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Immersive Systems and User Engagement Through NeuroIS Lens

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Immersive Systems and User Engagement Through NeuroIS Lens

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Abstract

Immersive systems (e.g., Virtual Reality) are at the forefront of the next generation of innovative technologies. Recent technological advancements have made them viable for businesses and individuals to adopt. For example, some realtors now offer virtual house tours in the absence of walk-ins. The concept of “immersion” is at the heart of these technologies. However, despite the fact that this concept has been studied for almost three decades, our understanding remains weak and inconsistent. Specifically, there remains a lack of consensus on what it is, its antecedents, and how it should be measured.

This dissertation includes two essays. In Essay 1, we build on prior literature to develop a holistic immersion model that incorporates sensory, cognitive, and affective factors and their interactions. An electroencephalography (EEG) lab study was conducted to measure subjects’ immersion while using technology in the lab and determine their engagement with technology in the presence of real-world distractors (e.g., iPhone text-sound). Findings suggest that immersion has a U-shape relationship with user performance such that, after a certain threshold, a unit increase in the users’ immersion level has an exponentially positive effect on their performance.

In Essay 2, we use the same study design and concept (immersion) to investigate the relationship between neurophysiological and psychometric measures of immersion. IS scholars have encouraged methodological investigations and triangulation using NeuroIS tools, yet there is a dearth of studies on how these tools interact and influence one another. Hence in Essay 2, our objectives are to (i) measure users’ experience of immersion using EEG and two psychometric-based methods (perceptual and observational); (ii) test these measures in a nomological network of antecedents of immersion and consequences of immersion; (iii) statistically compare and report how relationships differ across each measure; and (iv) build an aggregated measure of immersion using neurophysiological and psychometric tools and test its capabilities in explaining an outcome variable.

Keywords: Immersive systems, Immersion, NeuroIS, EEG, Virtual reality, User satisfaction, User performance

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Dedication

I would like to dedicate this thesis to Ghazaleh, my beloved wife, for all of her support and sacrifices. Also, to my parents for giving me the gift of life and teaching me never to give up.

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Chapter 1: Introduction

Immersive systems are changing the business landscape, and situations such as the COVID-19 pandemic outbreak adds to their growth and expansion. For example, in conditions where walk-ins are not possible, realtors now offer virtual house tours (Morris, 2020). However, the decades of study on this concept do not show one agreed-upon definition for it. Without a common ground on what this concept means, the efforts in studies of immersive technologies appear as scattered islands of disconnected knowledge (Georgiou & Kyza, 2017; Jennett, 2010; Calleja, 2014; Suh & Prophet, 2018). Prior research indicates that most work in this domain has focused on measuring this concept subjectively in a post-hoc fashion (e.g., Lowry et al. 2013). Recent developments in the fields of neuroscience and NeuroIS allow us to obtain a better understanding of users' immersion experience during interaction with immersive contents or technologies, which is one of the objectives of this dissertation. Therefore, in Essay 1, we reconceptualized the concept and tried to clarify its definition, then used NeuroIS tools to measure it.

Next, we sought to investigate the antecedents of immersion. Our literature review revealed that there is a stream of research that recognizes cognitive, affective, and sensory engagement with technology as the drivers of immersion (Robertson et al. 1997; Ahn et al. 2014; McGill et al. 2016; Lindgren et al. 2016; Raptis et al. 2018; Chisholm et al. 2014; Burns & Fairclough, 2015; Lowry et al. 2013; Georgiou & Kyza, 2018). We investigated the effect of the three forms of engagement on user's experience of immersion, and also investigated how immersion influences user performance. Therefore, in Essay 1, we addressed two research questions: (RQ1) What is immersion? (RQ2) What is the relationship between immersion and performance?

In Essay 2, we utilized the same experimental design and concept of immersion as in Essay 1 in order to investigate a research gap pertaining to a lack of studies on triangulation of NeuroIS and psychometric tools. Very few studies have ventured into this domain, and there is a need for further investigation. In particular, we identified two viewpoints regarding triangulation between neurophysiological and non-neurophysiological tools. The first viewpoint assumes that NeuroIS tools are highly correlated (Dimoka et al. 2011, 2012), while the other posits that they are alternatives and not statistically correlated (Tams et al. 2014). There is a dearth of studies on both sides, and thus one important goal of Essay 2 is to build on prior works and shed light on the relationship between these methodological approaches. In summary, first, we compare and contrast the relationship among different measures (intra-construct) of immersion (one EEG and two distinct psychometrics). Second, we build nomological networks of antecedents and outcomes of immersion (inter-construct) in which the effects of (i) neurophysiological on neurophysiological measures, (ii) psychometric on neurophysiological measures, and (iii) neurophysiological on psychometric measures are tested and discussed.

The contribution, theoretical findings, and practical implications for each essay are discussed separately in Chapters 2 (Essay 1) and 3 (Essay 2).

Chapter 2: (Re)Conceptualizing Immersion and its Performance Impacts: An EEG Lab Experiment

Abstract

Immersive systems (e.g., virtual reality) are at the forefront of the next generation of innovative technologies. Although immersive systems have been around for a few decades, recent technological advancements have made them valuable for businesses and individuals. The spread of COVID-19 has enhanced the need for immersive technologies. For example, some realtors are now offering virtual house tours in the absence of walk-ins. The concept of immersion is at the heart of these technologies. However, despite the past few decades of research on this concept, our understanding of it remains weak and inconsistent. Specifically, there remains a lack of consensus on what immersion is, its antecedents, and how it should be measured. In this study, we review the prior literature and develop a holistic model of immersion that incorporates the effects of sensory, cognitive, and affective factors and their interactions. An electroencephalography (EEG) lab study was carried out to measure subjects' immersion level while using technology in the lab and determine their engagement with technology in the presence of distractors such as iPhone text-sounds (to replicate a real workplace environment). Findings suggest that immersion has a U-shape relationship with user performance such that after a certain threshold, an increase in the users' immersion has a positive exponential effect on their performance.

Keywords: Immersive technology, NeuroIS, EEG, Virtual Reality, Immersion index, Performance

Introduction

The world around us has experienced unprecedented changes and magnified the dependency of businesses and individuals on technology. The COVID-19 pandemic and migration to remote working exemplify these changes. Some of these changes are here to stay even after the resolution of the situation. For example, Twitter announced an option to work-from-home forever for its employees (Brownlee 2020). With the endeavor to bring work to home (or the outside world to the inside), the role of immersive technologies in changing the landscape of businesses and their capabilities has become more apparent. For example, during the great shutdown of 2020, due to the pandemic, realtors started offering virtual home tours in the absence of open houses (Morris 2020). There are predictions of a rising surge in virtual shopping in the post-pandemic retail landscape by experts (Karim, 2020). These are a few examples of immersive technologies aiding businesses and shifting the landscape of our economy. Immersive technologies have the capability to open the gateways to the outside when people need to stay inside for reasons such as a virus outbreak or simply reducing commuting costs.

From a practical standpoint, a clear definition of immersion would enable its correct measurement and thus progress toward designing better immersive content and technologies. Prior research indicates that most work in this domain has focused on measuring this concept subjectively (e.g., Lowry et al. 2013). Recent developments in the fields of neuroscience and NeuroIS allow us to obtain a better understanding of users' experiences of immersion during interaction with immersive content or technologies, which is the main objective of this study.

A review of the concept of immersion in information systems (IS) indicates that despite the extensive literature, there is a lack of consensus on (a) its definition across IS, human-computer interaction, IT, and psychology (see Table 1); (b) its measures; and (c) its antecedents (Calleja

2014; Georgiou and Kyza 2017). Without common ground on what this concept means, studies of immersive technologies appear as scattered islands of disconnected knowledge (Georgiou and Kyza 2017; Jennett 2010; Calleja 2014; Suh and Prophet 2018). While prior works are putting more weight on the engagement part of the immersion, the literature on cognitive psychology suggests that immersion needs to be defined in the context of selective attention and distraction, which together create an immersive state for the individual.

The current business needs have created an opportunity for faster diffusion of immersive technologies, so by looking at where we stand with this concept, we can further refine our technologies to serve consumers and business needs. Accordingly, our first objective is to revisit the definition of this concept and then quantify an objective measure of immersion based on the new definition. Therefore, our first research question is: (*RQ1) What is immersion?*

Once the definition and measure of immersion are developed, we can (a) explore the effect of task type and technology features on immersion in an experimental setting, (b) predict how immersion influences user performance, and finally (c) test the model in a nomological network of antecedents that leads to immersion. Immersive technologies are increasingly being recognized as tools to improve user and organizational performance. The use of these technologies in car assembly, flight simulation, and medical training are examples of effects on user performance (Jennett 2010; Van Krevelen and Poelman 2010; Wang et al. 2016; Cavusoglu et al. 2019). Objectively assessing immersion (i.e., real time use of electroencephalography (EEG) during the activity) in an experimental setting can help assess how it affects user performance. In addition, we can compare our proposed measure with previously developed subjective measures of immersion. Therefore, our second research question is: *(RQ2) What is the relationship between immersion and performance?*

Finally, the last objective of this research is to *test the concept in a nomological network of antecedents of immersion.* We identify *engagement* as a key antecedent and argue that (a) it is distinct from immersion and (b) it has three forms that serve as antecedents of immersion. Regarding (a), IS research on immersion does not adequately define immersion using words such as engagement and involvement, each of which has a definition detached from immersion in light of how the brain processes selective attention (see next section on definitions of engagement and involvement). In concept development, this is the first issue that leads to "construct contamination" due to confusion surrounding the concepts (Mackenzie et al. 2011, p. 295). There are existing measures and definitions of engagement. Thus, we treat this concept separately from immersion (see next section). Regarding (b), there is a stream of research that recognizes cognitive, affective, and sensory engagement with technology as drivers of immersion (Robertson et al. 1997; Ahn et al. 2014; McGill et al. 2016; Lindgren et al. 2016; Raptis et al. 2018; Chisholm et al. 2014; Burns and Fairclough 2015; Lowry et al. 2013; Georgiou and Kyza 2018).

On the measurement front, NeuroIS research has focused on defining engagement through measuring power band oscillations and their ratios (Pope et al. 1995; Freeman et al. 2004). To the best of our knowledge, no research theorizes how psychometric measures of engagement map into each function of the cerebral cortex; in other words, the reconciliation between subjective and objective studies on user engagement is missing. After exploring the connection between immersion and performance, we coded previous studies and identified the type of engagement they were looking at by mapping each to the specific brain lobe that processes that particular type of engagement (e.g., cognitive or sensory). Then, we used a combination of subjective and objective measures for engagement in this study to examine the effect of engagement types on immersion.

For example, we used electrodermal activity (EDA) and an accelerometer to measure the emotional and sensory engagement that is discussed in the methodology section.

Overall, this study contributes to our understanding of immersion's black box through (a) redefining the concept of immersion by identifying deficiencies of previous definitions and proposing a new definition using literature on cognitive science—specifically, selective attention, (b) performing a lab experiment with multiple treatments to identify the specific task type and technological features that influence users' experiences of immersion and its relationship with user performance, (c) comparing the subjective and objective measures and discussing their similarity and differences, and (d) testing the concept in the nomological network of antecedents of immersion. In addition, the findings have implications for businesses and developers. For instance, providing an index for the immersiveness of tasks and technologies could enable developers to manipulate the desired degree of immersion to achieve their objectives. Furthermore, uncovering the relationship between immersion and performance could influence the businesses' decisions around integrating immersive technologies into their long-term strategies. This is particularly important in today's information era where companies struggle to keep the attention of employees and customers who are consistently bombarded with hundreds of information messages (Davenport and Beck 2000). Well-designed immersive technologies can intervene to sustain employees' attention to their tasks.

Background and Literature review

This section is dedicated to the background of immersion. We performed a keyword search of "immersion" on EBSCO, ProQuest, Web of Knowledge, and Google Scholar and tried to cover journal articles, conference proceedings, and dissertations on information technology, information systems, computer science, and psychology. Next, we performed a backward citation review of the relevant papers. A high-level view of the steps in which we reviewed and synthesized literature is presented in Figure 1. In section 2.1, we review the literature and identify the inconsistencies among the previous definitions of immersion in IS, information technology (IT), human-computer interaction (HCI), and psychology. Next, we propose our definition of immersion and show how it addresses the discussed issues. In section 2.2, we introduce immersion as a graded experience and identify the engagement types that cause immersion. In section 2.3, we review the antecedents of immersion from prior literature and cluster them into different forms of engagement. Finally, we differentiate immersion from similar concepts that are often confounded with it (Appendix A).

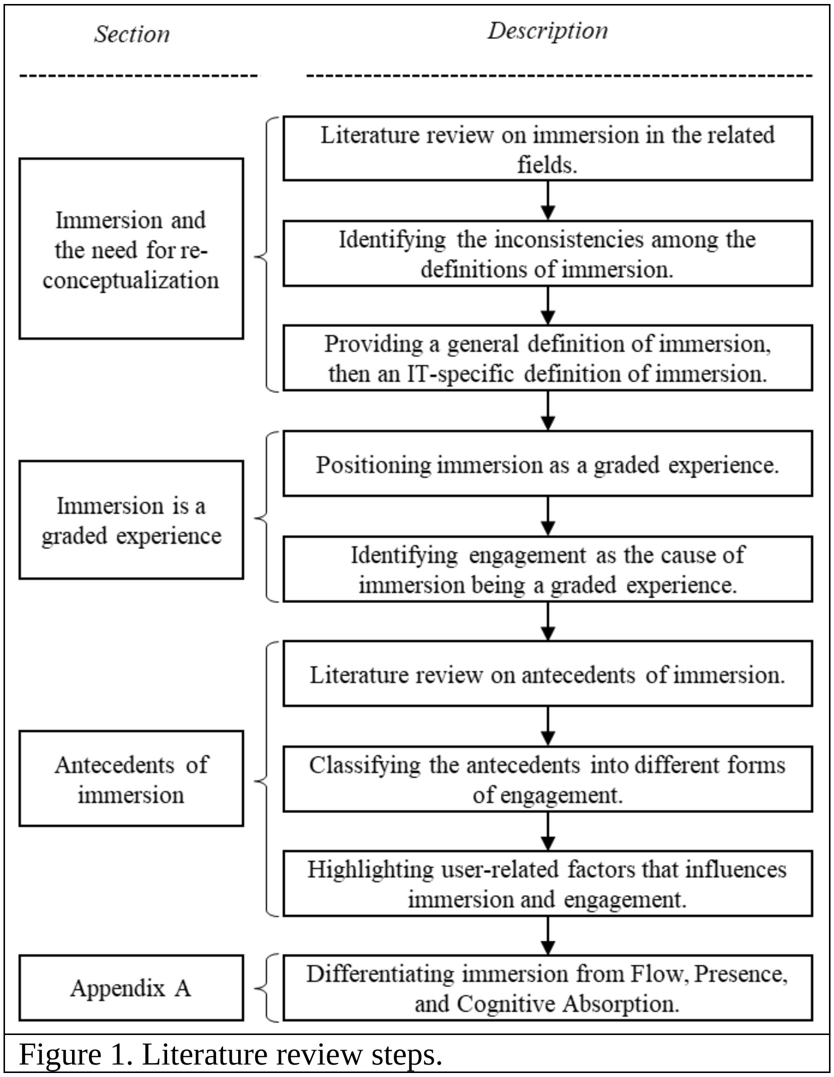

Figure 1. Literature review steps.

Immersion and the need for a reconceptualization

The term immersion was first introduced by technical designers of virtual environments to explain what happens to users who are absorbed in a virtual environment (Georgiou and Kyza 2017). In IS, immersion has been applied to a variety of contexts such as gaming (McGloin et al. 2016; Chan et al. 2014; Lowry et al. 2013), music (Cuny et al. 2015), the virtual world (Saunders et al. 2011; Goel et al. 2013), e-commerce (Lee et al. 2012), and online collaboration (Reychav and Wu 2015). For example, Lee et al. (2012) showed that immersion negatively influences online shoppers' perceived waiting time. It also affects virtual-world users' intentions to return and use the interface again (Goel et al. 2013). Cuny et al. (2015) focused on the sensory factors and showed that music affects consumers' immersion. Some view immersion as leading to enjoyment (Chan et al. 2014; McGloin et al. 2016), while others view it as an antecedent to enjoyment (Lowry et al. 2013). Furthermore, it has been found that immersion could be a function of several other factors, such as users' perceptions of realism, control, and curiosity. In sum, contemporary studies suggest that immersion has not been defined clearly, and there is a need for a comprehensive definition and broader conceptualization of its nomological network (Suh and Prophet 2018).

Immersion has been defined in several ways (see Table 1), with two perspectives seemingly dominant — a technological perspective (Slater and Wilbur 1997; Baños et al. 2004; Bowman and McMahan 2007; Schnall et al. 2012) and an experiential perspective (Witmer and Singer 1998; Robertson et al. 1997; Ermi and Mäyrä 2005; Brockmyer et al. 2009; Cairns et al. 2013; Cuny et al. 2015). To our knowledge, there are limited researches that have adopted the first view, and their definitions of immersion are inconsistent. For example, immersion has been defined as "A description of a technology that describes the extent to which the computer displays are capable of delivering an inclusive, extensive, surrounding and vivid illusion of reality to the sense of a human participant" (Calleja 2011). In this view, the main driver of the user experience of immersion is the sense of presence, which is defined as the sense of being located in a virtual environment (Cairns et al. 2013). The second group that conceptualizes immersion as an experiential state that relates to the user's psychological experience is more popular in the literature. Although there are several definitions for immersion from this perspective, a recurring theme of the attributes in the majority of the proposed definitions for immersion is presented in Table 1. The emergent themes in the proposed definitions across technological and experiential perspectives are (1) it is a psychological state, subjective perception, or a disposition; (2) it involves users' experiences or sensations; (3) it engages or involves users in one or more ways; and (4) it happens when the user interacts with an environment (i.e., digitally-mediated environment, virtual world, software, video game).

The above definitions seem to have the following six common problems, which are linked by their numbers below to various previous definitions in Table 1:

1. *Constitutive terms like engagement and involvement are used in the definitions*: Engagement is defined as "a positive, fulfilling, work-related state of mind that is characterized by vigor, dedication, and absorption" (Schaufeli et al. 2002). Similarly, involvement is defined as the situation in which individual(s) engage the status-seeking motive in their work (Lodahl and Kejner 1956). Consequently, engagement and involvement are similar and unclear concepts that need to be defined independently before being used to define immersion. These two concepts have their own definitions and developed measures; thus, the definition of immersion has to be free of concepts that have their own separate measurements. More recent studies of immersion in premier IS journals emphasize that engagement is more of an antecedent to immersion. For example, Li et al.

(2014) put forth the idea that game engagement significantly influences the psychological process of immersion.

2. *Definitions confound preconditions or antecedents of immersion*: One of the issues with the proposed definitions is that they are subject to conditions. For instance, Ermi and Mäyrä (2005) discuss the necessity of "being surrounded by a completely other reality" as a condition for immersion. Hou et al. (2012) suggest that "complete focus" (referring to complete attention) is a pre-condition of immersion. Similarly, "total engagement" or "being wholly absorbed" are conditions that some of the proposed definitions necessitate for immersion to take place (Lee et al. 2012; Soutter and Hitchens 2016). These conditions can help immersion. For example, blocking noises that could disrupt the individual's focused attention on one activity can facilitate immersion, but it is not part of the more generalizable definition of immersion as a psychological state.
3. *Definitions are context-specific*: Some of the definitions in Table 1 are very context-specific. The game environment and virtual reality (VR) settings are among the frequently-appearing contexts that are part of the proposed definitions (Bowman and McMahan 2007; Brockmyer et al. 2009; Carrozzino and Bergamasco 2010; Hou et al. 2012; Cairns et al. 2013). These definitions miss noting that immersion can happen in other settings as well, such as through reading a novel (Ryan, 2001; Qin et al. 2009).
4. *Immersion has been discussed as an attribute of the system*: There are a few definitions that define immersion as an attribute of a system, leaving out the subjectivity of this concept. For instance, Calleja (2011) views immersion as an attribute of computer displays. Similarly, Slater (1999) suggests that immersion is delivered through the sensory modalities of a system. Bowman and McMahan (2007) emphasize the sensory fidelity of

VR systems in their definition. This view is very narrow in the sense that they are neglecting the role of human cognition and behavior that result from reacting to systems.

5. *The definitions overlap with other concepts, such as flow, cognitive absorption, or presence.* In Table 1, five definitions have a considerable overlap with other concepts that are distinct from immersion, such as flow, cognitive absorption, or presence. Concept definitions that are close to each other will present obstacles to readers' abilities to distinguish between them. For instance, Robertson et al. (1997) define immersion as "The state of being absorbed or deeply involved" which is very similar to Agarwal and Karahanna's (2000) definition of cognitive absorption. Carrozzino and Bergamsco (2010) define immersion as the physical feeling of being in a virtual space, which is similar to the definition of presence proposed by Witmer and Singer (1998). Similarly, Lee et al. (2012) define immersion as "an experience of total engagement …" which significantly overlaps with the definition of flow (Csikszentmihalyi 1975). We have provided a brief summary of flow, cognitive absorption, and presence and compared them with immersion in Appendix A.
6. *Some definitions are tautological*. A couple of definitions use "immersed" and "immersive" (Dede 2009; Weibel et al. 2010), which make the definitions confusing. In defining immersion, the authors should have avoided using the term. This mistake is extensively referred to in concept-development literature as "concept contamination" (MacKenzie et al. 2011), which suggests that definitions should be clear, concise, and free of tautology.

