teaching was adopted by the Western schools of architecture and then spread around the world. It emerged around the seventeenth century in France to represent the authoritative needs at that time and lasted for over two hundred years as the only model for design education. Due to the change of the value system caused by technological development and the industrial revolution, an alternative approach emerged at the end of the nineteenth century in Germany called the Bauhaus model. Most of the design schools around the world are highly influenced by Beaux-Arts and Bauhaus models and still follow the same principles. These approaches of design pedagogy created a distance from the real world because of the lake of opportunities it provides to learn from the 'richness and depth of human experience' (A. Salama & Wilkinson, 2007).

In recent decades, technology has faced several major shifts, which also influenced the lifestyle and learning preferences of design students of today's digital age. The most recent shift from the Information Age to the Experience Age has brought a significant challenge for design educators (Hu-Au & Lee, 2017; Wadhera, 2016). Since the act of design is an individualistic, creative and diverse domain grounded on non-linear thinking and problem-solving process where rationale emerges from individual designer's level of experience, reflections, and perceptions. Therefore, an exploratory, constructive learning environment can improve the motivation, attention and overall learning outcome (Clark, D. 2006 in Piovesan et al., 2012). Tangible User Interfaces (TUI) coupled with virtual, immersive and augmented learning environments provide a unique contextual role playing and reasoning experience where early design students learn the essential skills such as creative thinking, empathy, conceptual understanding, system thinking, all through learning by doing. This also provides design students of this digital age the necessary active engagement (Capps & Crawford, 2013) and the relevance of the learning material to their professional life (Gee, 2009).

COGNITIVE LOAD, EPISTEMIC ACTION AND TANGIBLE INTERACTION

George Miller (1994) developed two fundamental theoretical ideas on cognitive psychology and information processing. His research has shown that short term memory has a limitation in simultaneously storing (not over plus-minus seven) meaningful information. Based on this, John Sweller (1988) constructed cognitive load theory relevant to instructional design where he suggested that- individual's knowledge is built upon a cognitive structure supported by schemes or combination of elements. Cooper (1998) defined cognitive load as the total amount of mental activities required on working memory while performing a task at any given time. Cognitive load theory also suggests an alignment of an individual's cognitive architecture and learning environment (mode of information delivery) for the effective learning outcome. Use of modalities and strategy of instructions should not burden learner's mental capacity for optimal instructions resulting in productive learning outcome. For instance, when a new knowledge is presented using an instruction modality or interface that is complicated, difficult to interpret and relate with prior knowledge, learners feel a higher degree of workload which reduces overall learning outcome.

Cognitive load can be reduced by epistemic actions- a physical action performed to make the mental calculation easier- to change one's own computational state and interpretation of the information presented. By reducing mental effort and memory involvement, epistemic actions reduced cognitive load, thereby stimulates information processing time, reduces errors while constructing meaning, and improves spatial cognition (Kirsh & Maglio, 1994). Additionally, by examining six distinct claims on embodied cognition, Margaret Wilson (2002) claimed that human interactions with the world are deeply rooted in their cognitive processes. Association with prior knowledge and epistemic actions to change the (work) environment are the two strategies people use for balancing their cognitive work (Wilson, 2002). Therefore, information delivered using methods with higher tangibility as XR environment that offers higher spatial cognition (contextual presence), interactions with provided information and direct involvement with the environment may reduce cognitive load at a significant level.

Extended reality (XR) interface offers a higher degree of tangible interaction where users can interact with both pictures, texts, and auditory information while virtually being present in the context of the information being presented. On the other hand, in traditional GUI based information delivery methods, often same modality (desktop screen, other visuals) is used to deliver different types of information which requires learners to split their attention to understand both diagrams, image and text-based information. This split-attention effect (Chandler & Sweller, 1992; Mayer & Moreno, 1998; Slijepcevic, 2013) significantly increases the cognitive load while processing new information. Chandler and Sweller (1992) found that integrated and simultaneously presented information reduces processing time and mental effort. TUIs as AR, VR and XR are highly capable of reducing split-attention effect because it can provide a holistic view by combining small chunks of information into one view (Haniff & Baber, 2003; Klatzky et al., 2008; Slijepcevic, 2013).