Table 1. Definitions of immersion and their associated key attributes.

Definition	**Key Attribute**	**Source**	**Reference to issue***
A description of a technology that describes the extent to which the computer displays are capable of delivering an inclusive and extensive surrounding and a vivid illusion of reality to the senses of a human participant.	- Technology capability - Environment - Sensory fidelity	Calleja 2011	2, 4
The extent to which the actual system delivers a surrounding environment, one which shuts out sensations from the “real world,” which accommodates many sensory modalities, has rich representational capability, and so on.	- Environment - Sensations - Representational capability	Slater 1999	4
The state of being absorbed or deeply involved.	- Psychological state - Absorption - Involvement	Robertson et al. 1997	1, 5
The sensation of being surrounded by a completely other reality […] that takes over all of our attention, our whole perceptual apparatus.	- Sensations - Environment (Other reality) - Attention	Ermi and Mäyrä 2005	2
Refers to the objective level of sensory fidelity a VR system provides.	- Objective - Sensory fidelity - Environment (Virtual reality space)	Bowman and McMahan 2007	3, 4
The physical feeling of being in a virtual space.	- Sensations - Environment (Virtual space)	Carrozzino and Bergamasco 2010	3, 5
Immersion is a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences.	- Psychological state - Environment - Subjective Perception	Witmer and Singer 1998	2
A disposition that determines the capability of individuals to become immersed or involved in mediated environments.	- Disposition - Individual capability - Involvement - Environment (Mediated)	Weibel et al. 2010	1, 2, 6
Experience of a complete focus on the game environment and an appealing engrossment free from distraction.	- Experience - Focus - Environment (Game) - Engrossment - Distraction-free	Hou et al. 2012	1, 2, 3
An experience of total engagement, where other attentional demands are rather ignored.	- Experience - Total engagement - Attention	Lee et al. 2012	1, 2, 5
The objective, quantifiable features of the display that result from the particular software and hardware and the extent to which they are comparable to the level of sensory input that would be received in the real world.	- Objective (Quantifiable) - Technology feature - Sensory input (Sensation) - Environment	Schnall et al. 2012	2, 3, 4
The suspension of disbelief possibly being given by any media.	- Disbelief suspension - Media	Boas 2013	3
- The experience of being “in the game”, that is, being heavily emotionally and cognitively invested in the activity of playing. - This is the sense of being “in the game” by which is meant being wholly involved or absorbed in the activity of playing to the neglect of the real world around the player. - The engagement or involvement a person feels as a result of playing a digital game.	- Experience - Sensation - Emotional involvement - Cognitive involvement - Absorption - Playing (Game) - Environment - Attention (Neglect Others) - Engagement - Involvement - Sensation (Feeling)	Cairns et al. 2013	1, 3, 5

Table 1. Definitions of immersion and their associated key attributes (Cont.).

Definition	**Key Attribute**	**Source**	**Reference to issue***
A psychological state, characterized by being connected with the world offered by the experiential context and disconnected from the real or ordinary world.	- Psychological state - Environment (Other than the physical world) - Connection to another world	Cuny et al. 2015	2
The experience of becoming engaged in the game-playing experience while retaining some awareness of one's surroundings.	- Experience - Engagement - Playing (Game) - Awareness - Environment	Brockmyer et al. 2009	1, 3
"The sense of being wholly absorbed in an activity to the complete loss of awareness of the real world".	- Sensation - Absorption - Activity - Awareness (Loss) - Environment (Another world)	Soutter and Hitchens 2016	2, 5
"The participant's suspension of disbelief that she or he is "inside" a digitally enhanced setting".	- Disbelief Suspension - Environment (Digitally enhanced setting)	Georgiou and Kyza 2017	2
Immersion is the subjective impression that one is participating in a comprehensive, realistic experience. Immersion in a digital experience involves the willing suspension of disbelief, and the design of immersive learning experiences that induce this disbelief draws on sensory, actional, and symbolic factors.	- Subjective - Comprehensive - Realism - Experience - Environment (Digital World) - Disbelief suspension - Sensation - Actional - Symbolic	Dede 2009	2, 6

* Numbers are discussed above the table. These are the six issues with the definitions that are identified here.

Against this backdrop, we provide our definition of immersion that does not have the fundamental shortcomings as discussed above. User interaction with technology happens through sensory cues that the technology produces to stimulate responses from the user. While most of the definitions directly or indirectly connect the concept of immersion to user attention, the connection is incomplete because the capacity of allocating attention to processing these cues is somewhat ignored. We realized the importance of rooting the definition in seminal works of classical cognitive information processing such as Schneider and Shiffrin (1977) and Shiffrin and Schneider (1977), which put forth the notion that the human brain has the capability to allocate its selective attention to technological cues while suppressing distractors or processing irrelevant information. A common theme that fewer problematic definitions emphasize is the role of the attention mechanism in the experience of immersion. (e.g., Lee et al. 2012). Therefore, we propose the following definition of immersion:

“The extent to which an individual performing an activity is oblivious to other attentional demands.”

This definition is general enough to signify the psychological experience of immersion in any activity. It could be reading a paper-based book, watching a movie in the theater, playing video games on an Xbox, or writing a report on a personal computer. Given that this study is done in the domain of IT and IS, the definition must be relevant so that the IT-specific definition can guide the hypotheses-building section as well. An IT-specific definition of immersion would be “The extent to which an individual performing an IT-facilitated activity is oblivious to other attentional demands.” The key to this definition is obliviousness to other attentional demands, while selective attention is dedicated to the main activity. Indeed, the level of obliviousness is a function of the level of user engagement with the activity, which leads to the conclusions that (a) engagement is an antecedent of immersion, and (b) immersion is a graded experience—higher levels of engagement results in higher immersion. The next sub-section is dedicated to establishing this argument.

Our definition does not have the six issues discussed above. By extension, it (1) is free of any term such as engagement that itself would need to be defined; (2) does not mention antecedents; (3) is not technology-specific;[1] (4) refers solely to the psychological state and excludes objective attributes of IT; (5) does not use any term that overlaps with the flow, cognitive absorption, or presence, such as total or deep involvement that is used in defining the flow and cognitive

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[1] We refer to IT-facilitated activity, which could be done using any IT artifact, not just VR.

absorption (Agarwal and Karahanna 2000); and (6) does not use the word “immersion” nor its other derivative forms (e.g., immerse and immersive) in defining immersion.

Immersion is a graded experience

Brown and Cairns (2004) conducted a qualitative study on immersion and proposed that immersion is a graded psychological process that players experience in sequential levels (phases): (1) engagement, (2) engrossment, and (3) total immersion. At the engagement level, the player has the lowest level of involvement with the game; at this stage, the player invests time, effort, and attention to become familiar with the game environment and its controls. During the engrossment phase, the player’s emotions will start to be affected by the game; therefore, the emotional investment is part of the engrossment phase. In the third phase, as the result of total immersion, the player will experience presence, which is characterized by the extent to which the player feels a detachment from the surrounding reality. While their study does not shed light on the exact mechanisms through which the user experiences immersion, the three discussed levels (engagement, engrossment, and total immersion) highlight the step-by-step process in which the users’ obliviousness to other attentional demands grows as the result of interacting with IT, thus increasing immersion.

The same conclusion from the work of Brown and Cairns (2004) comes from resource allocation perspectives on individual attention and mapping this allocation of resources to brain functionalities (Davenport and Beck, 2000). Prior works state that we are limited in the amount of attention we can dedicate to something because our brains can process a limited amount of information (Davenport and Beck, 2000). Marois and Ivanoff (2005) state that “It is generally accepted that our brain cannot process all the information with which it is bombarded, and that attention is the process that selects which stimuli/actions get access to these capacity-limited processes.” Automatic human information processing theory (Schneider and Shiffrin 1977; Shiffrin and Schneider 1977) posits that there are two modes of human information processing: *automatic detection*, which refers to automatic attention response to stimuli, and *controlled search*, which refers to a selective attention focus on the stimuli or any information presented to the individual. We cannot dedicate our full processing bandwidth to all of the incoming information, so we selectively allocate our attention to processing “the stimuli of interest” from the environment while we try to neglect other irrelevant information/stimuli (Pashler et al. 2001).

Figure 2 represents the brain functionalities in processing the incoming information. Per Figure 2, we allocate our attention to process sensory, cognitive, and emotional information. If all the brain lobes are occupied in processing information, the subject becomes oblivious to other attentional demands from the environment (technology included), simply because no bandwidth is left to process other sources of incoming information. Consequently, the subject becomes fully immersed. Each one of the discussed forms of information processing is how the user engages with the IT-facilitated activity. For example, an IT activity might require reading (vision), listening (hearing), and thinking (decision making and planning), so the user allocates attention to process these sources of information. Therefore, at an abstract level, there are three forms of user engagement (sensory, cognitive, and emotional) that can work together to maximize the experience of immersion.

In conclusion, immersion is possibly a graded experience; our minds engage differently with the environment leading to different levels of obliviousness to other attentional demands from the environment. The three types of incoming information that our brains process match the three forms of user engagement that are discussed in the next section. Next, we will review the literature on antecedents or causes of immersion, and then we cluster these antecedents into constructs that represent the essential forms of user engagement.

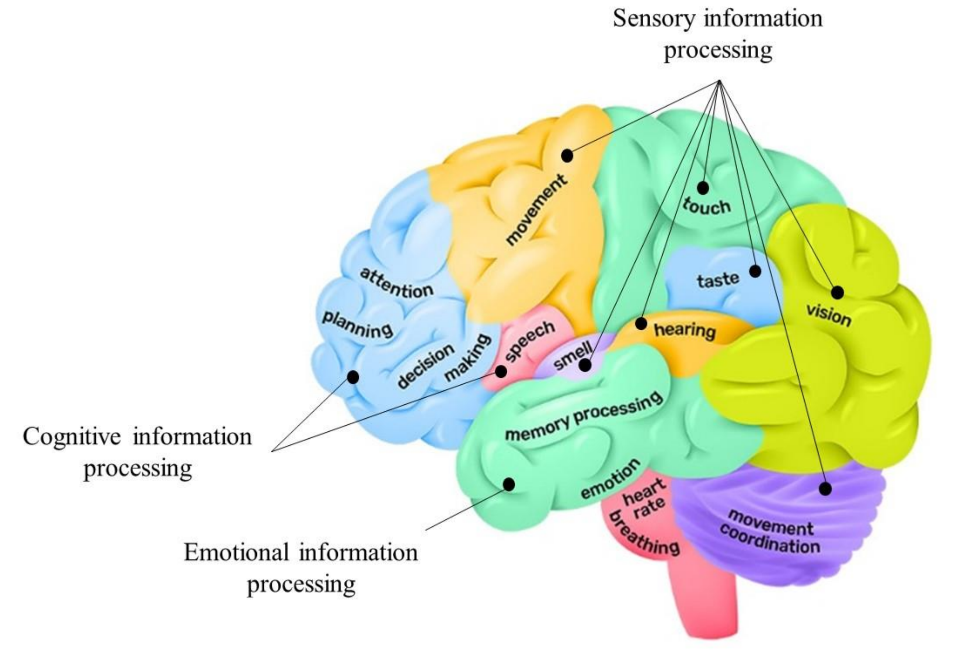

Figure 2. Functions of each brain lobe in information processing (Adopted from Queensland Brain Institute).[2]

Antecedents of immersion

This section reviews the literature on immersion's antecedents, whether empirically tested or theoretically proposed by prior works. Then, we cluster these antecedents into categories; each category demonstrates one form of cognitive, affective, or sensory engagement. The clustering is based on the information processing capabilities of the human brain proposed by relevant works.

We extracted three emerging themes from the constructs associated with immersion. Before describing the classifications and how the antecedents fit into each class, we consider how the user interacts with the technology. Figure 3 demonstrates that in an IS-use context, all user interactions with technology happen through the five Aristotelian senses. Therefore, in all respects, technology

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[2] The "attention" on the prefrontal cortex of the brain in the photo refers to cognitive attention which is tied to decision making and planning. In other words, it shows the mental focus on a certain activity (Dahlitz 2017).

is the artifact that engages with individuals through their natural senses (e.g., visual, audio, haptic). Figure 2 shows that the human brain processes three broad types of information: sensory, cognitive, and emotional. IT engages users' cognition and emotions only when it engages with the subject through the sensory layer. Building on this argument, we categorize antecedents into the sensory, cognitive, and affective engagement.

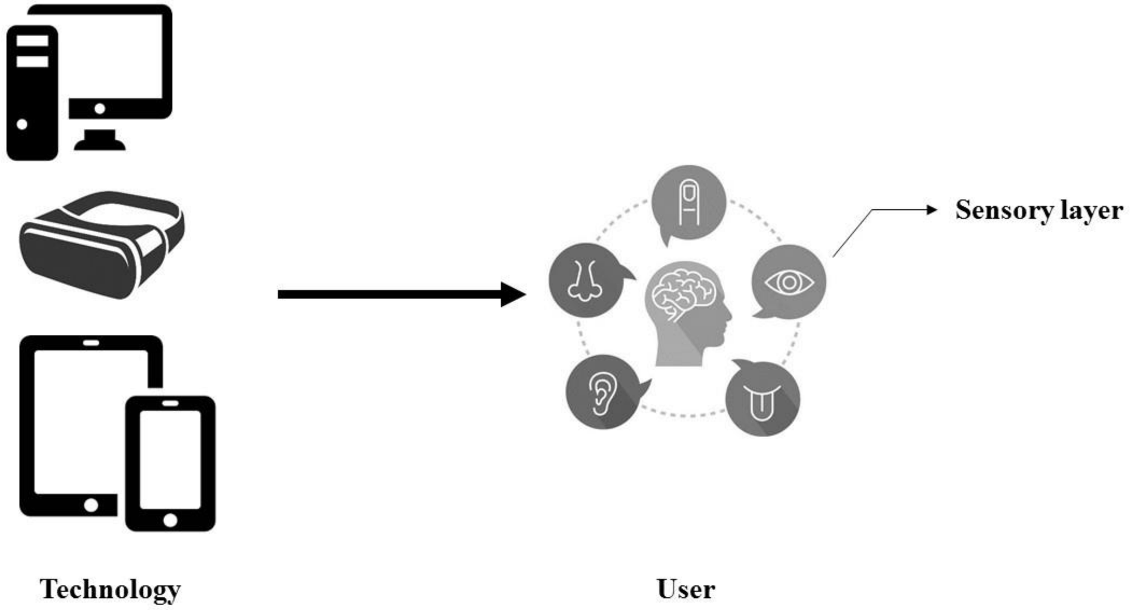

Figure 3. Human-computer interaction through the sensory layer.

IT-based sensory engagement

The five Aristotelian senses are proxies for how users perceive and respond to the environment. In the absence of technology, humans receive and respond to natural sensory stimuli in the environment. However, in the context of technology use, IT produces sensory stimuli, and users receive them. Figure 3 shows that at the most basic level, subjects receive sensory cues generated by technology. A cue is any piece of information related to some property of the environment (Fetsch et al. 2013). The five forms of sensory cues are visual, aural, haptic (e.g., touch, weight, thermal, motion), olfactory (smell), and gustatory (taste). Media richness theory suggests that media (IT) is considered rich based on the multiplicity of the cues and immediacy of feedback

(Dennis and Kinney, 1998; Dennis et al. 2008). In addition to the quantity discussed by media richness theory, the quality of the sensory cues was found to affect users' sensory attention (Lipscomb and Kim 2004). Hence, the user receives a combination of artificially produced sensory cues with various quality and quantity to engage user through sensory modalities.

A large body of research shows that people exhibit consistent cross-modal correspondence and constant interaction across different sensory modalities—mostly visual (e.g., optic flow) and vestibular (e.g., audio) cues (DeAngelis and Angelaki, 2012; Gu et al. 2008; Fetsch et al. 2009) in relation to body motion. Thereby, if a user observes an icon and moves the mouse cursor to click on it, the hand movement is the behavioral response to the IT-based visual cue, then another object might appear on the screen that requires another behavioral response. In this study, we define IT-based sensory engagement as the feedback loop process of internalizing IT-based sensory cues (e.g., audio, visual, haptic) and providing an appropriate behavioral response. As long as the user provides a feedback that the system is designed to understand, the sensory engagement with IT continues.

We reviewed studies on the intersection of IS, IT, HCI, and immersion. Table 2 lists the antecedents of immersion discussed or empirically tested by the literature. By extension, this table shows the type of the sensory stimuli, the construct name and description, and the study type. Audiovisual effects have the most salient impact on the user's experience of immersion. For example, prior research has established that sound effects and music have a direct influence on the user's experience of immersion (Chisholm et al. 2014; Cuny et al. 2015). Likewise, in an experimental setting, Van Der Land et al. (2013) and McGill et al. (2016) compare different screen types and quality and find them to affect immersion directly. Contemporary works emphasize the effect of other sensory cues such as tactile/haptic cues on various aspects of immersion, such as user control, curiosity, and the act of exploration of new content (Adams 2004; Yee 2006; Lowry et al. 2013; Grinberg et al. 2014; Harth et al. 2018). For instance, Pasch et al. (2009) emphasize the role of movement on immersion. In short, the examples mentioned are various representations of the sensory engagement effect (or sensory cues) on users' experiences of immersion.

Table 2. Technologically stimulated sensory factors as the antecedents of immersion.

Example from the literature	**Description**	**Study type**	**Reference**
3D environment	3-dimensional environment compared to 2-dimensional.	Empirical	Van Der Land et al. 2013
Music	Music was given to participants on the background of browsing an art website as part of an experiment condition.	Empirical	Cuny et al. 2015
Sound	Sound-attenuated room was used as part of the experiment to find the effect of sound.	Empirical	Chisholm et al. 2014
Display mode	Stereoscopic vs. monoscopic display was compared. Stereoscopic affected immersion.	Empirical	Ahn et al. 2014
Virtual reality cinema	Putting participants in a 3D virtual cinema scene, with media content playing on a cinema-sized virtual display.	Empirical	McGill et al. 2016
Virtual reality 360	Putting participants in 360◦ video sphere scene.	Empirical	McGill et al. 2016
Curiosity	The extent the experience arouses an individual's sensory and cognitive curiosity.	Empirical	Lowry et al. 2013
Control	Being in charge of the interactions in-game.	Empirical	Lowry et al. 2013
Spatial exploration	Individuals' spatial exploration in a highly controlled virtual environment. Measured through the count of participants' movements from one room to another.	Empirical	Grinberg et al. 2014
Social engagement	The time participants spent interacting with other avatars in the virtual environment.	Empirical	Grinberg et al. 2014
Curiosity	Arousal of senses and cognition and attraction to explore game narrative.	Theoretical	Qin et al. 2009
Spatial involvement	Very similar to the idea of presence, experienced when the user wanders around in the virtual game world.	Theoretical	Björk and Holopainen 2004
Sensory-motoric involvement	The result of the feedback loops the player receives by performing actions in the game and receiving sensory outputs from it.	Theoretical	Björk and Holopainen 2004
Sensory involvement	Audiovisual execution of games. The sensory information coming from the real world; the player becomes entirely focused on the game world and its stimuli.	Theoretical	Ermi and Mäyrä 2005
Tactical involvement	Refers to attention shift as the result of the moment-by-moment act of playing the video game. Normally associated with quick action video games, it is physical and immediate.	Theoretical	Adams 2004
Discovery	Finding and knowing things that most other players do not know.	Theoretical	Yee 2006
Customization	Having an interest in customizing the appearance of their game character.	Theoretical	Yee 2006
Control	The players' feeling of control over the game and his/her interactivity with the game.	Theoretical	Jennett et al. 2008; Qin et al. 2009
Virtual world exploration	Exploring the virtual setting/world by interacting with place and objects.	Theoretical	Harth et al. 2018
Self-exploration	Exploring the self (i.e., avatar) in the virtual setting.	Theoretical	Harth et al. 2018
Self-control	Understanding and learning the boundaries that allow the individual to control him/her self in the virtual world/setting.	Theoretical	Harth et al. 2018
Virtual world control	Understanding and learning the boundaries that allow the individual to exercise control over the virtual world/setting.	Theoretical	Harth et al. 2018
Movement-based involvement	For example, dancing in exergames (games that combine exercise and game).	Theoretical	Pasch et al. 2009

Cognitive engagement

The second theme that we extracted from the literature is the role of “cognitive engagement” in users’ experiences of immersion. In this study, cognitive engagement refers to any forms of self-conscious mental engagement with the technology that often requires users to analyze, think, process the incoming information (i.e., calculative activities), and formulate a response that all happen in their minds (Greene and Miller 1996; Greene et al. 2004; Zhu 2006; Walker et al. 2006; Dimoka 2012; Csikszentmihalyi 1990). This process consumes a portion of the information processing capability in the user’s brains as discussed earlier, so a considerable amount of attention is taken from the user, and the user becomes oblivious to some other attentional demands (Gazzaniga and Mangun 2014). While prior works measured instantiations or contextualized versions of cognitive engagement, this study takes one step back and integrates all cognitive factors used in the prior literature as antecedents of immersion into a single construct called cognitive engagement. Challenge is one of the notable forms of cognitive engagement that leads to immersion (Jennett et al. 2008; Ermi and Mäyrä 2005). Originally identified by Csikszentmihalyi (1975), challenges created by developers for video game players will push them to expand the boundaries of their skills to overcome them. The combinations of sensory cues will provide a higher level of engagement beyond the primitive sensory attention, which requires the player to analyze the situation and think of an appropriate chain of responses in order to overcome the challenge (Jennett et al. 2008). In this process, the user experiences a degree of obliviousness to other attentional demands. Moreover, this process also happens when the task that the user is engaged with is difficult (Burns and Fairclough 2015; Chisholm et al. 2014) or requires the user to strategize to achieve the objectives (Adams 2004). Table 3 represents a list of the most salient cognitive antecedents of immersion discussed in the extant literature.

Table 3. Cognitive factors as the antecedents of immersion.

Example from the literature	**Description**	**Study type**	**Reference**
Player interactions (player versus player)	Player versus player is a form of competitive engagement of individuals with each other in the game setting that involves both strategizing and close interactions.	Empirical	Cairns et al. 2013
Game difficulty	Refers to the level of the difficulty of the game, which increases the physical and mental efforts that are required by the game as the difficulty arises.	Empirical	Burns and Fairclough 2015
High-demand task	Playing the game with greater difficulty.	Empirical	Chisholm et al. 2014
Challenge	The game difficulty that demands more skills.	Empirical	Jennett et al. 2008
Challenge	Some relative difficulty in the game narrative for players.	Theoretical	Qin et al. 2009
Strategic involvement	Refers to cerebral (cognitive) involvement with the game and finding the path to victory; this involves the existence of less random elements in the game and more calculated actions that require thinking and engagement.	Theoretical	Adams 2004
Cognitive involvement	Refers to the abstract thinking process through which players engage in the problem-solving aspect of the game.	Theoretical	Björk and Holopainen 2004
Challenge-based involvement	A form of involvement that is at its most powerful when one can achieve a satisfying balance of challenges and abilities in games.	Theoretical	Ermi and Mäyrä 2005
Cognitive involvement	The extent to which the player is focused on the game.	Theoretical	Jennett et al. 2008

Affective engagement

The third antecedent that emerged by integrating similar concepts is “affective engagement,” which refers to any forms of emotional exchange users have with technology (Picard 1995). As discussed before, part of the human mind is dedicated to processing emotional information. If one's emotional processing capability is occupied, then the subject experiences a degree of obliviousness to other demands for emotional attention. This is simply because less of the remaining processing capability is free to be allocated to other attention-seeking stimuli. Similar to cognitive engagement, affective engagement is a higher level of engagement beyond the primitive sensory engagement of the user with technology. That means while the user is receiving sensory cues from the technology, the cues cumulatively trigger user's emotions and capture their emotional attention (Léger et al. 2014). For instance, the storyline in a video game is created through connecting chains of cues that cumulatively create events, incidents, and digital objects that the user will interact with; at a higher level, they tell a story that triggers the player's empathy (Qin et al. 2009). Narrative engagement is one of the most powerful forms of emotional engagement that a user can experience (Ryan 2001; Bormann and Greitemeyer 2015). Similarly, enjoyment is another trigger for immersion. For instance, Lowry et al. (2013) showed that for game players, joy directly influences the experience of immersion. Table 4 summarizes the affective factors that are utilized as antecedents of immersion in prior works.

In summary, there are a variety of cognitive, affective, and sensory factors (as shown in Tables 2–4) that can directly influence a user's experience of immersion. By a careful review of the literature, we categorized these variables into a higher level of concepts that can represent the category of factors that influence users' experiences of immersion.

Table 4. Affective factors as the antecedents of immersion.			
Example from the literature	**Description**	**Study type**	**Reference**
Fun	Fun and enjoyment experienced in the game.	Empirical	Bormann and Greitemeyer 2015
Joy	the pleasurable aspects of the interaction described as being fun and enjoyable rather than boring	Empirical	Lowry et al. 2013
Game story	The game story was part of the experiment condition.	Empirical	Bormann and Greitemeyer 2015
Empathy	Mentally entering into the imaginary game world. When players become absorbed in a game's stories, they begin to feel for and identify with a game character and the game world.	Theoretical	Qin et al. 2009
Narrative context & space	All the elements that will create a story, such as the setting of time and place, political and social conditions, individuals present, and their goals and agendas.	Theoretical	Brooks 2003
Imaginative involvement	One becomes absorbed with the stories and the world or begins to feel for or identify with a game character.	Theoretical	Ermi and Mäyrä 2005
Comprehension	Understanding the structure and content of the storyline. Comprehending the game story is a precondition to immersion in the game world.	Theoretical	Qin et al. 2009
Imaginative involvement	Readers experience imaginative projection of the body into the represented space.	Theoretical	Ryan 2001
Narrative involvement	Readers experience a moment-by-moment reenactment of the narrative of the passion.	Theoretical	Ryan 2001; Adams 2004
Emotional involvement	Readers experience participation in the emotions of the characters.	Theoretical	Ryan 2001; Björk and Holopainen 2004

Outcomes of immersion

The literature review informed our understanding of the different outcomes of immersion. Very few studies have investigated how immersion influences user performance. It is challenging to find consistency among these outcomes because they are mostly the situational dependent variables of interests. Indeed, these outcomes could be viewed as the desired performance in their own right. For instance, studies show that for video game players, immersion positively influences their intention to return to the game (Goel et al. 2013). The game developers' objective is to have players continue playing or keep coming back in order to generate revenue. Another study showed that immersion negatively influences the perceived waiting time of eCommerce customers who wait (Lee et al. 2012). Perhaps if immersion reduced the perceived wait time for users, the performance of the website would be improved. In the medical and healthcare fields, immersion has been studied as a tool to treat patients. For example, Krijn et al. (2004) showed that immersion influences acrophobia. Thus, it could be used as a method for treating patients who have acrophobia.

Theoretical model

Figure 4 represents the theoretical model of experiencing immersion as a result of interaction with IT. This model implies that users' experiences of immersion influence their performance and that immersion is affected by three forms of engagement. Whenever users interact with IT, they engage with digital objects. Therefore, IT becomes a tool that produces (or manipulates) sensory cues and engages individuals through their senses. For instance, music (Cuny et al. 2015) and sound influence (Chisholm et al. 2014) the individual's experience of immersion. Likewise, touching objects and exploring things in a virtual environment (Björk and Holopainen 2004) can influence users' experience of immersion. We previously discussed that IT could produce or manipulate sensory cues, which marks its role in facilitating immersion for users compared to other contexts, such as reading a paper-based novel that immerses the reader in its story. Cognitive and affective engagement happens in the user's mind where IT-produced cues cumulatively trigger an emotional response or induce a response that requires thinking and planning.[3] We developed this

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[3] As described earlier, per Figure 3, cognitive and affective engagement depend on IT-based sensory cues; these are the proxy layers through which all stimuli pass through and are then processed in the brain.

framework through mapping general functionalities of brain lobes (see Figure 2) in information processing to classified antecedents of immersion (see Tables 2, 3, and 4).

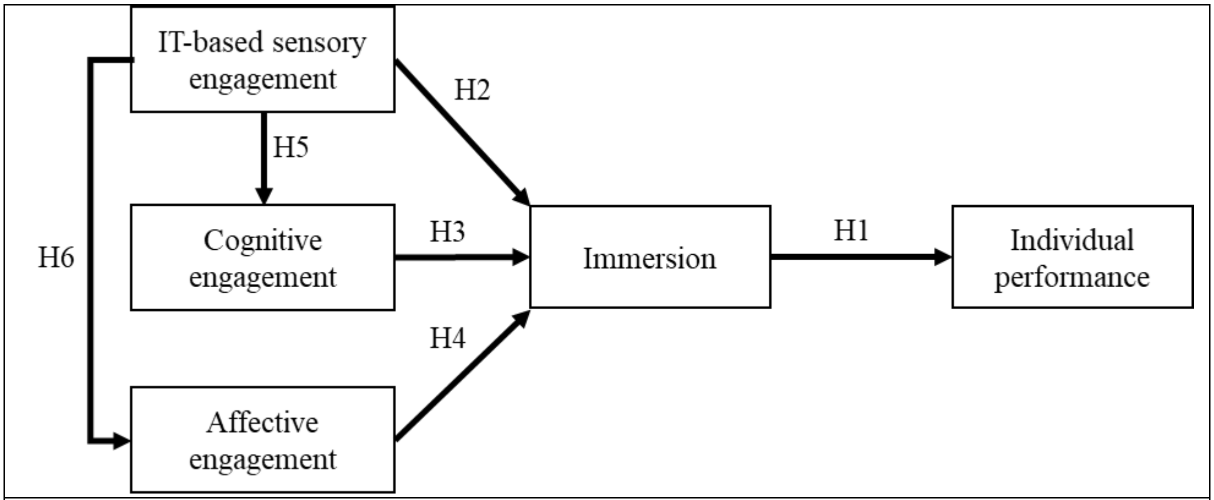

Figure 4. The research model.

Conceptualizing IT-based sensory engagement

As shown in Figure 3, the first layer of user interaction with IT happens through the sensory layer. Even if the objective is to stimulate an emotional response, the stimuli have to pass through one or more of the five senses first. Therefore, IT-based sensory engagement is the most important form of engagement, which happens in advance of cognitive and affective engagements. For instance, when a user is watching TV, before they start thinking, contemplating, and showing emotional reactions, the sensory part of their brain is engaged with the TV. Essentially, without the existence of IT-based sensory engagement, cognitive and affective engagements are not triggered. Therefore, arguably both cognitive and affective engagement depends on IT-based sensory engagement.

One seminal theoretical perspective that explains the sensory communication between IT and the user is the media richness theory (Daft and Lengel 1986). Media richness states that a medium's communication with the user could be viewed from the lens of the richness of the conveyed stimuli. Richness is characterized by the breadth (quantity) and depth (quality) of sensory cues (Dennis and Kinney, 1988). Breadth signifies the multiplicity of cues. For example, when listening to music, the user receives aural cues. While they watch TV, they receive aural and visual cues. TV is, therefore, richer in conveying cues compared to a music player (e.g., iPod). Similarly, depth or quality is important in the medium's capacity for communication. For instance, consider a computer monitor with 4K capabilities versus one with only 720p HD. In this example, the quality of the monitor could clearly present nuanced visual effects, so the quality of the communication between the medium and user is superior. Therefore, technologies that produce higher quality and more sensory cues should be more engaging.

On the user side, internalizing the sensory cues is a complex process, and the interaction of sensory modalities often aids behavioral performance or alters the quality of the sensory percept (Kayser and Logothetis 2007). Studies on intersensory or crossmodal interactions suggest that sensory modals correspond and interact such that one influences the other (Spence 2011). The implication of this is that one could observe and stimulate one form of sensory engagement while simultaneously stimulating the other forms of sensory cue. For example, studying body motion adjustment in relation to audiovisual processing (DeAngelis and Angelaki, 2012; Gu et al. 2008; Fetsch et al. 2009) could be one way to realize how aural, visual, and behavioral senses cumulatively engage and coordinate with the technology to form a response. Hence, as explained later in the research methodology section, this study adopts a measure for capturing body motion to account for IT-based sensory engagement.

In order to better understand how IT-based sensory engagement influences cognitive-affective engagement, we need to recognize the characteristics of sensory cues that translate to breadth and depth. For example, sound quality is a function of pitch, loudness, and duration; visual quality is identified by color, shape, size, location, and so forth (Lipscomb and Kim 2004; Lipscomb 2005;

Lipscomb and Zehnder 2004). The complexity of the relationship between IT-based sensory engagement comes into the picture when we realize a combination of these characteristics cumulatively triggers cognitive and affective engagement. In other words, not all sensory cues produced by the technology are targeted to engaging users' emotions or cognition; while some unique combinations of these characteristics are designed to induce cogno-affective engagement, others only capture users' sensory attention and would not trigger the other two forms.

Immersion is positively associated with user performance

One would expect if they focus their attention on an activity, they could finish it in a shorter time and make fewer errors. Anything that detracts a user from focusing on the primary task would increase task-completion time and error rate (Bailey and Konstan 2006), thereby reducing user-performance. The user experience of immersion, as defined in this study, accounts for users' focused attention on the cognitive, emotional, and sensory pieces of the activity through becoming oblivious to distractors or noises in the environment. Hence, with an increase in immersion, by allocating more brain information processing capacity to process cognitive, affective, and sensory aspects of the primary activity of interest, fewer resources are available for allocation to noises around the individual (obliviousness to other attentional demands increases). The environmental noises themselves can trigger emotional and cognitive distraction and take away focus on the primary activity. For instance, consider a programmer hearing his wedding music while writing complex lines of codes, suddenly he gets distracted because of his affective processing shifts from the primary activity to the distractor. However, if all three discussed forms of processing occupied (and focused) on the primary activity, no affective processing capacity would have been left to be allocated to emotional wedding music. Accordingly, we hypothesized that:

H1: Immersion positively influences user performance.

IT-based sensory engagement and immersion

Prior works found that technology is capable of engaging users through all five senses, but the most prevalent forms of sensory engagement that are also available to public use are audio, visual, and haptic (Yanagida et al. 2004; Lee et al. 2004; Nakamura and Miyashita 2011; Saunders et al. 2011; Cuny et al. 2015). But why is the user's attention drawn to and kept on the sensory cues provided by the technology?

The essential cognitive ability of users is selective attention, which allows them to effectively process and act upon relevant information while ignoring unwanted distracting events or information in their surroundings (Mangun 2012). By itself, technology actively produces sensory cues, but engagement happens when users decide to process these cues and respond to them. As soon as users start processing these cues, a portion of their selective attention is allocated to processing and responding to the cues. This, in turn, results in keeping their attention on the continuous sequences of sensory cues that are provided to them by the IT in the form of information and events (Rueda et al. 2015; Schneider and Shiffrin 1977; Shiffrin and Schneider 1977). For example, video game players passionately engage in playing games. Games are rich in providing audiovisual and haptic cues that, when combined, will continuously keep the users' attention and immerse them in the game (Chisholm et al. 2014; Raptis et al. 2018). Digital objects and game characters constantly move around on the screen; the user's eyes continuously move to track the objects, and the player must be aware of the game environment or the upcoming events embedded in the game and constantly provide feedback through the hand controller, mouse, and keyboard (Raptis et al. 2018; Schmierbach et al. 2012). This visual communication is accompanied by sound effects that further engage the user's sensory attention (Chisholm et al. 2014). An increase in the give and take between players and the game in the form of audiovisual and haptic feedback will increase the users' immersion (Burns and Fairclough 2015).

Considering breadth and depth, if a technology is an enabler of higher quality and more sensory cues, then the user engagement with these cues through the mouse, keyboard, and/or hand controllers, as discussed in the previous paragraph, will cause higher levels of immersion. Given that crossmodal studies have suggested there is a correspondence between sensory modalities, as described earlier, an increase in audiovisual engagement could be reflected in an increase in motion response (e.g., pushing more buttons on the keyboard, mouse, or controllers; more cursor activities, or controller movements, etc.). Thus, higher levels of haptic activity with technology correspond to higher levels of audiovisual processing; therefore more sensory processing capacity is being occupied, and less is available to be allocated to other attentional demands; consequently, immersion increases. Accordingly, we hypothesized that:

H2: Individuals' IT-based sensory engagement is positively associated with their immersion.

Cognitive engagement and immersion

Beyond simple sensory information that the user's brain processes are the cumulative effects that a combination of sensory cues can convey to the user's brain. Consider a warning message on a computer screen, for example, that combines a simple visual sign of warning (i.e., a yellow triangle with an exclamation mark) with a text message and a warning sound; the visual and audio cues combined convey the idea that the user needs to pay attention to the message on the screen, which will cause consequences if neglected. This is another level of information processing that requires contemplation (i.e., thinking and understanding), more time to be analyzed or understood, or requires a response in the form of behavioral reactions (e.g., inputs through typing, clicking on a button, strategizing a response, planning a reply, and so forth). This process engages the user's cognition, meaning that in addition to allocating processing capacity to sensory information, the user needs to allocate some capacity for thinking, strategizing, understanding, formulating a response, and so on. The more attention that is allocated to these tasks, the more immersed the user becomes due to having less capacity available for allocation to other attention-demanding events. For instance, in video games, a common mechanism for cognitive engagement of the players is strategizing about the next move in the game (in addition to processing visual and aural cues that the game produces). When the game becomes more demanding (Chisholm et al. 2014) through its increased difficulty (Burns and Fairclough 2015), users must strategize, leading to higher levels of immersion. The cognitive engagement still consumes users' attention and immerses them in non-gaming settings as well. In virtual- and augmented-reality environments, users still need to interact with technology, and the response from the users is generated through information-processing and thinking. For instance, when users collaborate with virtual avatars, they still need to socially engage in communication that requires mental thinking, strategizing, and planning (Grinberg et al. 2014; Georgiou and Kyza 2018). Hence, we hypothesized that:

H3: Individuals' cognitive engagement is positively associated with their immersion.

Affective engagement and immersion

Similar to the way that cumulative IT-based cues trigger cognitive engagement, they can also trigger affective engagement. The affective factors can influence users' immersion because they capture the emotional attention caused by the human mind's role in the emotional processing of information received from IT-based sensory modules (Vuilleumier, 2005). This process is particularly more apparent in negative emotions, such as anxiety. For example, individuals with acrophobia get very anxious when they are exposed to great heights, and this anxiety makes them oblivious to other attentional demands to the extent that they cannot behave normally (Krijn et al.

2004). Immersive technologies, as in the natural world and other socially interactive settings, can stimulate both negative and positive emotions in users. A common strong mechanism that uses audio–visual effects to evoke emotional responses is the implementation of narrative, story, or plots into the content (Gorini et al. 2011; Bormann and Greitemeyer, 2015). Gorini et al. (2011) showed that, in a virtual hospital, having a scenario and a story engages subjects, as they show arousal, valence, or an increased heart rate. Likewise, enjoyment as a form of emotional engagement causes video game players to experience immersion (Lowry et al. 2013; Chan et al. 2014). Consequently, we hypothesize that affective engagement is positively associated with users' experiences of immersion:

H4: Individuals' affective engagement is positively associated with their immersion.

IT-based sensory engagement and cogno-affective engagement

One of the concepts discussed earlier was the role of users' five senses in filtering all incoming stimuli (pieces of information) before cumulatively combining and triggering cognitive and affective engagement. This could imply that IT-based sensory engagement influences both cognitive and affective engagement. If a user wants to mentally process an IT-related task, they need to receive a combination of "visual," "aural," and "haptic" pieces of information from the IT. Based on these, the user mentally processes, thinks, and forms a logical or emotional response. For example, if a user selectively ignores one form of the IT-based sensory cues, such as playing a video game without sound, they are automatically deprived of the intended cognitive and emotional engagements that the designer implemented through sounds (e.g., game music, sound effects). Therefore, given that both cognitive and affective information processing depend on forms of "sensory" cues that one receives from IT (see Figure 3), we hypothesize that:

H5: Individuals' IT-based sensory engagement is positively associated with their cognitive engagement.

H6: Individuals' IT-based sensory engagement is positively associated with their affective engagement.

Research Methodology

In this section, we present our study design to test the theoretical model using an objective measure of immersion. The focus is on measuring immersion during the IT-based activity and capturing its influence on user performance in addition to demonstrating the effect of engagement types on users' immersion. Below, we have described our experimental design and our approach to measuring the discussed concepts. The experiment uses three treatments, each of which has an influence on immersion and/or performance. Furthermore, this study relies on objective measures for all discussed concepts and uses subjective measures as a form of robustness check to corroborate the findings of the original model that is being tested using objective variables of interest.

Experiment design

We conducted a single-session lab experiment that lasted approximately 60–90 minutes. To examine the theoretical model and understand how immersion, performance, and the relationship between the two unfold across different (a) contexts; (b) technologies; and (c) tasks, we created three manipulations in the design stage. Recognizing the role of technology and task in the experiment was motivated by task-technology fit theory (DeLone and McLean, 1992). The compatibility between task and technology is an important pre-condition to user performance, as well as the experience of immersion.

Furthermore, our literature review suggested that, while immersion is studied in a variety of contexts, it was largely investigated in hedonic contexts where subjects play games. Therefore, to account for this context, we considered studying a hedonic activity versus a utilitarian activity. To be exact, a video game and virtual house tours were selected as the primary activities for the experiment. The choices of technology were the Oculus VR goggles, which came with two natural controllers, or a traditional desktop computer with a pair of speakers. A desktop computer is capable of running programs for both hedonic and utilitarian activities and is easy to administer, which reduced the amount of effort in the different stages of conducting the study, including minimizing the training required for users and reducing the effort for the lab operator. In addition, we selected the VR device because it is one of the few devices capable of blocking distractors (e.g., visual distractors) and has the potential to execute a variety of hedonic and utilitarian activities.

Lastly, to create complexity in the task, we manipulated the difficulty of the tasks to be either “easy” or “difficult.” Given that the experiment uses existing software and games, manipulating the task's complexity level was the most feasible and accessible method for this study. In conclusion, the experiment is a 2 (hedonic and utilitarian) x 2 (VR and desktop) x 2 (easy and difficult) design and subjects were randomly assigned to each group. We strived for consistency across technology platforms, which narrowed our options to hedonic and instrumental tasks that were available on both VR and desktop. In particular, we selected a video game called SuperHot because it was available on both desktop and VR platforms and was simple to learn. In addition, we selected virtual house tours, which were available on both desktop and VR platforms. To find the right degree of difficulty, we performed a pilot study and changed scenario instructions to expose subjects to differing levels of difficulty[4]. The scenario description and user objectives are presented in Appendix B.