EXTENDED REALITY AS A TANGIBLE USER INTERFACE FOR DESIGN EDUCATION

Extended Reality (XR) is the umbrella platform that encompasses phenomena from Virtual Reality, Augmented Reality and Mixed Reality. By definition, it incorporates real and virtual environment and relevant interactions between humans and computers. The goal is to offer tangible feedback based experiences mainly involving the senses of existence, confirming cognition and interaction with contextual geometry and design elements. Digital modalities can facilitate human memory and learning by refining mental models, adding interpretations, and providing experience by augmenting the real world (Perkins, 1992). Virtual, Augmented, and Mixed Reality technologies have proven their potential by providing a constructivist learning environment that creates a natural and social interactive platform to mediate interaction with the contents (C. Dede, 1995).

By reducing cognitive load, learners can easily construct knowledge and meaning from experience, active participation and performing tasks in the context which allow learners to contextualize the process of constructing knowledge instead of being a passive learner (Salomon & Perkins, 1998). With various methods of active participation through TUIs, students get engaged based on his or her specific character, talent and preference; therefore, it is considered a useful method of disseminating information in design studios (Jones & Brader-Araje, 2002; Naylor & Keogh, 1999; Rovai, 2004; Soygenis, 2009).

Learners make a tentative interpretation of experience, elaborate and test those interpretations based on their reflections until a mental structure is formed and satisfactory structure emerges. The learning environment and the information delivery method need to be supportive of the development of this inherent constructivist character. By facilitating human memory and intelligence extended reality based digital modalities create effective learning platforms and offer multiple interpretations, mental models and experience of the built environment (C. J. Dede et al., 1996; Perkins, 1991).

METHOD

The research question this study investigated was- how does interface type used to deliver information affect students' cognitive load? By adopting a quantitative research method using the analysis of subjective survey data, this study attempted to find answers to the research question. The hypothesis was that- information delivery methods affect students' cognitive load caused by the type of interfaces used, thereby affecting overall learning outcome.

The information delivered to both groups was- application and strategies of universal design in residential settings. The universal design focuses on manipulating and designing a built environment for not only accessibility but also to accommodate a greater extent of users regardless of individuality, culture, and ability. Two interfaces were used for information delivery: traditional text and image-based (GUI) and XR based (TUI) interface. Participants were divided randomly into two groups (GUI and TUI). Both groups received the same amount of information in two different formats (traditional text-image based format via desktop monitor and XR based interactive format using the Oculus rift device). After the institutional review board approval, purposeful sampling was used to select the participants who are design students (juniors, seniors and graduate) at a Midwestern university in the US. The participants were then randomly assigned to either of the two interfaces for delivering information. Table 1 shows the demographic information of all participants.

Information regarding applications of universal design was given to the participants using GUIs (traditional text and image-based method) in pdf file format on a computer monitor (Figure 1 showing screen capture). The participants used keyboard and mouse (GUI interfaces) to scroll through while reading from the computer monitor. There was no design task involved in this study. After general instructions, participants were asked to read the document as provided material given by the studio instructor after the lecture. The goal of the study was to understand how information delivery system and its interfaces affect learning effectiveness; therefore, the universal design principle and its applications were provided in a case study format with numerous images supporting text descriptions. Some of the external factors as the participant's exposure and experience were negligible due to demographic similarities

Secondly, in the TUI (Extended Reality) participants used a Virtual Reality device (Oculus Rift®) attached to a computer. A three dimensional model of the same case study residence was prepared using Autodesk Revit and Unity 3D game engine. Later,

Table 1. Demographics in the Two Groups

	Gender		Age			Academic		
	M	F	18-25	30-35	35+	Senior	Junior	Graduate
GUI (Traditional)	1	15	14	2	0	10	2	4
TUI (XR)	2	14	14	1	1	9	3	4