Electroencephalography (EEG)

Recent advances in neuroscience in terms of accuracy and affordability has allowed IS researchers to invest and utilize EEG tools to answer important research questions in the field. One distinct advantage of EEG is that it reflects real time cerebral activity, which provides a unique index of brain function with a reasonable resolution (Kennett, 2012). Commercialized EEG tools are now available at affordable prices for IS researchers and have great levels of accuracy compared to more expensive equipment (Kuan et al. 2014). The long history of neuroscience studies on human attention provides the support for this study to measure immersion using EEG tools, as our definition of immersion is closely tied to user attention and obliviousness to other stimuli. EEG tools record the power of brainwave patterns that are identified by any active electrode on the scalp (Schomer and Lopes da Silva, 2017). Here, we are interested in the beta, alpha, theta, and gamma activities in the prefrontal cortex because (a) our objective measure of cognitive engagement uses gamma; and (b) our objective immersion is measured using these three parameters. Beta waves are associated with attention (van Son et al. 2018), whereas alpha and theta are associated with attention suppression and distraction (Foxe and Snyder, 2011; Freeman et al. 2004).

In this study, we used a MyndPly EEG headband that uses a NeuroSky ThinkGear microchip for capturing waves at 512 Hz. This is one of the very few commercialized and affordable dry

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[4] Subjects who played the easy game started from level 1 and subjects who were assigned the difficult game started from level 5. For virtual house tours, the easy-level group completed a tour of four houses, while the difficult-level group completed the a of eight houses.

sensor devices on the market that is compatible with VR goggles[5], which was the main motivator for our investment in it. This is a single channel sensor device (FP1) with a reference point at mastoid. Prior EEG experiments have validated the reliability of this single electrode device by comparing it to other conventional, expensive EEG equipment (16 reference points) and found it to have an adequate level of quality and reliability (Rieiro et al. 2019; Rogers et al. 2016). Because the device is a dry sensor, prior to their appointment with the lab, we asked subjects to avoid wearing make-up or face cream on the experiment day to allow sensors to come in direct contact with the subject's skin.

Measurement strategy

In this study, we use objective (measured during the use) and subjective (post-hoc questionnaire survey) measures. However, the goal is leveraging objective measures. The primary reason for this endeavor is that, realistically, objective measures are the closest we can get to capturing user behavior and cognitive, affective, and sensory reactions while they interact with IT. Nonetheless, we use the subjective measures (a traditional questionnaire) in a post-hoc fashion after users complete their tasks.

Objective (implicit) measures

Objective immersion (Immersion index)

Our definition of immersion proposes two conditions that must be present for the user to experience immersion, and we looked for an approach that reflects both together. The two conditions are derived from "obliviousness to other attentional demands." For the first, to be oblivious to the surrounding stimuli, the user needs to "focus attention" on the main task. For the

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[5] The VR device had big and tight straps on top of and around the head to hold it firm in front of a user's eyes. We predicted that it would add pressure and dislocate the electrodes if we were to attach electrodes onto the scalp to F7-F8, T3,T4, Cz, Pz, O1, O2, T5, and T6 in the traditional 10-20 system.

second, there must be distractors in the environment to which the user shows obliviousness or negligence to. To satisfy the existence of the second condition, we created some real world sound distractors and randomly played irrelevant sounds in the room.

We quantified immersion using beta, alpha, and theta power[6] obtained from the EEG recordings during the task. A few studies have suggested that beta is often associated with focused attention in a nonresting state (Freeman et al. 2004), which resonates with our definition of immersion. If users focus attention on one task, they experience a degree of obliviousness to other attentional demands (neglecting noises and irrelevant sounds). On the other hand, there is sufficient evidence suggesting that alpha-band oscillations in the presence of beta changes are associated with the sensory suppression mechanism during selective attention (Foxe and Snyder, 2011). Moreover, prior works have suggested that theta band is associated with a decrease in attention (Scerbo et al. 2003). Therefore, we used the power of beta in the numerator to reflect focused attention on the main task and combined theta and alpha in the denominator to reflect changes in attention focus from the main activity to other stimuli (distractors) in the environment. Equation 1 presents the immersion index:

Eq1.

$$Immersion\ index = \frac{beta}{alpha + theta}$$

We expected that user reactions to distractors would show an effect on this index through the combination of alpha and theta. Klimesch (2012) found that alpha-band oscillations have two roles (inhibition and timing), which are closely linked to fundamental functions of attention: suppression

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[6] Power = A measure that estimates the magnitude of oscillatory amplitude within a defined time window.

and selection. Hence, one way to put it is that, if beta reflects the main focus on the activity, then swings in alpha reflect changing attention from one to the other. Conceptually, an increase in beta reflects the focused attention, and alpha plus theta monitors whether the focus is on the primary activity, such that the fluctuations in alpha and theta represent an attention suppression mechanism. Specifically, they reflect the brain's effort to stay focused on the main activity while ignoring the other attentional demands that were discussed. It is important to note that this index (and its adaptations) has been validated empirically and used in a few neuroscience studies related to performance, attention, engagement, and distraction (Pope et al. 1995; Freeman et al. 2004). However, to our knowledge, no research has used this index with the injection of real-world sound distractors to see how users' attention and obliviousness to distractors influence immersion and the relationship between immersion and performance.

Performance

In this study, we measure user performance objectively using "completion time" and "success rate." For the house tour task, the subjects were instructed to complete the task in the shortest time possible. We used the number of minutes needed to complete the task as the measure of the DV (performance). In the gaming scenario, subjects were told that they must complete as many levels as they could. We used the average time needed to complete a level, and the number of total levels passed as measures of user performance (both time and success rate). We created two performance measures called "Performance 1" and "Performance 2." Performance 1 is the completion time for subjects in the house tour group plus the average time to complete a level for subjects in the gaming group. Performance 2 (which was essentially used for robustness-check purposes) combines, again, the completion time for house tour group subjects, but with the number of total levels passed for gaming group subjects. To help with interpretation and because needing less time to complete a task represents higher performance, the variables that involved time were multiplied by -1.

Engagement

We measured IT-based sensory and cognitive and affective engagements using neurophysiological tools. For cognitive engagement, the relative power of gamma bands is used as the measure for cognitive engagement. Some prior studies found that cognitive activities (e.g., mental calculation) augment EEG gamma power (Fitzgibbon et al. 2004). As mentioned before, the sampling rate for this band is 512 Hz. Some works have suggested that the autonomic innervation of sweat glands is reflected in measurable changes in skin conductance at the surface, which is defined as electrodermal activity (Critchley, 2002). EDA is another NeuroIS tool that has been adopted and promoted by recent IS studies and has been used as a tool to measure emotional arousal and engagement (Minas et al. 2014). Therefore, we use EDA to measure emotional engagement objectively. The EDA recorded in this study was sampled at 4 Hz, and the unit of analysis is microSiemens.

For IT-based sensory engagement, measuring haptic engagement appeared to be the most feasible way with our setup due to difficulty in tracking and measuring visual and aural engagement in real time, especially when the user put on the VR headset. However, numerous neuropsychological studies on human self-motion adjustment and response to outer environment suggest that there is a correspondence with and constant interaction across sensory modalities—mostly visual (e.g., optic flow) and vestibular (e.g., audio) cues (DeAngelis and Angelaki, 2012; Gu et al. 2008; Fetsch et al. 2009) in relation to body motion. Based on the provided argument, measuring the feedback loop between body motion response to audiovisual sensory modalities also represents audio–visual engagement to some degree. We used the accelerometer (ACC) that was attached to the subjects' wrist to capture hand motion response during interaction with IT. We selected the wrist because while using a computer mouse or VR touch controller, hands are the most engaged and continuously moved parts. The ACC was sampled at 32 Hz and recorded in the range of -2g to 2g. To record both EDA and ACC, we used Empatica E4, which is a biosensor attached to the subjects' wrist, and recorded both EDA and ACC together. As mentioned in the experimental design, we attached the wrist band to their left or right hand if they were left- or right-handed, respectively.

Subjective measures

Subjects completed a short online survey after the experiment. Except for performance, the constructs are operationalized using established pre-existing measures. Appendix C represents the list of constructs, their measures, and sources that we adopted them from. The survey used a 7-point Likert scale to measure perceptions. We decided to use subjective measures with the objective of corroborating the findings of the tested model using objective measures. Other than performance, all other constructs listed in the theoretical model (Figure 4) were measured using the available measures in the IS and psychology literature.

Protocol

Figure 5 summarizes the experiment workflow for any subject in the lab. Participants were university students recruited from psychology and business majors. Subjects with pre-existing conditions that could influence the EEG recordings (or affect the individual's health) were prevented from participation[7]. Participants registered online for participation and completed a

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[7] We excluded: 1. Pregnant and elderly; 2. Participants who suffer from PTSD (post-traumatic stress disorder); 3. Participants who suffer from heart conditions or psychiatric disorders; 4. Participants who are prone to seizures; 5. Participants with pre-existing binocular vision abnormalities; 6) Participants who are on medication(s) that induce sleepiness and reduce brain performance (e.g., cold, flu, or sleep medicine) that they must take within 48 hours before the experiment, as that would disrupt brainwave data that we have planned to collect.

short demographic survey before the experiment day. We selected a room large enough to support the safe space suggested by the Oculus manual and a room that provides isolation from any sound outside of the room. On the experiment day, each subject went through seven phases. In Phase 1, when subjects arrived at the lab, the operator greeted them and asked them to leave electronic devices outside of the room. The lab operator attached the EEG headband and helped the subjects put the biosensor wristband on their left or right hand, depending on whether they were left-handed or right-handed. They also received a brief introduction about what would happen step-by step-during their session in the lab. In Phase 2, subjects received a brief explanation about the activity and received the scenario sheets (see Appendix B). In Phase 3, after they read the scenario and asked clarification questions, the lab operator trained the subjects to use the VR goggles and its controller or showed them how to use a keyboard and mouse to complete the task (depending on the platform that the subject was assigned to). In Phase 4, the lab operator helped subjects wearing VR goggles or sitting behind a computer get into the correct position, then started a relaxing 3-minute video clip of a waterfall (we used this as the baseline task for comparison against the main), asking them to watch it and relax. The operator left the room and returned after 3 minutes. In Phase 5, the lab operator closed the clip and launched the game or house tour. The operator left the room as soon as they instructed the subjects to start the task and began monitoring the situation. The operator used a virtual connection to the user computer as well as two cameras in the room to observe the subjects' behaviors to ensure that procedures were being followed accurately. The operator could interfere if the subjects encountered any issues[8]. In Phase 6, one minute into the task, the operator started playing the distractive sounds and voices (see the previous section for details). In Phase 7, after finishing the task, the operator detached all devices from the user and

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[8] An independent researcher watched the recorded videos to make sure that the protocol was being followed correctly.

immediately guided them to another room to complete an online questionnaire about their experience.

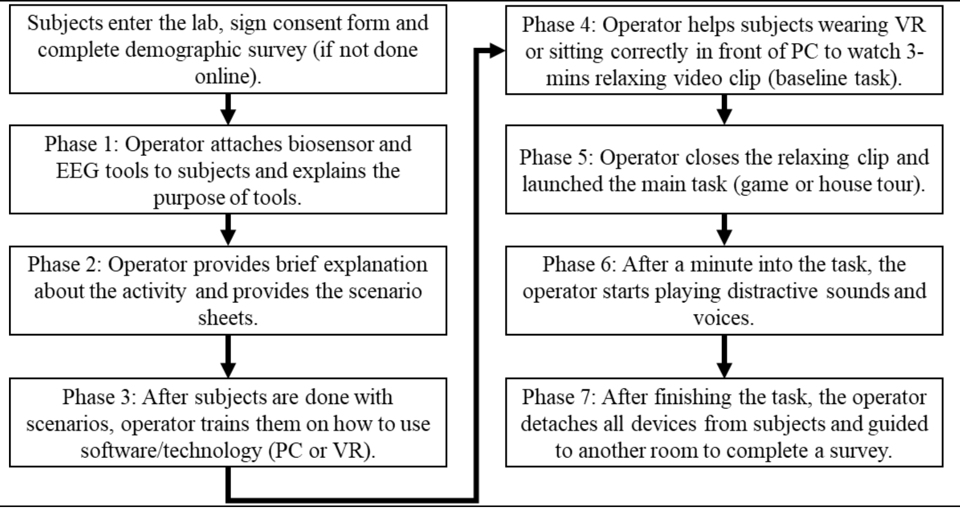

Figure 5. Experiment execution protocol.

As explained, the neurophysiological measures were recorded while the participants used the technologies to accomplish the experimental tasks. Conversely, subjective measures were captured via a questionnaire, which was administered after the task was completed. Table 5 presents a list of concepts and our approach to measuring them (objectively or subjectively).

Table 5. List of concepts and measurement approaches.

Concepts	**Objective measures**	**Subjective measures (alternative approach)**
IT-based sensory engagement	Accelerometer	Perceived IT-based sensory engagement
Affective engagement	EDA	Perceived affective engagement
Cognitive engagement	Relative power of gamma	Perceived cognitive engagement
Immersion	Objective immersion (Eq1)	Perceived immersion
Performance	- Time until complete (for house tour) - Average time per level and the total number of levels completed (for game)	None

Analysis and results

In this section, we present the results of the analyses that were carried out to test the hypotheses. As demonstrated in Figure 6, given that we measured all primary variables objectively and subjectively, we analyzed two models. First was the full model analysis using objective measures. The second was full model analysis using subjective measures. The goal of using a secondary measure was to bring more insight to our findings. Hereafter, objective immersion refers to the EEG measure of immersion (immersion index per Eq1), and subjective immersion refers to the subjective measure of immersion that was measured through the questionnaire using the pre-existing set of items.

EEG, ECG, and ACC analysis

The EEG data that was used in this study were obtained during the baseline activity (relaxing video clip) and the primary activity (game or house tour). To give the lab operator a sufficient amount of time for walk-ins and walk-outs, a five-second time window from the activity's start timestamp and its end timestamp for all subjects were excluded. Next, the obtained EEG waves were filtered for eye-blink using the manufacturer's software plug-in. Furthermore, the software filtered data at a low pass of 0.1 Hz and a high pass of 100 Hz. Then, we obtained delta (0.1–3 Hz), theta (4–7 Hz), alpha (8–12 Hz), beta (12–30 Hz), and gamma (30–100 Hz) that was generated through a standard fast Fourier transformation (FFT) by the software. We log normalized the extracted EEG data and used average band power to estimate "immersion index," which allowed us to obtain two separate immersion indexes for each participant based on their experience during the primary or baseline activity. For cognitive engagement, we used the relative power of gamma, which was obtained after applying the same filtration and proxies as those applied to the immersion index.

For EDA and ACC, we followed a similar approach in that we first excluded time windows that were not part of the primary activity and the 5-second windows at the beginning and end of the activity. Then, we used the average number of output for EDA and ACC.

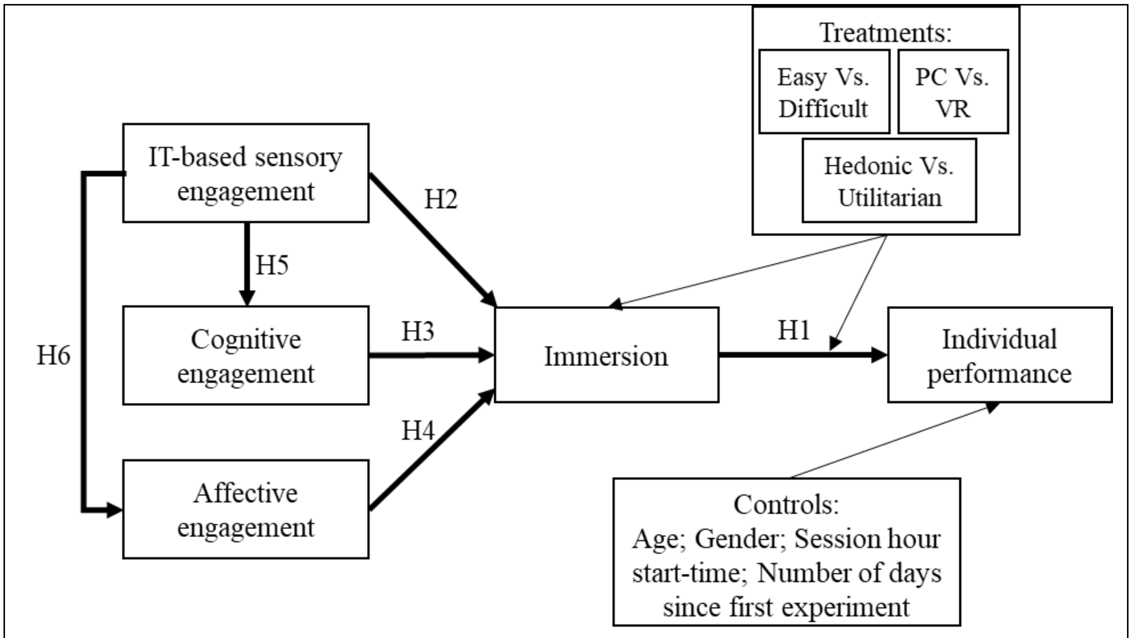

Figure 6. Analyzed model.

Descriptives and the effects of treatments on immersion (ANOVA).

Overall, 132 subjects (61 females and 71 males) participated in this study with an average age of *M* = 20.17 (*SD* = 2.91). Each subject went through the discussed phases in the protocol. We used the blink detection feature that came with the main software of the device to eliminate such artifacts, then extracted EEG data. The blink detection uses a thresholding procedure for identifying blinks based on signal strength. After eliminating this factor, we extracted the power spectrum, which was computed using an FFT. Next, we estimated the relative power of each frequency band and used this to estimate objective immersion (Freeman et al. 2004). The estimated objective immersion was between 0 and 1 (*M* = 0.48, *SD* = 0.20). Having a baseline is important in showing that the activity does indeed influence brain regions. We compared the objective immersion to the baseline task (i.e., resting-state) and main task. Given that objective immersion was the measure of interest, we estimated the objective immersion for both resting state and main activity, then compared them using a t-test only to find a statistical difference between the two ($M_{\text{base}} - M_{\text{main}} = -0.22$, $t = -11.65$, df= 131, $p < 0.0001$). Before presenting the results of the hierarchical regression, we conducted ANOVA on objective immersion for the main activity across treatments. The analysis is presented in Table 6 and found that technology type had a significant effect on immersion (F (1,124) = 15.62, $p < 0.001$).

Table 6. Analysis of the treatment effects on objective immersion.

Effect	**Partial SS**	**d.f.**	**MS**	**F**	**P**
Task difficulty (easy vs difficult)	0.412	1	0.412	0.68	0.41
Task type (utilitarian vs hedonic)	0.033	1	0.033	0.06	0.81
Technology type (VR vs desktop)	15.62	1	15.627	25.9	< 0.001
Task difficulty × task type	0.002	1	0.002	0	0.95
Task difficulty × technology type	0.021	1	0.021	0.04	0.85
Task type × technology type	1.864	1	1.864	3.09	< 0.10
Task difficulty × task type × technology type	0.142	1	0.142	0.24	0.62
Error	74.806	124	0.603		
Model	18.920	7	2.702	4.48	< 0.001

Full model results

Objective immersion model results

In a model with all objective measures, we selected regression as the most appropriate tool for the analyses. We employed a step-by-step analysis using PLS-SEM[9] and, in addition to the direct relationships and interaction effects, we included “age,” “gender,” “session start time,” and “number of days since the beginning of the experiment” as control variables. The reason for the inclusion of “time of day” and “days since the beginning of the experiment” was that, because the sessions ran from 9:00 am to 9:00 pm 4 days per week for about two months, we considered that

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[9] To remain consistent with the analysis of the subjective model, we used PLS-SEM because, regarding the subjective measures, only two items were retained. When two items are used in subjective measures, using PLS-SEM is advised.

subjects who participated later in the day might not perform well due to exhaustion. Also, students who participated earlier might have spoken to other participants and informed them about how to perform better in the task. Considering that this study measured completion time for the utilitarian task and two distinct performance measures (time per level and number of levels completed for the hedonic task), we combined the performance of the utilitarian task with each performance measure of the hedonic task (using the standardized values). Thus, we analyzed two possible combinations after the standardization of the measures. The reason for combining the hedonic and utilitarian groups was to be able to obtain a high-level view of the effects of immersion on performance regardless of conditions. Table 7 represents the results.

Table 7. Stepwise analysis of the full model using objective measures.

Variables	**M 1**	**M 2**	**M 3**	**M 4**	**M 5**	**M 6**	**M 1**	**M 2**	**M 3**	**M 4**	**M 5**	**M 6**
OIT Sen → OCog	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
OIT Sen → OAff	0.38^{***}	0.38^{***}	0.38^{***}	0.38^{***}	0.38^{***}	0.38^{***}	0.38^{***}	0.38^{***}	0.38^{***}	0.38^{***}	0.38^{***}	0.38^{***}
	DV = Immersion											
OIT Sen	0.37^{***}	0.37^{***}	0.37^{***}	0.37^{***}	0.37^{***}	0.37^{***}	0.37^{***}	0.37^{***}	0.37^{***}	0.37^{***}	0.37^{***}	0.37^{***}
OCog	0.25^{**}	0.25^{**}	0.25^{***}	0.25^{***}	0.25^{***}	0.25^{***}	0.25^{***}	0.25^{***}	0.25^{***}	0.25^{***}	0.25^{***}	0.25^{***}
OAff	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
	DV = Performance 1						**DV = Performance 2 (robustness check)**					
Age	0.02	0.03	0.03	0.03	0.03	0.01	0.05	0.05	0.05	0.05	0.05	0.04
Gender (Male=0)	-0.09	-0.09	-0.10	-0.08	-0.06	-0.07	-0.07	-0.11	-0.11	-0.09	-0.09	-0.10
Session hour	0.04	0.04	0.04	0.06	0.05	0.04	0.05	0.02	0.02	0.05	0.04	0.02
# days since start day	0.20^{**}	0.10	0.10	0.11	0.12	0.13	0.19^{**}	0.12	0.12	0.12	0.13	0.15
Task difficulty (Easy=0)		-0.50^{***}	-0.50^{***}	-0.50^{***}	-0.49^{***}	-0.46^{***}		-0.48^{***}	-0.48^{***}	-0.49^{***}	-0.49^{***}	-0.46^{***}
Task type (Utilitarian=0)		0.25^{***}	0.25^{***}	0.26^{***}	0.24^{***}	0.38^{***}		0.25^{***}	0.25^{***}	0.26^{***}	0.24^{***}	0.39^{***}
Technology type (VR=0)		-0.001	-0.01	0.01	-0.04	0.13		0.05	0.05	0.06	0.04	0.06
Objective Immersion (OI)			0.01	0.02	-0.03	0.06			-0.02	-0.08	-0.07	0.33^{*}
OI × Task difficulty				-0.20^{**}	-0.16	-0.21^{*}				-0.13	-0.10	-014
OI × Task type				0.07	0.05	-0.02				0.03	0.05	-0.06
OI × Technology type				0.10	0.15	0.19^{*}				0.15	0.18	0.20^{*}
OI^2					0.16^{*}	0.64^{***}					0.14	0.61^{***}
OI^2× Task difficulty						-0.10						-0.06
OI^2× Task type						-0.40^{**}						-0.42^{**}
OI^2× Technology type						0.23^{*}						0.21
R^2	0.05	0.34	0.35	0.37	0.39	0.43	0.05	0.34	0.34	0.36	0.37	0.41
SRMR	-	-	0.41	0.041	0.051	0.051	-	-	0.041	0.041	0.051	0.08
Chi^2	-	-	210.34	21.30	36.24	36.94	-	-	20.77	20.89	35.34	256.366

Note: N = 132; M = Model; All VIF's were under 8; * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; All interactions in the table are factorial interactions, so they were compared against the baseline; OIT Sen = Objective IT-based sensory engagement; OCog= Objective cognitive engagement; OAff = Objective affective engagement; Performance 1 = Completion time in minutes (multiplied by -1) for utilitarian group and total number of levels passed for hedonic group; Performance 2 = Completion time in minutes (multiplied by -1) for utilitarian group and average time in minutes (multiplied by -1) to pass a level for hedonic group.

For M1 and M2 we executed two distinct models given that the effect of immersion on DV was not tested.

Initial analyses (models 1–4) did not show any direct effect of immersion on performance; thus, we explored the curvilinear relationship. Model 6 shows that immersion^2 is positively associated with user Performance 1[10] and Performance 2[11]. Model 6, which introduces the interaction effect of treatments and immersion squared to Model 5, yielded that immersion is positively associated with Performance 1 (B = 0.64, $p < 0.05$) and Performance 2 (B = 0.61, $p < 0.05$); thus, H1 is supported. The task difficulty negatively influenced Performance 1 (B = -0.46, $p < 0.01$) and Performance 2 (B = -0.46, $p < 0.01$). The hedonic task was positively associated with Performance 1 (B = 0.38, $p < 0.01$) and Performance 2 (B = 0.39, $p < 0.01$), compared to the utilitarian task. Through the analyses, we found that immersion-squared and task type had negative interaction effects on Performance 1 (B = -0.40, $p < 0.05$) and Performance 2 (B = -0.42, $p < 0.05$). Furthermore, the plots of quadratic effects are presented in Figure 7, and the interactions of task type and objective immersion are presented in Figure 8. The inflection point, per Figure 7, is where immersion = -0.14 and Performance 1 = -0.55 for the left plot. For the right plot, it is where immersion = -0.13 and Performance 2 = -0.54.

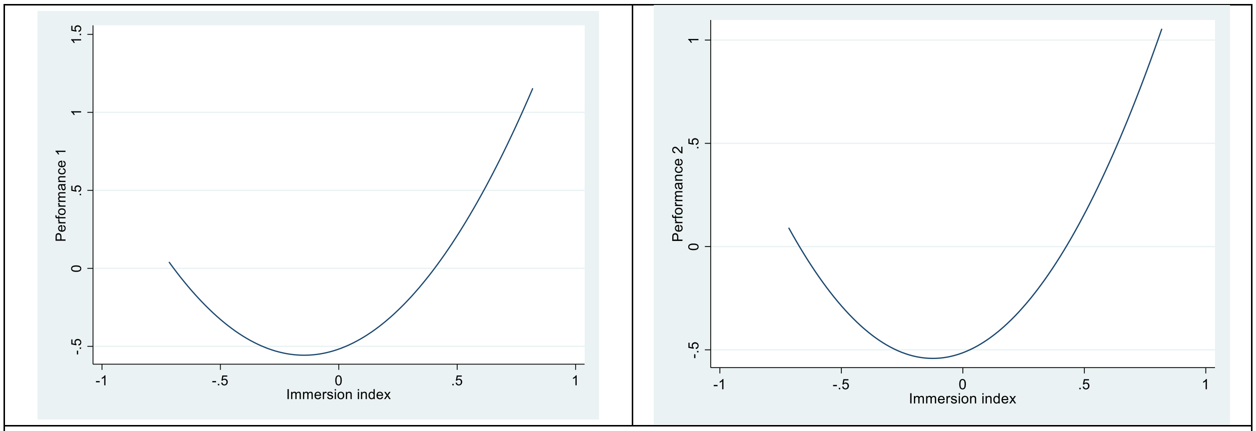

Figure 7. Quadratic relationship between objective immersion and performance.

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[10] Performance 1 = Completion time (n minutes (multiplied by -1) for the utilitarian group and total number of levels passed for the hedonic group.

[11] Performance 2 = Completion time in minutes (multiplied by -1) for the utilitarian group and average time in minutes (multiplied by -1) to pass a level for the hedonic group.

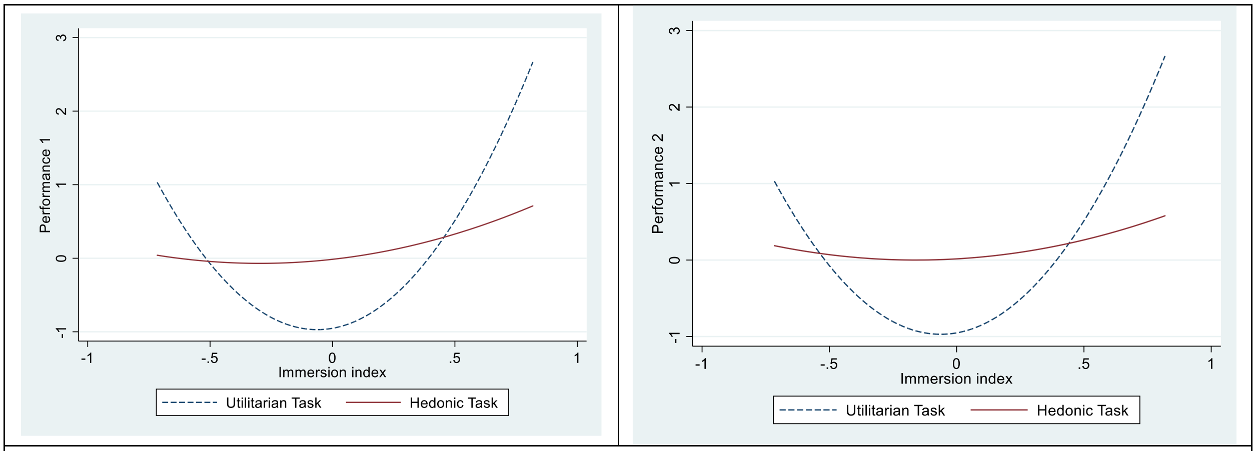

Figure 8. Interaction of objective Immersion and Task type on performance.

The analysis supported the effect of objective measures of IT-based sensory (Haptic) engagement (B = 0.37, $p < 0.01$) and cognitive engagement (B = 0.25, $p < 0.01$) on objective immersion. Therefore, H2 and H3 are supported. While we found support for H6 through the effect of IT-based sensory engagement on affective engagement, the results showed no effect of affective engagement on objective immersion (H4 rejected). Lastly, we found no support for the effect of IT-based sensory engagement on cognitive engagement; thus, H5 is rejected.

Subjective model results

Next, as a form of a robustness check we tested the model using the psychometric data that we obtained using questionnaires after the experiment. This approach allowed us to compare the behavior of the newly proposed objective immersion and already existing subjective measures of immersion. We tested the obtained measures for standard reliability and validity. The factor analysis showed that all loadings were above 0.70 on their respective constructs, and Cronbach's alpha value for all constructs was also above 0.70. Appendix F represents the factor analysis and confirmatory factor analysis performed on the psychometric measures of the model. After dropping immersion items with low reliability, the factor analysis depicted that, for the three-item measure of immersion, the factor loadings were above 0.72 and Cronbach's alpha value was 0.70, which were accepted thresholds for the reliability of the measures. After establishing reliability and validity, we tested the model, as shown in Table 8. By extension, Model 4 yielded the highest R-squared and highest F-statistic, which shows a positive relationship between immersion and Performance 1 ($B = 0.27$, $p < 0.05$) and Performance 2 ($B = 0.21$, $p < 0.05$); thus, H1 is supported. Besides this, Model 4 shows weak moderating effects of technology type on the relationship between immersion and performance ($B = 0.18$, $p < 0.10$).

In presenting the results for the subjective model, we base our inferences on Model 4. We analyzed Model 5 and Model 6 to keep both objective and subjective analyses consistent, but we did not have any basis for pursuing a curvilinear relationship between perceived immersion and objective measure of performance. In the case of objective immersion, the curvilinear tests highlighted that such an effect exists, which was not the case for subjective immersion.

Our results showed that perceived immersion had a consistent effect on performance across both measures of performance ($B = 0.24$, $p < 0.05$), though it was weak. Therefore, H1 is supported for the subjective model as well. We did not find support for the effect of perceived IT-based sensory engagement on perceived immersion; consequently, H2 is rejected ($B = 0.13$, $p = 0.11$). However, we found support for the effects of perceived cognitive engagement ($B = 0.32$, $p < 0.05$) and perceived affective engagement ($B = 0.19$, $p < 0.05$) on perceived immersion, so H3 and H4 are supported. Furthermore, we found that perceived IT-based sensory engagement influences users' perception of both cognitive ($B = 0.32$, $p < 0.05$) and affective engagements ($B = 0.19$, $p < 0.05$). Hence, H5 and H6 are supported for the subjective model. Moreover, we performed a robustness analysis by running the models over separate dependent variables in the hedonic group and the utilitarian group to enrich our understandings of the behavior of the relationships across the two mentioned task types (only for objective and subjective immersion and performance). Appendix D and Appendix E provide detailed analyses.

Table 8. Stepwise analysis of the full model using subjective measures.

Variables	**M 1**	**M 2**	**M 3**	**M 4**	**M 5**	**M 6**	**M 1**	**M 2**	**M 3**	**M 4**	**M 5**	**M 6**
SIT Sen → SCog	0.26^{***}	0.26^{***}	0.26^{***}	0.26^{***}	0.26^{***}	0.26^{***}	0.26^{***}	0.26^{***}	0.26^{***}	0.26^{***}	0.26^{***}	0.26^{***}
SIT Sen → SAff	0.34^{***}	0.34^{***}	0.34^{***}	0.34^{***}	0.34^{***}	0.34^{***}	0.34^{***}	0.34^{***}	0.34^{***}	0.34^{***}	0.34^{***}	0.34^{***}
	DV = Immersion											
SIT Sen	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13
SCog	0.32^{**}	0.32^{**}	0.32^{**}	0.32^{**}	0.32^{**}	0.32^{**}	0.32^{**}	0.32^{**}	0.32^{**}	0.32^{**}	0.32^{**}	0.32^{**}
SAff	0.19^{**}	0.19^{**}	0.19^{**}	0.19^{**}	0.19^{**}	0.19^{**}	0.19^{**}	0.19^{**}	0.19^{**}	0.19^{**}	0.19^{**}	0.19^{**}
	DV = Performance 1						**DV = Performance 2 (robustness check)**					
Age	0.01	0.03	0.03	0.04	0.04	0.02	0.05	0.05	0.06	0.07	0.06	0.05
Gender (Male=0)	-0.05	-0.09	-0.09	-0.09	-0.09	-0.10	-0.07	-0.11	-0.10	-0.10	-0.10	-0.10
Session hour	0.07	0.04	0.04	0.03	0.02	0.03	0.05	0.02	0.03	0.01	0.03	0.02
# days since start day	0.20^{**}	0.10	0.10	0.10	0.10	0.08	0.19^{**}	0.12	0.11	0.11	0.11	0.09
Task difficulty (Easy=0)		-0.50^{***}	-0.50^{***}	-0.06	-0.15	-0.17		-0.48^{***}	-0.48^{***}	0.01	0.06	0.03
Task type (Utilitarian=0)		0.25^{***}	0.26^{***}	-0.09	-0.15	0.22		0.25^{***}	0.25^{***}	-0.08	0.06	0.01
Technology type (VR=0)		-0.001	-0.01	-0.68^{*}	-0.65	-0.30		0.05	0.04	-0.59	-0.54	0.20
Subjective Immersion (SI)			-0.03	0.27^{*}	0.24^{*}	-0.04			-0.04	0.21	0.24^{*}	0.12
SI × Task difficulty				-0.45	-0.36	0.19				-0.51	-0.55	-0.55
SI × Task type				0.35	0.40	-0.50				0.18	0.20	0.29
SI × Technology type				0.72^{*}	0.65^{*}	0.37				0.66^{*}	0.61	0.32
SI^2					0.12	-0.33					-0.04	-0.23
SI^2× Task difficulty						0.18						0.09
SI^2× Task type						-0.04						0.01
SI^2× Technology type						-0.17^{**}						-0.15
R^2	0.05	0.34	0.35	0.38	0.38	0.39	0.05	0.34	0.34	0.37	0.37	0.38
SRMR	-	-	0.079	0.08	0.094	0.094	-	-	0.08	0.08	0.90	0.94
Chi^2	-	-	297.28	298.70	370.60	370.53	-	-	299.51	300.712	372.30	372.40

Note: N = 132; M = Model; All VIF's were under 8; * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; All interactions in the table are factorial interactions, so they were compared against the baseline; SIT Sen = Subjective IT-based sensory engagement; SCog= Subjective cognitive engagement; SAff = Subjective affective engagement; Performance 1 = Completion time in minutes (multiplied by -1) for utilitarian group and total number of levels passed for hedonic group; Performance 2 = Completion time in minutes (multiplied by -1) for utilitarian group and average time in minutes (multiplied by -1) to pass a level for hedonic group.

Model 5 and Model 6 are not used in interpretations, they are provided with the goal of informing the reader about additional tests that we performed. For M1 and M2 we executed two distinct models given that the effect of immersion on DV was not tested.

Cross effects of objective and subjective measures

In order to enrich the discussion and develop further insights into the theoretical model, we tested the cross effects of objective and subjective measures on immersion. While in the above sub-sections, we only tested a full objectively measured model and a subjectively measured model (apart from performance), in this sub-section, we explore the cross effects of objectives on subjectives and vice-versa. We used PLS-SEM for this analysis because, as explained later, for one construct, only two measurement items satisfied reliability and validity tests. In scenarios such as this, PLS-SEM is often used. Table 9 summarizes the results of the analysis.

Table 9. Antecedents of immersion.

	Subjective immersion	**Objective immersion**
Objective IT-based haptic engagement (ACC)	0.16^{*}	
Objective cognitive engagement (RPG)	0.18^{**}	
Objective affective engagement (EDA)	0.27	
Perceived IT-based sensory engagement		0.11
Perceived cognitive engagement		0.12
Perceived affective engagement		0.15
R^2	0.07	0.07

Note: N = 132; M = Model; All VIF's were under 3; ACC = Accelerometer; EDA = Electrodermal activity; RPG = Relative power of gamma.
* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Table 10. Tested hypotheses and conclusions.

	Tested relationships		Conclusion
Relationship	**Objective model of immersion**	**Subjective model of immersion**	
Immersion → Performance	Supported	Supported	H1 supported
IT-based sensory engagement → Immersion	Supported	Not supported	H2 partially supported
Cognitive engagement → Immersion	Supported	Supported	H3 supported
Affective engagement → Immersion	Supported	Supported	H4 supported
IT-based sensory engagement → Cognitive engagement	Not supported	Supported	H5 partially supported
IT-based sensory engagement → Affective engagement	Supported	Supported	H6 supported

Discussion

One of the fundamental premises of this research is that there is a need to readjust our understanding of immersion because the environment is in desperate need of immersive technologies (see our earlier discussion in the introduction about the pandemic situation and need for virtual technologies). Immersive experiences are necessary for user performance while interacting with such technologies. Accordingly, we first reviewed the literature on immersion and provided a slightly modified definition that better resonated with cognitive science theories and findings of brain capacity and functionalities in information processing. Second, we provided an immersion index that accounted for users' focused attention and distraction by irrelevant information. We also captured this index through a lab experiment using an EEG headband. Third, we tested the provided objective measure in a nomological network of antecedents of immersion. A separate analysis with a focus on the inherent relationship between immersion and performance was also performed. Finally, we measured immersion using pre-existing items through survey studies conducted alongside EEG experiments, which enriched our understanding of the behavior of objective (new) and subjective (old) approaches toward immersion. In the following paragraphs, we discuss each finding with its theoretical and practical implications.

Insights into immersion and performance

One of the hypotheses in this study was concerned with the relationship between immersion and performance. Immersive technologies are capable of improving user performance and solving business issues. One aspect through which immersion can help users perform better is helping them become oblivious to distractors around them (Bailey and Konstan, 2006), which are consistently found to be detrimental to performance (Addas and Pinsonneault, 2015, 2018). This study showed that immersion influences performance, but this relationship is quadratic. Per Figure 7, initially, as immersion increases, performance slightly drops. Then, when immersion reaches a certain threshold (inflection point), performance is enhanced exponentially. Similar to contemporary works, we found subjective immersion to be positively associated with user performance. However, to our knowledge, there is no study that investigates the curvilinear relationship between immersion and performance. Furthermore, the analysis of the relationship between the subjective measure of immersion and user performance revealed new insights about the differences between objective and subjective measures of immersion. The reverse effect of immersion on performance was found because, at low levels of immersion (shallow immersion), alpha and theta are higher. This could be due to users paying more attention to distractors, making their performance low. The bottom of the U-shaped graph is where beta starts to increase compared to alpha and theta, which may signal that the user is focusing their attention more on the activity and ignoring irrelevant information. After the inflection point, a slight increase in the focused attention of the user and negligence of distractors exponentially boosts performance (we call this deep immersion). The post-hoc survey, which captures subjective immersion, did not determine this inflection point, which has theoretical and practical value.

The new finding discussed above (regarding the U-shaped relationship) has theoretical implications. The findings contribute to the ongoing stream of research on user engagement and performance by finding that immersion is a predictor of user performance. Prior works have only focused on traditional linear relationship, while we discovered that the incremental changes in focused attention and neglecting distractors could exponentially boost performance. While other works have theorized about the possible effects of distractor type on user performance, no study has ever attempted to quantify how users' immersion increases or decreases performance. Another possible implication is that there is a certain threshold for processing irrelevant information (e.g., distractors) that influences performance. After passing that threshold, performance increases.

The practical implication of finding this curvilinear relationship is that developers could utilize a similar approach to calibrate their systems and technologies under different circumstances before releasing them. For example, if the left-hand side of the U-shape relationship is more salient in a task on VR (skewed U-shape), then developers need to modify their content before making million-dollar investments upon launch and release. The immersion index accounts for distractors that organizations would very much like to eliminate so that their employees can perform better. In IS, the role of interruption and distraction has been studied several times. It is a contemporary issue in the workplace (Addas and Pinsonneault, 2015, 2018). Very few studies have tried to objectively measure the effect of distractors in the workplace; the majority only relied on self-report measures.

Another finding that merits discussion is why there is a curvilinear effect for objective immersion and why a linear for subjective. One potential explanation is that in general neurophysiological measures are more sensitive to changes so this sensitivity is reflected in their relationships (Riedl et al. 2014), or perhaps due to self-report biases in which user might not have assessed their own level of immersion accurately (Dimoka et al. 2011).

Insights into engagement and immersion

This study found full support for the hypotheses that stated that engagement influences immersion. In particular, the primary goal of this study was to test the model using all available measures to capture user experience in real time as opposed to using subjective measures. While we did capture user experience through a post-hoc questionnaire, we only used it as a means to compare and contrast findings and enrich our understanding. The results indicated that users' experiences of immersion could be a function of their haptic engagement with IT. The technology is designed to require subjects to move their arm in order to interact with the technology. Whether they are using a computer mouse or touch controllers (VR), the element of sensory engagement is present. The measure that we used for haptic engagement was the acceleration of hand movements. We found that this influences the immersion index. The increase in average acceleration signified the intensity of haptic engagement through interaction with IT. Furthermore, some studies have suggested that visual and aural information processing corresponds to self-motion adjustment (DeAngelis and Angelaki, 2012; Gu et al. 2008; Fetsch et al. 2009), so an increase in haptic engagement is possibly also a sign of an increase in audio–visual engagement with IT. Although IT-based sensory engagement did not influence users' perceived immersion, we found that that effect on perceived immersion is mediated by perceived affective engagement. If subjects perceived more IT-based sensory engagement, they perceived more affective engagement and performed better. We conclude that IT-based sensory engagement certainly exists and plays an important role in users' experience of immersion.