Figure 1. GUI (Traditional method of information delivery) presented via desktop computer monitor, keyboard and mouse

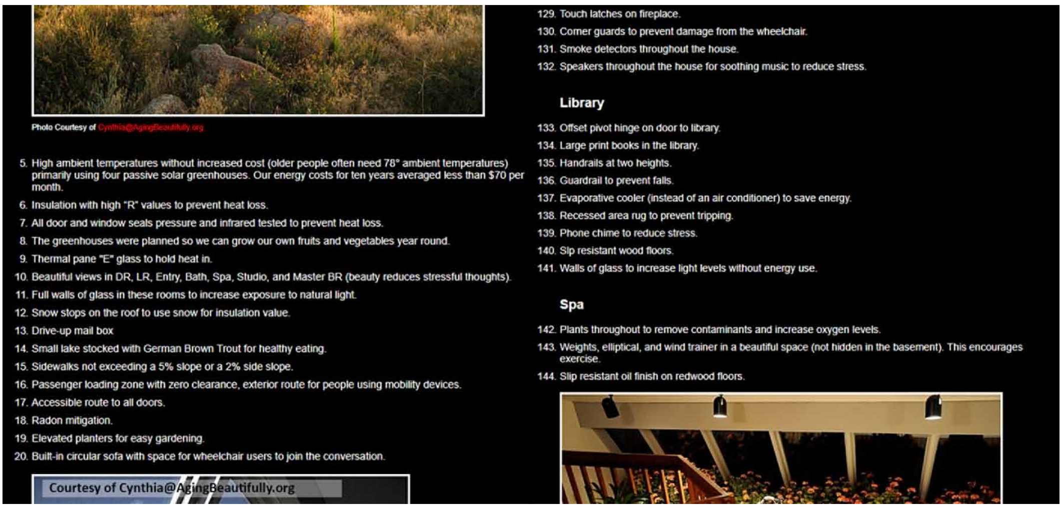
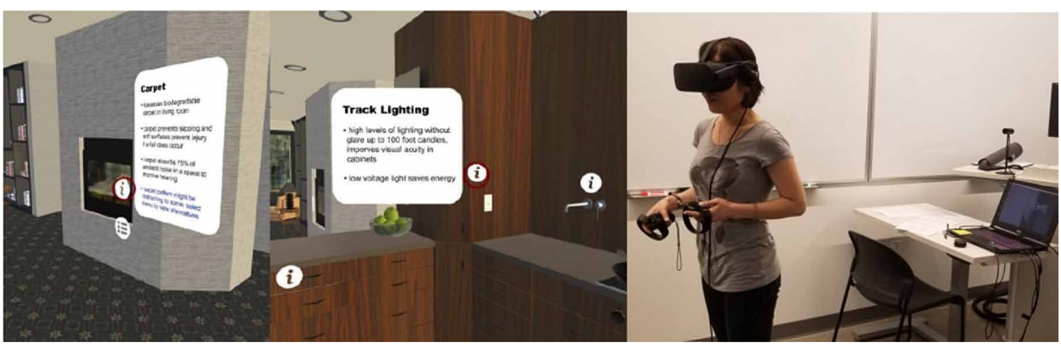


Figure 2. TUI (Extended Reality based information delivery) presented via Oculus rift. Interaction environment on left and subject working on right



hotspot markers were applied to all key spatial and design attributes where universal design aspects were implemented. Using Oculus Rift head-mounted display (TUI interface) device and controllers participants were able to move through the virtual environment (different spaces within the residence), interact with various components as opening doors, windows, kitchen cabinet doors, turning on and off lights and such to evaluate the accessibility and ergonomics etc. (Figure 2, right side image). At the same time gazing at or using controller button hotspots could be activated, which allowed the participants to see a detailed description of the universal design attributes applied to that specific design feature and fixture. Participants also could select from an array of different materials as carpet texture or furniture selections to experiment with multiple aspects of universal design in the context (Figure 2, left side image).