The second and third hypotheses of this study focused on cognitive and affective engagement. We found support for their influence on the immersion index. Gamma power band was used to measure engagement objectively, given that some studies have suggested gamma is associated with mental activities (Fitzgibbon et al. 2004). Contemporary studies have not made arguments regarding the processing capacity and attention allocation aspects of cognitive and affective engagement (Lowry et al. 2013; Nah et al. 2011), while this study does. Prior works have investigated the effects of cognitive and affective engagement on subjective immersion (Jennett et al. 2008; Lowry et al. 2013), yet our findings are consistent with theirs. In addition to showing the effects of objective measures, we found support for the effects of subjective cognitive and affective engagements on the immersion index as well.

Yet again, our attempt at measuring emotional engagement through EDA and finding its effect on immersion was successful, as we found that increase in EDA is positively associated with the immersion index. Drachen et al. (2010) investigated the relationship between EDA and immersion and found a strong negative correlation between the two. However, this study's conceptualization and measure of immersion is different.

Insights into the interaction among engagement forms

Interestingly, we found that perceived cognitive and affective engagement are influenced by perceived IT-based sensory engagement. Also, we found that objectively measured affective engagement is influenced by objectively measured IT-based sensory engagement. There is a lack of studies on this phenomenon in business and IS research. One tangible outcome of investigating the underlying mechanisms of how IT-based sensory engagement influences cogno-affective outcomes is encouraging the design of more engaging user interfaces (GUI's) or systems in general. For instance, by implementing certain cues, one could make their system more cognitively engaging.

Conceptually, the sensory layer is the first proxy for users' interaction with IT. Thus, we expected to see IT-based sensory cues influence users’ experiences of cognitive and affective engagement, which we found support for. However, we did not find any support for the effect of objective IT-based sensory engagement and objective cognitive engagement. The discrepancy between objective and subjective findings of whether sensory engagement influences cognitive engagement pointed us at the literature of using gamma band for wrist movement, for which we found conflicting results. For example, some have found an effect in different gamma ranges (28 Hz - 40 Hz or 32 Hz - 48 Hz) and different electrode locations, while others found no effects (Amo Usanos et al. 2020). Based on our findings, ACC is not associated with the general gamma (30 Hz - 100 Hz) band in the prefrontal cortex

With regard to interactions between cognitive and affective engagement, we found that perceived cognitive engagement and perceived affective engagement are correlated (see Appendix F). However, we did not observe any statistically meaningful correlation between our objective measures of cognitive and affective engagement, which gives room for future investigations.

Treatment effects

This study found mixed results regarding the effects of treatments on immersion and performance. For example, we found that VR is more immersive (as expected), but task difficulty and task type did not influence immersion. VR has clear superiority in eliminating distractors. For example, visual distractors in the room are completely eliminated for users, which might provide an explanation for why users’ levels of immersion were higher. Finding no effect of task type on immersion disproves the myth that “games are immersive, while non-games are not.” Some HCI, IT, and IS scholars believe that immersion has to be studied only in relation to games, but our finding showed no evidence that immersion is higher for subjects who played video games compared to those who completed the house tours (Cairns et al. 2013; Brockmyer et al. 2009). On the other hand, we found that task difficulty influences performance: if a task is difficult, performance is lower. We also found that task type influences performance, meaning that, while the level of immersion for users was the same, they performed better on the hedonic task. In addition, we found that task type moderates the relationship between immersion and performance. Per Figure 8, there is a clear distinction between the U-shape relationship of immersion in utilitarian and hedonic tasks and user performance. The slope is steep for the utilitarian task, which reveals that users' experiences of immersion were very sensitive to performance compared to when doing hedonic tasks. In the shallow immersion zone, the unit increase in immersion leads to a more aggressive drop in performance for utilitarian users, while in the deep immersion zone, the unit increase in immersion has higher exponential effects on user performance. The difference between the two could be due to the unique purposes of utilitarian and hedonic tasks, where performance is taken more seriously for utilitarian tasks. The practical implication of finding this moderator relationship is that, depending on the audience and purpose of the content, the relationship between immersion and performance could be different. This is something developers need to consider to better manipulate immersion and achieve higher performance.

Insights into subjective vs. objective measurements of engagement

A brief comparison of the two groups of adopted approaches informed us of the similarities and differences in patterns of effects. The fact that users did not perceive IT-based sensory interactions (see Table 7) could be due to two or more reasons. First, the lack of delicate awareness toward one's behavior during the activity means it is very difficult for users to keep track of the intensity of their behavioral engagement with IT. Haptic engagement happens simultaneously with use, and the biosensors are very nuanced in capturing movements, which are more sensitive than perceptions towards haptic engagement. The second reason could be down to the conceptual gap between IT-based sensory engagement's subjective and objective measures. The pre-existing measures of sensory engagement were based on media richness theory (Jiang et al. 2013). As one may realize from the items presented in Appendix C, the measure is generalized and tries to capture visual, aural, and haptic engagement. In contrast, our objective measure only focuses on haptic engagement.

From a theoretical perspective, an important implication is that general media richness might not be the perfect tool for measuring sensory engagement with IT. Instead, there should to be more distinct and precise tools to capture sensory engagements at different sensory levels (aural, visual, haptic, etc.). From a practical standpoint, for a developer, the intensity of haptic engagement certainly influences users' focused attention on the activity and makes them more oblivious to other environmental stimuli. It means that VR allows for more haptic engagement, and it has promising potential to increase users' focused attention and immersion. Another practical value inferred from this finding is that some mundane computer-based activities could be made more enthusiastic by increasing haptic engagement to influence users' focused attention and immersion. If this is not possible, it could also be implemented into VR. Furthermore, we find it difficult to justify the disconnect between EDA and subjective immersion, but one logical explanation could be that the gap in conceptualization accounts for the differences of the immersion index and subjective immersion in the nomological network of antecedents of immersion.

In conclusion, while subjective measures exist, proposing an objective measure triggers discussions about the congruencies of the measures, which this study tried to address by investigating subjective measures as its secondary approach to objectively measured concepts. Therefore, this study contributes to the engagement and immersion literature through the empirical testing of proposed engagement factors on immersion and showing their differences. The objective measures that we identified and used to capture real time experiences were not falling short of self-report measures. A practical implication of engagement findings suggests that developers need to strategize in terms of combining cognitive, affective, and sensory engagements to create an optimal immersion experience for users. Here, we showed that these factors are clearly separate, and any IT content could be categorized as cognitive, affective, sensory engaging, or a combination of the three. For example, in order to make a system or technology more immersive, a developer should employ a combination of tasks that require thinking, and contemplation, some level of positive valence, high-quality and correctly induced visual and aural stimulus, and (if possible) increased haptic engagement.

Limitations and future research

First, we suggest that future studies investigate the relationship between the immersion index and performance in a variety of contexts. As this study only explored two tasks, there is a need to expand the range of tasks and investigate this curvilinear relationship more thoroughly. Second, this study showed that objective measures are more sensitive in capturing engagement. For example, this study used a broad measure of media richness for the operationalization of IT-based sensory engagement. Future works should carefully split this measure to represent a viable measure for evaluating the engagement of each sensory cue. In addition, this study measured only one aspect of sensory engagement (haptic), but we suggest future works also utilize measures for visual engagement and aural engagement as separate variables. Third, one of the main challenges of this study was encountered during the experimental development stage—finding a task that was available across platforms (PC and VR). We encourage future researchers to collaborate with developers to develop their own unique content that helps them tease out desired results in experimental stages. Fourth, we only explained the conceptual distinctions among immersion, flow, telepresence, and cognitive absorption. One potential avenue for future studies is to investigate the proposed immersion index in this study and compare its relationship with flow, telepresence, and cognitive absorption, as there are still studies that fail to distinguish between these concepts. Lastly, while we do understand that there are objective measures for visual engagement (eye movement or eye focus), integrating them into VR is rare. Perhaps with further advancements in technology, future studies could implement eye tracking in their analysis.

The findings of this study should be seen in light of its limitations. First, this study had subjects perform two tasks (one calibration, the other the main activity). Still, we encourage future studies to have each subject perform multiple tasks to enrich our understanding of individual differences across EEG studies. Second, this study used IT-based haptic engagement as the representative of sensory engagement. Instead, a distinct measure of each sensory cue had to be developed or adopted. For example, the study needed IT-based visual and aural engagement in addition to haptic. Third, having eight cells in the factorial design needs at least 20 subjects per cell to achieve satisfactory power. However, we had to stop data collection procedures due to COVID-19 restrictions. While we believe this did not influence the strong relationships that we found in the study, it could have influenced the weaker relationships that we expected to find effects for (e.g., other moderations).

Conclusion

This study contributed to the ongoing stream of research on immersive technologies and provided a richer understanding of the relationship between immersion and performance by redefining the concept and providing an empirical index for measuring immersion. Furthermore, this study highlighted the antecedents of immersion: cognitive, affective, and IT-based sensory engagements. In summary, we designed a lab experiment to test the proposed empirical index and found it to capture essential experiences of user immersion during IT use, while prior works have only relied on post-hoc measures, such as psychometric questionnaire-based measures of immersion. Moreover, this study showed that immersion has a U-shaped relationship with user performance, for which we discussed theoretical and practical implications in the discussion section.

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Appendix

Appendix A: Related concepts to Immersion

In this section, we briefly review the concepts that are believed to be related to immersion based on prior works. Table A1 summarizes the similarity and differences between immersion and these concepts (Flow, cognitive absorption, and presence). We compared these concepts based on their impact on the three types of engagements discussed earlier. In short, the literature and conceptual mappings of these concepts suggest that presence is just a feeling, which is a consequence of immersion and is experienced by the user when only their sensations are oblivious to the physical world. On the other hand, cognitive absorption and flow are not antecedent or consequence of immersion. Rather they differ in the forms of engagements that subjects have to experience in order to grasp flow or cognitive absorption. Figure A1 shows that among the three identified types of engagement, only immersion is induced by the three, while cognitive absorption and flow theories only happen through two forms of engagement. In conclusion, given that each of these concepts is stimulated with different forms of engagements, the psychological feeling and experience of each concept are different from the other.

Table A1. Similarities and differences between immersion and presence/flow/cognitive absorption.

Concept	**Definition**	**Similarities and differences**
Presence	The subjective experience of being in one place or environment, even when one is physically situated in another (Witmer and Singer 1998).	**Similarities:** - Sensory engagement is an antecedent to immersion and presence. **Differences:** - Presence does not explicitly discuss the role of cognitive and emotional engagements. Although they might help create the delusion of physical space, they are not necessary conditions as sensory engagement. - When the technology captures the users' sensory attention to the extent that the user’s senses become oblivious to environmental (surrounding) sensory-attentional demands, the subject will feel presence and realism. Therefore, presence is a consequence of immersion in which only sensory attention is occupied.
Cognitive Absorption (CA)	A state of deep involvement with software (Agarwal and Karahanna 2000)	**Similarity:** - Similar to immersion, CA accounts for affective engagement by using “heightened enjoyment.” - Similar to immersion, CA accounts for cognitive engagement by using “curiosity” and “control.” **Differences:** - While original authors of this theory claim the curiosity dimension is “tapping into the extent the experience arouses an individual's sensory and cognitive curiosity” (Karahanna and Agarwal, 2000), they measure only “cognitive curiosity,” and it has nothing to do with “sensory engagement[12].” There is no dimension in CA that captures sensory engagement, sensory attention, or sensory information processing. - CA only accounts for one form of emotion, that is ‘heightened enjoyment’ while different forms of emotions were studied in relation to immersion.
Flow	The holistic sensation that people feel when they act with total involvement (Csikzentmihalyi 1975)	**Similarities:** - “Challenge-skill balance” is a form of cognitive engagement that is mutual in both flow and immersion. - The “autotelic experience,” which is one of the dimensions of flow, explains the physical and sensory engagement of the user that leads to flow (Csikszentmihalyi 1975, p. 25). Therefore, similar to immersion flow accounts for sensory engagement. **Differences:** - The original theory does not discuss enjoyment or any other emotions as the antecedent of flow. Instead, enjoyment is considered one of the favorable outcomes of the flow state. In fact, Csikszentmihalyi (1975) states that the purpose of achieving flow is enjoyment. However, affective engagement is an antecedent of immersion.

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[12] Agarwal and Karahanna, measured Curiosity using these items, none of which involves sensory engagement: (1) Using the Web excites my curiosity; (2) Interacting with the Web makes me curious; and, (3) Using the Web arouses my imagination.

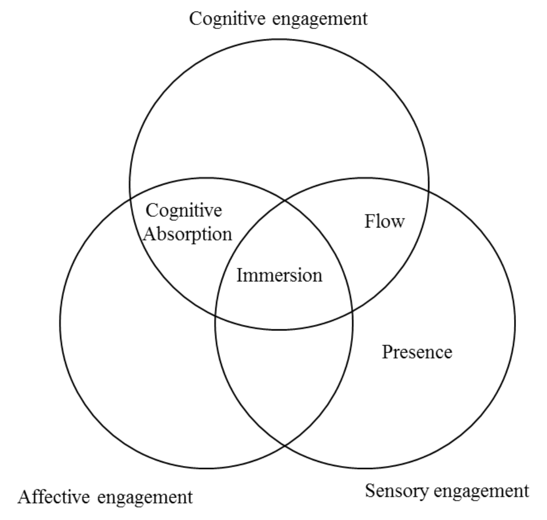

Figure A1. Comparison of immersion with other concepts.

A.1. Flow experience:

Another important concept that relates to immersion is the flow theory introduced by Csikszentmihalyi. Flow is referred to as “the holistic sensation that people feel when they act with total involvement” (Csikszentmihalyi 1975; Nah et al. 2011). Agarwal and Karahanna (2000) defined flow as a state in which people are so involved in an activity that nothing else seems to matter. Faiola et al. (2013) characterized flow as an optimal experience, which is a highly enjoyable state of consciousness that occurs when skills match the challenges. Initially, the flow has been studied as part of the larger field of intrinsic motivation and enjoyments (Faiola et al. 2013). The intrinsic motivations, rewards, or incentives act as the underlying stimuli for the user to engage in activities in a way that they focus their attention on that specific task to the extent that they forget about personal problems, sense of time, and sense of themselves (Csikszentmihalyi and Csikszentmihalyi 1992; Faiola et al. 2013). There are three pre-conditions for entering into the flow: Challenge-skill balance, instant feedback, and clear goals (Kaur et al. 2016). In general, flow studies could be viewed in three groups. First, antecedents of flows, which we discussed as pre-conditions, have been studied. For instance, the effect of challenge-skill balance, clear goal(s), and feedback mechanism on the flow of online shoppers studied by Guo and Poole (2009). Second, they focused on the flow experience. For instance, Sweetser and Wyeth (2005) investigated the flow experience by analyzing two video games. The third group looked at the consequences of flow. For example, Bilgihan et al. (2015) considered how flow affects e-loyalty and trust among customers of a hotel booking website.

The flow experience and enjoyment that people experience are very similar irrespective of social class, age, or gender (Sweetser and Wyeth 2005), which is an important part of making flow a universal concept that can be applied to a variety of human-related studies, including IS. Some examples are in e-commerce (Koufaris 2002; Nah et al. 2011; Guo and Poole 2009; Faiola et al. 2013; Bilgihan et al. 2015; Ozkara et al. 2016), m-commerce (Reychav and Wu 2015; Gao et al. 2015), video gaming (Sweetsner and Wyeth 2005; McGloin et al. 2016; Soutter and Hitchens 2016), virtual environments (Goel et al. 2013), and e-learning systems (Choi et al. 2007; Guo et al. 2016; Laffan et al. 2016). According to Csikszentmihalyi (1990), the flow has nine dimensions; 1) challenge-skill balance; 2) clear goals; 3) immediate feedback; 4) focused attention; 5) perceived control; 6) merge of action and awareness; 7) altered sense of time (or time distortion); 8) loss of self-consciousness; and 9) autotelic experience. One or more of these factors are frequently utilized in other flow-related studies. In general, flow is the most appropriate when enjoyment is consistent across the whole interaction of the user, which applies to video games (Csikszentmihalyi and Csikszentmihalyi 1988).

Here we differentiated flow from immersion not by looking at their dimensions. Instead, we considered how each form of engagement leads to each psychological state. In particular, the nine dimensions that are discussed by Csikszentmihalyi (1975, 1990) are referring to sensory and cognitive forms of engagement that leads to flow. Furthermore, enjoyment, which is loosely coupled with the flow in the majority of studies, is an antecedent of flow. Subjects only experience enjoyment when they are in the state of flow. However, immersion is a combination of all three forms of engagements, which comprehensively explains that all three forms of engagements are the tools for capturing our attention and make us oblivious to other attentional demands, while immersion leaves out the direct role of affective engagement in this process. Moreover, by emphasizing the word “total” involvement, the flow state only refers to a certain situation in which engagement leads to flow. However, as discussed, immersion is a graded experience, ranging from low to high.

A.2. Cognitive Absorption:

Cognitive absorption conceptualizes involvement with information technology (Chandra et al. 2012). Agarwal and Karahanna (2000) defined cognitive absorption as “a state of deep involvement with software.” Chandra et al. (2012) offer a more generalizable definition: it is a state of deep involvement or holistic experience of an individual when they cognitively engage with information technology such as the internet and video games. The notion of absorption, like flow, originated from psychology and referred to “an individual’s trait involving a high propensity to engage in events with total attention, where the object of attention consumes all the individual’s resources” (Saadé and Bahli 2005; Tellegen and Atkinson 1974). In essence, cognitive absorption represents an intrinsic situational motivator that conceptualizes state, trait, and attitudinal variables in a single construct (Agarwal and Karahanna 2000; Lee et al. 2012). The same pre-conditions that are applicable to flow (clear goals, responsiveness, and challenge-skill balance) could be used to explain information technology users’ experience of cognitive absorption (Deng et al. 2010). Since this concept has emerged in the IS field, it has been combined with technology acceptance predictors to explain better adoption (Lee et al. 2012; Lowry et al. 2013). Cognitive absorption provides the tool to conceptualize optimal user experience (Deng et al. 2010).

Cognitive absorption has five dimensions that are (Agarwal and Karahanna 2000): 1) Temporal dissociation, inability to sense the passage of time; 2) focused immersion[13], the experience of total engagement; 3) heightened enjoyment, capturing a pleasurable aspect of interaction; 4) control, user's perception of being in control of interaction; and 5) curiosity, the extent of users' experience of sensory and cognitive curiosity. Furthermore, in IS research, this concept has been utilized to predict user adoption (Saadé and Bahli 2005; Lowery et al. 2012), enjoyment (Wakefield and Whitten 2006), trust (Chandra et al. 2012), and satisfaction (Deng et al. 2010; Reychav and Wu 2015) that are done in e-commerce, m-commerce, e-learning, virtual environment, social network, and gaming contexts. There are overlaps between flow and cognitive absorption as prior literature suggests (Chandra et al. 2012; Reychav and Wu 2015).

The five dimensions that Agarwal and Karahanna (2000) identified for cognitive absorption could be categorized into affective and cognitive engagements that lead to the users' experience of cognitive absorption. This view easily differentiates cognitive absorption from immersion because immersion accounts for sensory engagement in addition to the other two (cognitive and affective engagements). It should be noted that cognitive absorption only discussed one form of emotional engagement that is enjoyment, which makes this psychological state almost a limited experience that has to happen under certain conditions. However, with broader perspectives, any form of emotional, cognitive, and sensory engagement that makes the user experience a degree of obliviousness contributes to immersion.

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[13] Focused immersion differs from our definition of immersion because in this concept, it refers to only 'cognitive attention' that individual dedicate to a particular task, but not emotional attention, or sensory attention.

A.3. Presence:

Presence and telepresence are two related concepts that refer to the sense of being “there.” Witmer and Singer (1998) defined presence as “the subjective experience of being in one place or environment, even when one is physically situated in another.” Telepresence, which is adapted from the presence, specifically defines the environment as a computer-mediated space such as a virtual world (Nah et al. 2011; Ermi and Mäyrä 2005). Guo et al. (2016) defined telepresence as “the feeling of being a part of the phenomenal environment created by a medium.” Faiola et al. (2013) emphasized the role of virtual space and stated that it refers to the feeling of being present in a virtual space. The subtle difference between the two is that the telepresence only defines computer-generated environments as “there.” For example, a user could feel presence (not telepresence) when they are video conferencing if the associated technologies allow them to completely feel they are there.

The users’ sense of presence enhances when their interaction quality is enhanced (Nah et al. 2011). Similar to immersion, presence requires a high degree of interactivity through the user’s sensations; images, sounds, and touch could optimize the users' feeling of being present in the virtual environment (Faiola et al. 2013). Besides, the intensity of presence could differ based on the form, content, and user’s characteristics (Nah et al. 2011). The mechanism by which the computer-mediated environment (virtual environment) stimulates the sense of being in a different location is through creating the perceptual illusion of being there (Nah et al. 2011; Guo et al. 2016). Several other alternative terminologies such as co-presence, social presence, and co-location all refer to the same concept of presence under different labels (Goel et al. 2013; Soutter and Hitchens 2016). For virtual environment designers, the fundamental assumption is that they should leverage all available technological resources to refine and polish their designed environments in order to stimulate presence in users. By using virtual objects, users can better experience presence in virtual worlds (Saunders et al. 2011). Another common virtual architecture that increases the user's sense of being there is through enabling exploratory behavior in virtual environments (Faiola et al. 2013). Moreover, users' avatars, which is the virtual representation of the user in the virtual environment, could affect their feelings of presence (Saunders et al. 2011).

For the most part, presence in IS research has been applied to virtual environments (Nah et al. 2011; Saunders et al. 2011; Cummings and Bailenson 2015; Faiola et al. 2013). Nah et al. (2011) showed that the 3-D environment affects users' feelings of telepresence influenced their enjoyment and behavioral intention to use 3D websites. Guo et al. (2016) incorporated telepresence in an online learning environment and found that telepresence affects users' flow state. Saunders et al. (2011) showed that virtual environment, moderated by the place conditions and user's prior experience, could lead to both presence and immersion.

Presence is more about feeling than a state of mind. Presence has been discussed as a consequence of immersion, so these two concepts are distinct (Gorini et al. 2011; Hou et al. 2012; Bulu et al. 2012). Only sensory engagement is a common antecedent of both.

Appendix B: Experiment scenarios

Table B1. House hunting scenario for difficult group (Easy group presented with House A - D).

You will perform a house hunting task. In the house hunting task, your goal is to buy a house based on your preferences. The cost of the houses does not play a role and you can select any houses that you like to buy! Try to spend enough time to select the house that matches with your preferences from the available options on the second page. So, your objectives are:

1. Review the available options on the second page and select one house that you like. Complete the task carefully. Try to be quick but spend necessary time to learn about details of the available options.
2. Inform the person in charge about the option that you selected.
3. On the score column in the table (page 2) rank the importance of each option to you by distributing 100 points between the available options, but the total sum of the scores for all options must be hundred so try to spend necessary times in distributing scores based on importance (e.g. if cabinet color is more important to you than number of floors in the house then you should give cabinet color more points).
4. After giving scores to these options inform the person in charge.
5. You have to visit the same houses using 3D technology and then find the house that you selected on the paper from the available options in page 2 (this will be the house that you want to buy)!

I addition, you will be asked a couple of questions about the details of each house if you answer them correctly, you will receive an extra $2 on this task. So do your best to learn about each house and their differences.

Please select one of the houses that matches with your preferences. Select the one that you like the most from the table on the second page!

Score	**Factor**	**House A**	**House B**	**House C**	**House D**	**House E**	**House F**	**House G**	**House H**
	Average Room sizes (Sq/ft)	150	250	250	200	250	300	250	200
	# of Bathrooms	4.25	5	4	4	4	6	5	3
	Floors	2	2	2	3	3	2	2	2
	Decoration level	Half-furnished	Full furnished	Half-furnished	Full furnished	Full furnished	Full furnished	Full furnished	Full furnished
	Living room	Small; no TV	Large; has TV	Medium; no TV	Average; has TV	Large; has TV	Large	Large; has TV	Small; has TV
	Kitchen Size	Small	Large	Small	Large	Medium	Large	Medium	Small
	Kitchen style	Island open	Island open	Island open	Open	Island open	Island open	Island open	Open
	Pantry	Yes	No	No	Yes	No	No	No	No
	Kitchen window	1	2	0	1	1	1	0	1
	Laundry room	Small; 2nd floor.	Large; 2nd floor.	Small; 2nd floor.	Small; 3rd floor	Small; 1st floor; part of bathroom	Large; 2nd floor.	Medium; 2nd floor.	Small; 1st floor.

Table B1. House hunting scenario for difficult group (Easy group presented with House A – D; Cont.).

Score	**Factor**	**House A**	**House B**	**House C**	**House D**	**House E**	**House F**	**House G**	**House H**
	Living room sunlight	Great day light penetration	Great day light penetration	Great day light penetration	Average day light penetration	Average day light penetration	Great day light penetration	Great day light penetration	Weak day light penetration
	Dining room/area	Has one large that is near the kitchen	Has two: one large separate from kitchen; one small close to kitchen	Has one large that is near the kitchen	Has one large that is near the kitchen	Has one large that is near the kitchen	Has two: one large separate from kitchen; one small near the kitchen	Has two: one large separate from kitchen; one small near the kitchen	One large separate from kitchen
	# of Bedrooms	5	4	5	3	3	5	4	4
	BBQ	Yes	Yes	No	No	No	Yes	1	1
	Balcony	2 (Front and rear)	None	1	3	2	1	1	1
	Patio	1	2	1	1	1	1	3	2
	Backyard size	Very Small	None	Very Small	None	None	None	Average	Small
	Pool	No	No	No	No	No	No	No	Yes
	Kitchen cabinets	White	Dark brown	Brown	White tile	Dark brown	Brown	White	Dark brown
	Exterior color theme	White	Brown	Cream / Brown	cream / orange	White	Yellow / cream	Beige	White / brwon
	Interior decoration color theme	Blue	Dark brown / blue	White	Light grey	White	White / light grey	White	Mixed
	Floor material	Light brown parquet	Dark brown parquet	Brown parquet	White tile	Cream parquet	White tile	Dark brown parquet	Brown tile

Table B2. Game scenario.

You shouldplay a video game called SuperHot. Your goal in the gaming task is to:

- Kill enemies in each round in the shortest time possible and pass as many levels as you can.
- You are immortal in the game, but you have to redo each round when you die. Try to minimize the number of times you die by carefully assessing the situation of your enemies in each round. You will continue playing until the lab operator instruct you to stop (approximately for 10 minutes).

If you die less than three times (not more than that) throughout the whole task you will receive extra $2.

Appendix C: Survey items

Table C1. Constructs and item measures.

Cognitive engagement:		**Source**
CogEng1.	I put in a lot of mental effort while performing the activity.	Ben-Eliyahu et al. 2018; Smiley and Anderson 2011; Rotgans and Schmidt 2011
CogEng2.	The activity required me to actively think.	
CogEng3.	When performing the activity, I planned out or strategized about what to do next. *	
CogEng4.	During and after the activity I tried to reflect on how I am doing.*	
Affective engagement:		
AffEng1.	The activity was fun.	Skinner et al. 2009; Fredricks et al. 2005; Ben-Eliyahu et al. 2018
AffEng2.	I felt happy while performing the activity.	
AffEng3.	I felt excited while performing the activity.	
AffEng4.	I liked being in the environment of the activity.	
Perceived IT-based sensory engagement (Perceived media richness):		
MedRich1.	I believe that the technology interacted with me through a variety of different cues (such as visual, auditory, and haptic/tactile).	Jiang et al. 2013.
MedRich2.	I believe that the technology I was using allowed me to use rich and varied language (such as body motion, quality graphics, animations, and sound effects) in our interaction.	
MedRich3.	I believe that the technology I was using allowed customizability to meet my personal requirements.	
MedRich4.	I believe that the technology I was using allowed me to give and receive timely feedback. *	
Subjective immersion:		
OldImer1.	While performing the activity my attention was not diverted very easily.	Jennet et al. 2008; Agarwal and Karahanna 2000; Yoo et al. 2018
OldImer2.	I become unaware of my surroundings while performing the activity.	
OldImer3.	While performing the activity I was oblivious to other attentional demands	
OldImer4.	I lost track of time while performing the activity. *	

Note:
Unless otherwise noted, items were measured on a 1 = Strongly Disagree, 7 = Strongly Agree scale.
* Dropped due to low reliability or in the process of establishing convergent and discriminant validity.

Appendix D: Robustness analysis of Utilitarian versus Hedonic subgroups for objective immersion and performance

D 1. Effects of objective immersion on performance for hedonic and utilitarian groups.

DV:	**Game (Total number of levels passed)**						**Game (Average time to pass a level)**						**House (Completion time)**					
	M 1	**M 2**	**M 3**	**M 4**	**M 5**	**M 6**	**M 1**	**M 2**	**M 3**	**M 4**	**M 5**	**M 6**	**M 1**	**M 2**	**M 3**	**M 4**	**M 5**	**M 6**
Age	0.11	0.005	0.006	0.003	0.01	0.01	0.25^{**}	0.12	0.12	0.12	0.12	0.11	0.07	0.05	0.05	0.07	0.05	0.05
Gender (Male=0)	-0.08	-0.17^{***}	-0.17^{**}	-0.16^{**}	-0.17^{**}	-0.17^{**}	-0.11	-0.19^{**}	-0.19^{**}	-0.18^{**}	-0.19^{**}	-0.19^{**}	-0.08	-0.04	-0.05	-0.03	-0.03	-0.05
Session hour	0.22^{*}	0.10	0.10	0.11^{*}	0.10	0.11	0.18	0.06	0.06	0.06	0.06	0.07	0.02	0.03	0.04	0.07	0.002	0.001
# days since start date	0.21^{*}	-0.10	-0.10	-0.07	-0.10	-0.11	-0.27^{**}	-0.12	-0.12	-0.12	-0.12	-0.13	0.38^{**}	0.49^{***}	0.50^{***}	0.47^{***}	0.55^{***}	0.57^{***}
Task difficulty (Easy=0)		-0.84^{***}	-0.84^{***}	-0.85^{***}	-0.83^{***}	-0.89^{***}		-0.78^{***}	-0.78^{***}	-0.78^{***}	-0.78^{***}	-0.82^{***}		-0.10	-0.10	-0.11	-0.10	-0.21
Technology type (VR=0)		0.12^{*}	-0.13	-0.12	-0.13^{*}	-0.22^{**}		-0.05	-0.05	-0.05	0.05	-0.11		0.26^{*}	0.25^{*}	0.28^{**}	0.25^{*}	0.10
Objective Immersion (OI)			-0.007	-0.15	0.01	0.05			-0.01	-0.01	-0.01	0.02			-0.04	-0.11	0.09	0.17
OI × Task difficulty				-0.17^{**}						-0.001						-0.27^{*}		
OI × Technology type				-0.02						0.02						0.12		
Objective Immersion^2 (OI^2)					0.04	0.21^{*}					-0.006	0.10					0.33^{***}	0.71^{**}
OI^2× Task difficulty						0.14						0.08						0.21
OI^2× Technology type						0.17^{**}						0.11						0.33
R^2	0.17	0.78	0.78	0.79	0.78	0.79	0.13	0.71	0.71	0.71	0.71	0.72	0.14	0.20	0.20	0.26	0.29	0.32
F (df_1, df_2)	1.65 (4,64)	47.09^{***} (6,62)	4.13^{***} (7, 61)	34.96^{***} (9,59)	35.23^{***} (8,60)	26.90^{***} (10,58)	3.05^{**} (4,64)	42.81^{***} (6,62)	37.17^{***} (7, 61)	30.28^{***} (9,59)	32.03^{***} (8,60)	25.56^{***} (10,58)	3.85^{***} (4,58)	3.79^{***} (6,56)	3.25^{***} (7,55)	3.37^{***} (9,53)	4.80^{***} (8,54)	3.97^{***} (10, 52)

Note: Since there is only one DV here, we used regression for the robustness check; N (game) = 69; N (House) =63; M = Model; All VIF's were under 8; All interactions in the table are factorial, so they were compared against the baseline; * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Appendix E: Robustness analysis of Utilitarian versus Hedonic subgroups for subjective immersion and performance

E 1. Effects of subjective immersion on performance for hedonic and utilitarian groups.

DV:	**Game (Total number of levels passed)**						**Game (Average time to pass a level)**						**House (Completion time)**					
	M 1	**M 2**	**M 3**	**M 4**	**M 5**	**M 6**	**M 1**	**M 2**	**M 3**	**M 4**	**M 5**	**M 6**	**M 1**	**M 2**	**M 3**	**M 4**	**M 5**	**M 6**
Age	0.11	0.005	0.006	0.007	-0.006	-0.008	0.25**	0.12	0.12	0.13	0.11	0.10	0.07	0.05	0.06	0.08	0.06	0.04
Gender (Male=0)	-0.08	-0.17***	-0.18**	-0.18***	-0.16**	-0.14**	-0.11	-0.19**	-0.19**	-0.19**	-0.17**	-0.16*	-0.08	-0.04	-0.04	-0.03	-0.06	-0.07
Session hour	0.22*	0.10	0.10	0.10	0.09	0.08	0.18	0.06	0.06	0.07	0.06	0.04	0.02	0.03	0.03	0.006	0.05	0.003
# days since start date	0.21*	-0.10	-0.09	-0.11	-0.07	-0.08	-0.27**	-0.12	-0.13	-0.15	-0.11	-0.10	0.38**	0.49***	0.49***	0.48***	0.50***	0.46***
Task difficulty (Easy=0)		-0.84***	-0.84***	-0.84***	-0.86***	0.83**		-0.78***	-0.78***	-0.77***	-0.81***	-0.72***		-0.10	-0.10	-0.12	-0.08	-0.21
Technology type (VR=0)		0.12*	-0.11	-0.15**	-0.10*	0.003		-0.05	-0.05	-0.09	-0.04	0.03		0.26*	0.23*	0.25*	0.24*	0.25
Subjective Immersion (SI)			0.02	0.15	-0.01	-0.05			-0.02	0.06	-0.05	-0.08			-0.10	0.15	-0.21	-0.20
SI × Task difficulty				-0.11						-0.10						-0.17		
SI × Technology type				0.10						0.05						0.17		
Subjective Immersion^2 (SI^2)					-0.09	-0.21**					-0.09	-0.07					-0.17	-0.71*
SI^2× Task difficulty						-0.02						-0.14						0.58
SI^2× Technology type						-0.20**						-0.09						-0.08
R^2	0.17	0.78	0.78	0.79	0.78	0.80	0.13	0.71	0.71	0.72	0.72	0.73	0.14	0.20	0.21	0.23	0.23	0.27
F (df$_1$, df$_2$)	1.65 (4,64)	47.09*** (6,62)	40.03*** (7, 61)	32.21*** (9,59)	34.75*** (8,60)	44.22*** (10,58)	3.05** (4,64)	42.80*** (6,62)	35.82*** (7, 61)	28.45*** (9,59)	31.48*** (8,60)	46.34*** (10,58)	3.85*** (4,58)	3.79*** (6,56)	3.25*** (7,55)	2.75** (9,53)	2.91*** (8,54)	2.32** (10,52)

Note: Since there is only one DV here, we used regression for the robustness check. Standardized summated measure of immersion was created for this analysis. N (game) = 69; N (House) =63; M = Model; All VIF's were under 8;All interactions in the table are factorial, so they were compared against the baseline; * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Appendix F: Factor analysis of the subjective measures in the antecedent model.

Table F1. Factor analysis.

	Mean	**SD**	**Cognitive engagement**	**Affective engagement**	**Media Richness**	**Subjective Immersion**
CogEng1	5.75	1.00	0.877	0.315	0.214	0.340
CogEng2	6.04	0.95	0.877	0.176	0.263	0.385
AffEng1	6.17	1.09	0.235	0.826	0.309	0.245
AffEng2	5.49	1.43	0.216	0.916	0.266	0.254
AffEng3	5.49	1.36	0.295	0.878	0.387	0.295
AffEng4	5.56	1.34	0.226	0.844	0.199	0.271
MedRich1	6.08	1.00	0.306	0.190	0.748	0.218
MedRich2	5.58	1.36	0.262	0.293	0.910	0.277
MedRich3	5.43	1.29	0.126	0.326	0.810	0.183
OldImer1	5.23	1.33	0.230	0.214	0.132	0.734
OldImer2	4.70	1.62	0.370	0.241	0.294	0.785
OldImer3	5.52	1.25	0.368	0.273	0.204	0.847

CogEng = Cognitive engagement; AffEng = Affective engagement; MedRich = Media Richness; OldImer = Subjective Immersion.

Table F2. AVEs, correlations, and reliabilities.

Construct	**Mean**	**SD**	**C.R.**	**C.A.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1.Perceived cognitive Engagement	5.89	0.85	0.87	0.70	**0.88**									
2.Perceived affective engagement	5.68	1.13	0.92	0.89	0.24^{***}	**0.86**								
3.Perceived IT-based sensory engagement	5.69	1.01	0.86	0.75	0.26^{***}	0.32^{***}	**0.82**							
4.Objective cognitive engagement (RPG)	0.28	0.07	-	-	0.06	0.18^{**}	0.17^{*}	-						
5.Objective affective engagement (EDA)	1.75	1.87	-	-	0.01	0.10	0.22^{***}	-0.06	-					
6.Objective IT-based sensory engagement (ACC)	14.60	10.98	-	-	0.15^{*}	0.05	0.29^{***}	0.05	0.37^{***}	-	-			
7.Objective immersion	0.48	0.20	-	-	0.20^{**}	0.17^{**}	0.10	0.15^{*}	0.22^{***}	0.37^{***}	-	-		
8.Perceived immersion	5.15	1.10	0.87	0.70	0.32^{**}	0.27^{***}	0.15^{*}	0.08	0.02	0.10	0.21^{**}	**0.79**		
9.Performance 1	-0.31	1.10	-	-	-0.11	-0.01	0.05	0.01	-0.03	0.12	-0.02	0.03	-	
10.Performance 2	-0.30	1.12	-	-	-0.05	0.04	0.10	0.02	-0.01	0.18	0.01	0.04	0.97^{***}	-

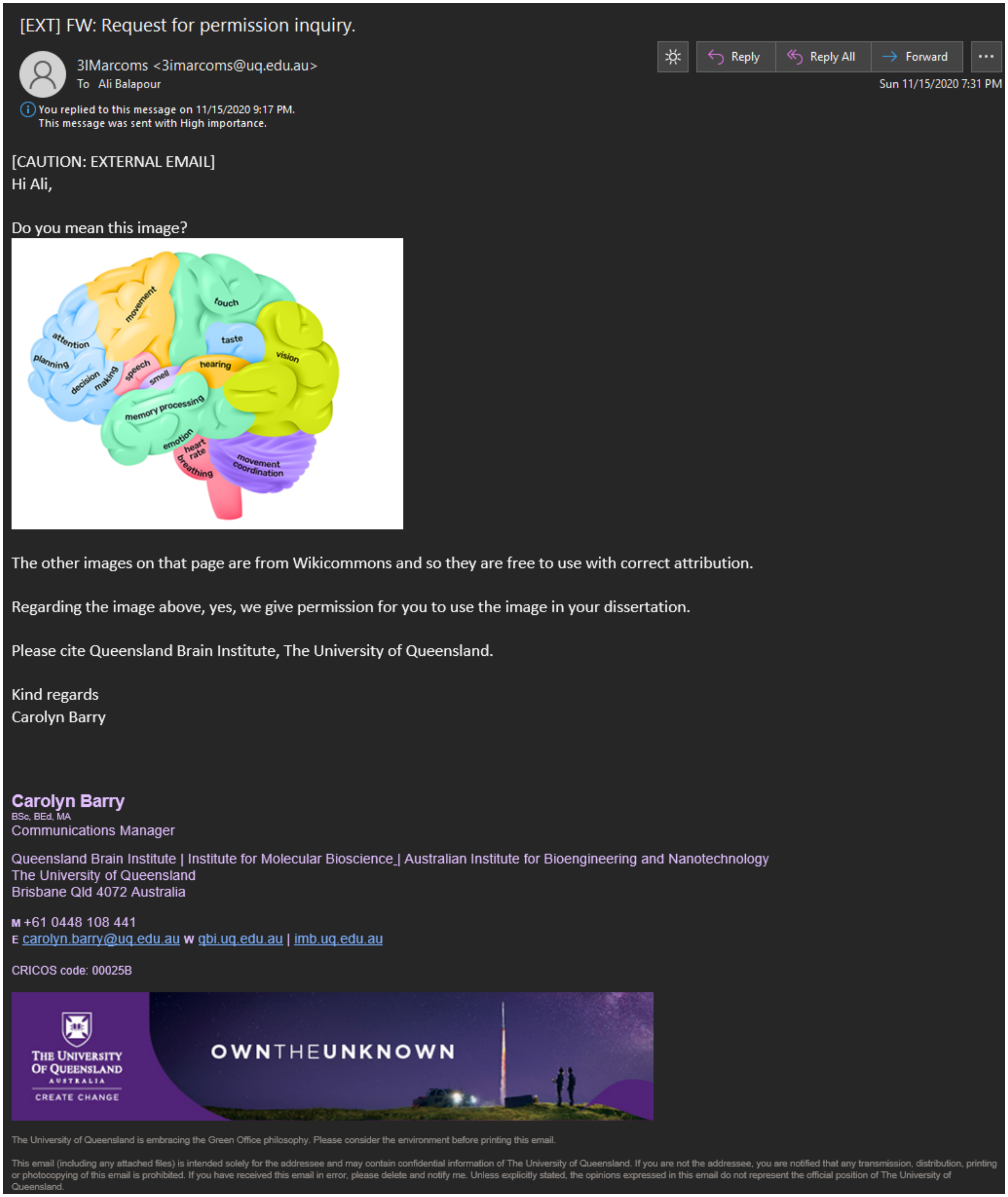
Note:

* $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

C.R. = Composite reliability; C.A. = Cronbach’s alpha; diagonal is the square root of average variance extracted (AVE).

RPG = Relative power of gamma; EDA = Electrodermal activity measure; ACC = Accelerometer.

Appendix G: Queensland Brain Institute permission to use image



[EXT] FW: Request for permission inquiry.

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This message was sent with High importance.

[CAUTION: EXTERNAL EMAIL]
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Regarding the image above, yes, we give permission for you to use the image in your dissertation.