The task in this experiment was to review and explore universal design strategies implemented in a residential case study through TUIs (computer-generated Extended Reality environment) and GUIs (text and image-based document) (Figure 1 and 2) to identify cognitive load associated with each of the information delivery methods. All participants answered the NASA task load index (TLX) questionnaire afterward. NASA TLX can be downloaded and used for non-commercial use. It measures six subscales associated with accomplishing a task as- mental demands, physical demands, temporal demands, own performance, effort, and frustration. The online version of this tool was used in this study and was administrated after the task was performed to obtain participants' perceived overall scores for cognitive engagement and load. This two-section evaluation process measures weight and ratings for both interfaces (TUI and GUI).

ANALYSIS AND DISCUSSION

After measuring all 32 participants perceived cognitive load, the data were compared between the TUI and GUI interfaces (information delivery methods). ANOVA (One-way analysis of variance) was executed to compare the effects of interface types on cognitive load. The result showed a significant difference between the two interface types at the $p<.05$ level on the perceived cognitive load [$F(1,30) = 7.43$, $p = 0.01$). Findings suggest that TUI interfaces require less cognitive involvements than GUI while processing and interpreting the same amount of information (Table 2).

CONCLUSION

This study investigated the effects of user interface types used for information delivery on the perceived cognitive load learners experience by the interfaces. Researches have shown that lower cognitive load enhances understanding and interpreting new information resulting in effective learning. Epistemic actions performed within tangible

Table 2. One-way ANOVA Summary Table for TUI and GUI based information delivery methods and Cognitive Load

	Sum of Sq.	*df*	*Mean Sq.*	*F*	*P-value*	*F crit*
Between Groups	2596.32	1	2596.322	7.43	0.01	4.17
Within Groups	10481.86	30	349.39			
Total	13078.18	31				

user interfaces as XR interface reduces cognitive load compared to other interface and modalities. Cognitive load was identified significantly lower in TUI compared to GUI for processing the same information. This is because of the epistemic actions extended reality offered through interactions with the information in context and enhanced spatial cognition through virtual presence. Few studies have advocated any connection between the cognitive load of interfaces used for delivering information in design studios and effective learning outcome. Results of this study suggest that XR based interfaces used to teach new knowledge produces a lower cognitive load. When the cognitive load is lower, learners enjoy the freedom to develop a constructivist learning environment where they can reflect on their prior knowledge, interoperate and construct new meanings resulting in effective learning outcome.

Tangible user interfaces (TUI) are being used in the design education and industry for several decades, but a gap exists in the knowledge on their effectiveness as a pedagogical tool to teach design students, especially novice design students. It is crucial to understand how learners of this digital age prefer to learn, experience, interact, and perceive information and technologies, to develop effective design curriculum and information delivery systems. Due to the advancement of the technology and availability of new hardware, various TUI based devices and applications are becoming increasingly popular. These new TUIs can offer 'experience' rich learning, which is the preference of today's learners.

Design students are predominantly visual and kinaesthetic learners. The outcomes of this study suggest that the TUI based information delivery method was easier to use and more effective than GUI while teaching design ideas and principles. Selection of different types of instructional interfaces and methods affect how effectively learners construct meaning and use the provided information due to the incurred cognitive load from the interfaces. This insight can be useful for design researchers and educators in developing a learner-centered design pedagogy.

Limitations

This study has several limitations. First, a relatively small number of participants recruited in the study. One of the reasons for this small sample size was obtaining participants. No financial incentive was offered and it was difficult to dedicate some time out of mostly commuter student's busy schedule. These reasons collectively contributed to the students' decision to not to participate.

Secondly, all of the participants were from the same geographical region and from one Midwestern university studying interior design. The study focused on only learning universal design's concept and its application as the information delivered. Even though the participants were randomly assigned to two groups, unequal distribution of gender and academic status may have a contribution to the results of the study. This is because some senior and graduate students are more experienced and have exposure to the information derived from other sources.

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