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Kind regards
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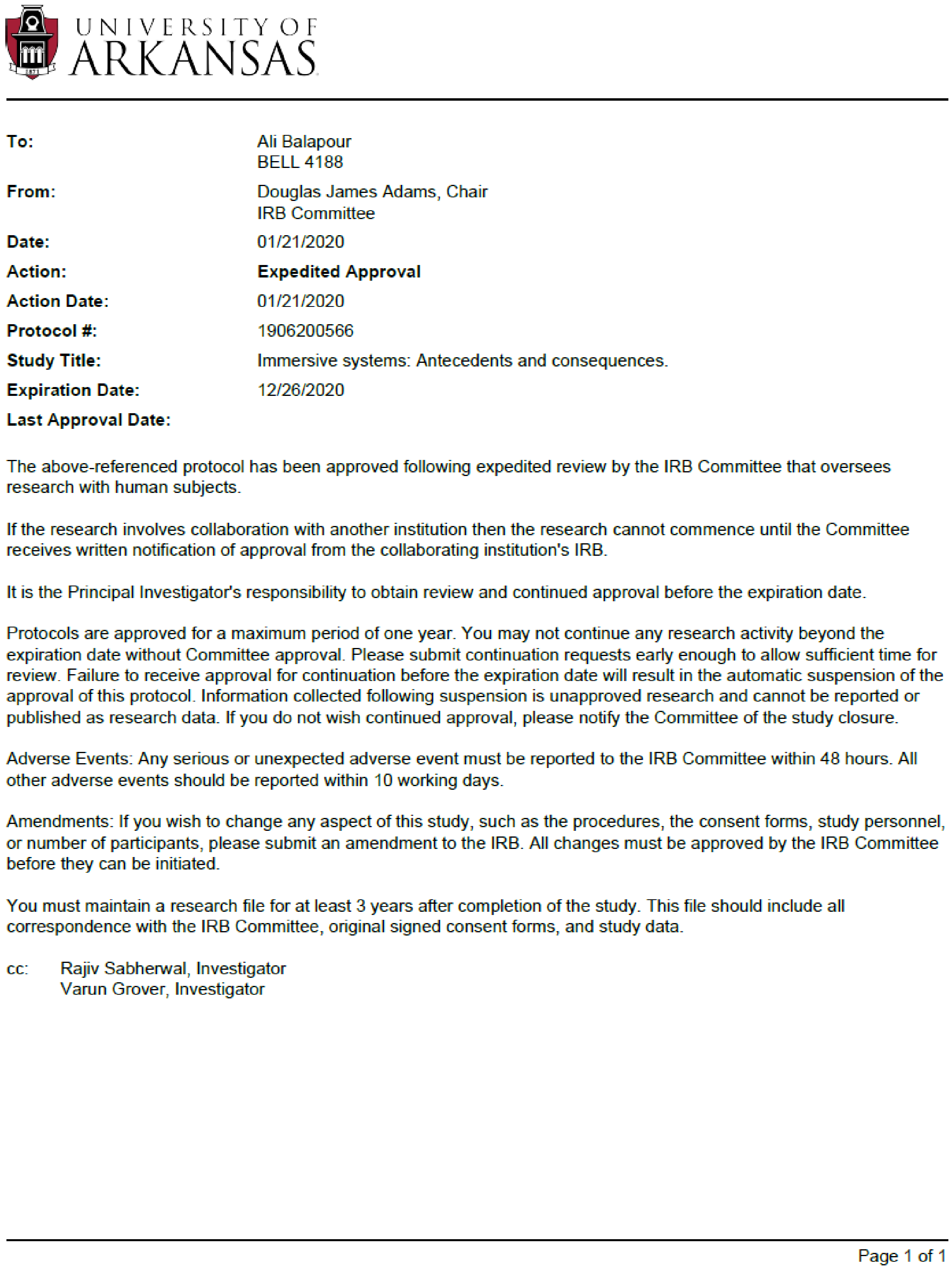
Appendix H: IRB approval



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ARKANSAS

To:	Ali Balapour BELL 4188
From:	Douglas James Adams, Chair IRB Committee
Date:	01/21/2020
Action:	**Expedited Approval**
Action Date:	01/21/2020
Protocol #:	1906200566
Study Title:	Immersive systems: Antecedents and consequences.
Expiration Date:	12/26/2020
Last Approval Date:	

The above-referenced protocol has been approved following expedited review by the IRB Committee that oversees research with human subjects.

If the research involves collaboration with another institution then the research cannot commence until the Committee receives written notification of approval from the collaborating institution's IRB.

It is the Principal Investigator's responsibility to obtain review and continued approval before the expiration date.

Protocols are approved for a maximum period of one year. You may not continue any research activity beyond the expiration date without Committee approval. Please submit continuation requests early enough to allow sufficient time for review. Failure to receive approval for continuation before the expiration date will result in the automatic suspension of the approval of this protocol. Information collected following suspension is unapproved research and cannot be reported or published as research data. If you do not wish continued approval, please notify the Committee of the study closure.

Adverse Events: Any serious or unexpected adverse event must be reported to the IRB Committee within 48 hours. All other adverse events should be reported within 10 working days.

Amendments: If you wish to change any aspect of this study, such as the procedures, the consent forms, study personnel, or number of participants, please submit an amendment to the IRB. All changes must be approved by the IRB Committee before they can be initiated.

You must maintain a research file for at least 3 years after completion of the study. This file should include all correspondence with the IRB Committee, original signed consent forms, and study data.

cc: Rajiv Sabherwal, Investigator
Varun Grover, Investigator

Page 1 of 1

Chapter 3: Methodological Comparison of EEG and Survey-Based Measures:The Case of User's Experience of Immersion

Abstract

NeuroIS tools, methods, and measures have received considerable attention from the IS community because they allow researchers to answer research questions about complex phenomena where alternative (e.g., psychometric) tools fall short of providing an explanation. However, NeuroIS is still in a nascent stage, and there has been a call for investigations on various aspects of it, including research design, implementation, data collection, measurement, and analysis. This essay focuses on some major gaps related to triangulation, convergence, and relationships between neurophysiological and psychometric tools. More specifically, we: (i) measure users' experience of immersion using Electroencephalography (EEG) and two psychometric-based methods (perceptual and observational); (ii) test these measures in a nomological network of the antecedents and consequences of immersion; (iii) statistically compare and report how relationships differ across each measure; and (iv) build an aggregated measure of immersion using neurophysiological and psychometric tools and test its capabilities in explaining an outcome variable. The results suggest that neurophysiological and psychometric tools have weak or non-significant correlations. In addition, our empirical results revealed that predominantly, subjectively measured constructs influence subjectively measured outcomes, while objectively measured constructs influence objectively measured outcomes. These results shed light on the possibility of inconsistent measurement bias associated with the tool's nature within neurophysiological and psychometric measures. In conclusion, one direction for future NeuroIS studies is to use measurement aggregation approach as a test for finding whether different measures of the same construct correctly capture the construct content and whether they are prone to measurement bias..

Keywords: NeuroIS, EEG, Virtual Reality, Immersion index, User Satisfaction, Methodlogical comparison.

Introduction

Producing informative NeuroIS research (scientific inquiry to inform IS research drawing upon cognitive neuroscience literature; Dimoka et al. 2011) is a formidable task because it requires careful design and a high degree of monitoring during execution. NeuroIS has received considerable attention from IS scholars (Dimoka 2012; Vance et al. 2018; Walden et al. 2018) in recent years, mainly because they have opened unique gateways for IS researchers to investigate user cognition through neurophysiological measures in real time, which is a feature that was previously unavailable. Few NeuroIS studies have investigated the connection between NeuroIS and alternative data collection techniques such as psychometric tools (Li et al. 2014; Wang and Hsu, 2014). As Tams et al. (2014) stated, triangulation between NeuroIS and non-NeuroIS tools (e.g., psychometric) has rarely been employed. Also, Tams et al. (2014) argued that there are various assumptions about the relationship between NeuroIS and non-NeuroIS measures of the same construct. For example, one assumption is that self-report measure alone can fully capture a concept such as ‘workload’, while studies have found that the self-report measure of workload without considering physiological context is problematic (O’Donnell and Eggemeier 1986).

Our literature review of the current state of NeuroIS yielded that there are two differing assumptions about the relationship between neurophysiological and psychometric measures that need to be investigated and clarified. The first view assumes that NeuroIS measures of the same construct complement each other and are highly correlated (Dimoka et al. 2011, 2012), while the other posits that they are alternatives, thus each captures one dimension of a holistic construct (Tams et al. 2014). There is a dearth of studies on both sides: because very few have investigated this phenomenon. Therefore, our knowledge of the nature of the relationship between psychometric and neurophysiological measures has remained limited. The NeuroIS literature informed us that for the most part, prior multimethod NeuroIS studies used neurophysiological and non-neurophysiological approaches in separate experiments (e.g., experiment one with EEG, experiment two with psychometric), and often did not compare or contrast neurophysiological and non-neurophysiological measurements of the same construct (Jenkins et al. 2016; Vance et al. 2018). Therefore, our first objective is to investigate the relationship between neurophysiological and psychometric measures of the same construct and shed light on the nature of their relationship and how they should be treated in the analysis.

Furthermore, while there are a few multimethod NeuroIS studies, they often used a neurophysiological measure with a psychometric measure (e.g., Vance et al. 2014; Moravec et al. 2019) to study a phenomenon. However, little is known about the relationship between two constructs that are measured using distinctive neurophysiological tools—for instance, an EDA measure of construct A and an EEG measure of construct B. The interaction between different neurophysiological measures is seldom studied in IS and merits investigation because it can expand our knowledge about the tools' limits and capabilities (Riedl et al. 2014a). Moreover, recent works have emphasized the need for building and testing structural models to examine inter-construct relationships in NeuroIS studies. As Reidl et al. (2014a) stated: "…a considerable number of IS scholars are well trained in applying structural equation modeling (SEM). Because this method is not yet well established in psychophysiological and brain research, IS experts in SEM may provide methodological contributions to the Cognitive Neuroscience literature" (p. i-xxxvi). Therefore, the second methodological gap pertains to the lack of diversity in analytical techniques and investigation of relationships in broader structural models of antecedents and consequences that adopts not one, but multiple measures for each construct, which this study attempts to address.

Against this backdrop, this study investigates the relationship between an EEG measure of immersion (defined here as the extent to which an individual performing an IT-facilitated activity becomes oblivious to other attentional demands) and two psychometric-based alternative measures of immersion to address the discussed gaps. Immersion is a complex construct for which several definitions and measures have been proposed (Jennett et al. 2008; Lowry et al. 2013). Immersion has been selected, as the focal concept in this study, because it is directly related to virtual and augmented reality technologies that are believed to shift the business landscape (Karim 2020), and have been adopted and diffused rapidly because they are affordable (Suh and Prophet 2018). In addition, immersion has ties to user attention, which is widely studied in neuroscience.

To build a structural model and test inter-construct relationships, specifically, we look at the effects of cognitive engagement (Björk and Holopainen 2004; Jennett et al. 2008) and affective engagement (Ryan 2001; Björk and Holopainen 2004; Bormann and Greitemeyer 2015), both of which have been studied as antecedents to the user's experience of immersion. We use a combination of psychometric tools, electrodermal activity (EDA), and EEG to measure cognitive and affective engagement. Additionally, we examine the effects of the three immersion measures on both subjective and objective measures of user performance. The objective performance is based on task completion time, while the subjective performance is measured using perceived user satisfaction with IT (Wixom and Todd 2005). User satisfaction with the use of immersive technologies is an important outcome since it plays a critical role in users' continued intention to use the technology (Gao et al. 2015; Guo et al. 2016; Shin and Biocca 2018).

In summary, first, we compare and contrast the relationship among different measures (intra-construct) of immersion (one EEG and two distinct psychometrics). Second, we build nomological networks of antecedents and outcomes of immersion (inter-construct) in which the effects of (i) neurophysiological on neurophysiological measures, (ii) psychometric on neurophysiological measures, and (iii) neurophysiological on psychometric measures are tested and discussed.

This study attempts to build on and extend prior works on the methodological value of NeuroIS research by comparing and contrasting an EEG measure to psychometric approaches. Thus, one contribution is generating new knowledge about the relationship between neurophysiological and psychometric measures, which has been a point of debate (Tams et al. 2014). In addition, this study sheds light on different behaviors of EEG measures and psychometric tools in relation to user performance and satisfaction with IT. Besides, by exploring the creation of an aggregated measure (formative construct), this study attempts to inform NeuroIS literature about a consolidated approach to looking at the relationship between psychometric and neurophysiological measures. Lastly, we investigate the cross effects of (a) different neurophysiological measures on each other, (b) psychometric measures on neurophysiological measures (and vice versa). The findings have implications for NeuroIS researchers seeing to obtain robust findings through multimethod NeuroIS and psychometric studies. In the next section, we briefly review previous NeuroIS attempts in using multiple tools to shed light on the phenomenon of interest.

Literature review

NeuroIS research

NeuroIS research has received prominence in recent years because of the ability to use neuro-based instruments and their potential to investigate interesting and unique IS topics. Dimoka et al. (2011) mentions a few of these areas. Below, we briefly review them and provide examples that introduced new insights into IT research studies.

Cognitive neuroscience has enabled scholars to 1) capture hidden mental processes (e.g., habits, ethics) that are impossible to measure with existing methods, 2) challenge IS assumptions by identifying differences between existing IS relationships (e.g., the curvilinear relationship between immersion and performance as depicted in Essay 1), thus helping to build IS theories, 3) complement existing sources of data with brain imaging/wave data that can provide objective responses that are not subject to measurement biases (e.g., social desirability, common method), 4) measure constructs associated with different brain regions, 5) identify antecedents of IS constructs and show how they influence outcomes of interest, and 6) study stimulus and its effect on IS constructs over time.

Several examples of NeuroIS studies contributed to the field in one or more of the ways mentioned above. For example, Warkentin et al. (2016), studied fear appeal and its influence on user security behavior. By using the fMRI tool, they could assess users' cognitive response to threats in real-time. This helped reconcile a major conflict in the literature about fear appeals and users' outcome behavior, suggesting that a focus on threats might be misplaced (which was the main assumption up to that point).

Vance et al. (2018) provided a repeated stimulus to subjects and captured its effect on users' habitual responses. Habitual studies are one of the areas in which real time data (objective data such as fMRI or EEG) could inform the topic beyond other methods' capabilities. Likewise, Jenkins et al. (2016) studied the effect of interruption messages on user performance using fMRI and mouse-tracking in two experiments. In the first experiment, they used fMRI, and claimed the second experiment that used mouse-tracking data provided a different view of the phenomenon. Another example in which NeuroIS inquiry stands out is when real time emotion is of utmost importance to explain a phenomenon. Compared to survey-based studies, NeuroIS could show how emotions influence attitude and behavior during the activity, as Kuan et al. (2014) depicted. Similarly, in Essay 1, we found a curvilinear relationship between EEG measure of immersion and performance, while at the same time, we found a linear relationship of perceived immersion and performance. This finding opened an opportunity for theoretical discussions and should inform future theoretical models of immersion.

Methodological gaps in NeuroIS research

Since late 2000, when neuroscientific studies started to appear in IS journals, there have been numerous NeuroIS studies with diverse methods and data collection approaches. Table 11 summarizes the current state of NeuroIS research and its efforts in using one or more data collection techniques such as fMRI, EEG, psychometric tests, eye-tracking, and/or mouse-tracking. Despite the progress and tremendous advancements, this study identified two research gaps, that will inform the future NeuroIS studies by investigating them.

Our review of existing NeuroIS studies yielded few insights about methodological comparisons and triangulations. Limited studies have ventured into this domain to investigate the nature of the relationship between NeuroIS and non-NeuroIS tools. Thus far, it appears that there are two approaches in multimethod NeuroIs studies. The first approach relies on using a neurophysiological tool in an experiment, then a non-neurophysiological tool in another (e.g., second experiment). For instance, Vance et al. (2018) investigated security warning disregard in two longitudinal experiments that leveraged various tools such as fMRI, eye-tracking, and psychometric tools. The results of eye-tracking and psychometric tools in the second experiment were used to further inform the topic. Similarly, Jenkins et al. (2016) performed two separate experiments, using fMRI in one and psychometric and mouse-tracking in the other, with the goal of validating the findings of the fMRI study where it failed to find theoretically valid results. The second approach uses Neuro and non-Neuro tools in the same experiment. For example, Ortiz de Guinea et al. (2014) collected EEG and psychometric data from the same subjects in a single experiment and analyzed a nomological network of dependent and independent variables, each measured using a combination of Neuro and non-Neuro tools. Likewise, Vance et al. (2014) used EEG and psychometric tools in an experiment on security threats; they evaluated the predictive validity of EEG and psychometric tools.

Against this backdrop, two gaps merit investigations, and each has ties to the two discussed approaches. The first gap pertains to the assumption about the conceptual relationship of NeuroIS and non-NeurIS measures. *Are neurophysiological and psychometric measures of the same concept interchangeable?* The implication of assuming the answer as "yes" is that the scholar could adopt different Neuro and non-Neuro tools in independent studies while assuming the same construct is being measured but with a different approach (Riedl et al. 2014a). For example, Anderson et al. (2016a) conducted two experiments and used fMRI (Experiment 1) and mouse-tracking (Experient 2) as measures of attention in a study of habitual response to security warnings. While both tools are relevant, they assumed fMRI and mouse-tracking are both measures of habitual response without empirical tests to show whether that is true.

On the other hand, several studies have suggested that Neuro and non-neuro measures might not be correlated, with each representing different aspects of a construct. For example, Tams et al. (2014) investigated the relationship between Salivary α-Amylase (sAA) and psychometric measures of technostress and found no statistically meaningful correlation. IS often tackles applied problems and, by and large, studies socio-technical phenomena that are considered relatively complex. In such scenarios, the conceptualization and operationalization are a blend of cognitive, behavioral, and biological phenomena which have to be accounted for (Riedl et al. 2014a). Thus, one way to capture a complex (and sometimes multilevel) phenomenon is the use of multiple measures of the same construct (Strube and Newman 2007; Riedl et al. 2014a) because each measure could capture a piece of a construct tht the other tool might not capture. As shown in Table 11, there is a large subset of studies that only relied on one way of operationalization and measurement of the constructs (Leger et al. 2014; Walden et al. 2018; Meservy et al. 2019). A single measurement approach in one experiment has been known to put validity at risk because they are more narrowly focused (Ortiz de Guinea et al. 2013).

In summary, the first gap pertains to the relationship between NeuroIS and psychometric measures of the same construct and whether they holistically represent a construct. As one could see from table 11, EEG and fMRI are the predominantly used NeuroIS tools; thus, we investigate this question using EEG and psychometric measures. This research inquiry contributes to this domain by providing an additional insight because NeuroIS tools are different, and assuming they are interchangeable, correlated, or unrelated might be misleading without appropriate theoretical and empirical supports (Riedl et al. 2014a).

The first gap was concerned with intra-construct comparisons of multiple measures, whereas the second gap is concerned with inter-construct relationships in a broader network of antecedents and outcomes. Our review of structural models in which the effects of neurophysiological measures on non-neurophysiological measures (or vice versa) were examined yielded limited insight. For example, Ortiz de Guinea et al. (2014) investigated the Technology Acceptance Model (TAM), measured engagement using EEG, and examined the effect of EEG measures on TAM constructs. The discussed limitation is even further when we tried to find causal effects of different neurophysiological measures on each other. Typically the multimethod studies have attempted to investigate the relationship between Neuro and non-Neuro measures. This study broadens the scope by examining a nomological network of antecedents of immersion and possible outcomes, then investigates the following causal relationships through repeated analysis of the structural model with different combinations of Neuro and non-Neuro measures: (a) neurophysiological measure on psychometric measure; (b) psychometric measures on neurophysiological measure; (c) psychometric measures on psychometric measures, and (d) neurophysiological measures on neurophysiological measures.

One implication of testing extensive structural models (each with a combination of measures) is that we can enrich our understandings of the inter-construct relationship, not only between neurophysiological and non-neurophysiological, but also between two distinct neurophysiological measures which are rarely studied in NeuroIS literature. Riedl et al. (2014a) mentioned that "…a considerable number of IS scholars are well trained in applying structural equation modeling (SEM). Because this method is not yet well established in psychophysiological and brain research, IS experts in SEM may provide methodological contributions to the Cognitive Neuroscience literature" (p. i-xxxvi). Therefore, by examining the mentioned relationships in a structural model of antecedents and outcomes, this study uncovers the causal effects of different NeuroIS tools to each other, and contributes to the growing body of knowledge about analytical methods that can inform NeuroIS literature.

Table 11. Summary of multimethod and non-multimethod NeuroIS studies.

Study	**Task (Sample size)**	**NeuroIS tool**	**Description**
Moravec et al. 2019	Identify fake news on social media (83)	EEG Psychometric	Psychometric and EEG were used, but no statistical evidence in showing a connection between the methods or how one complemented, corroborated, or undermined the findings of the other.
Meservy et al. 2019	Software development (29)	fMRI	fMRI was the only method used in this study.
Walden et al. 2018	Visual plot analysis and answering questions about it. (20 Exp 1; 20 Exp 2)	fMRI	Conducted two independent experiments with similar tasks, while fMRI was the only tool used. Experiment two was performed to confirm the experiment one's results.
Vance et al. 2018	Security warning disregard (16 Exp 1; 102 subjects study 2)	fMRI Eye-tracking Psychometric	Performed multimethod NeuroIS experiments by collecting both fMRI and eye-tracking. They presented the second experiment as a complementary approach to the first one.
Warkentin et al. 2016	Identifying threat and responding to security threats (17)	fMIR	fMRI was the only method used in this study.
Jenkins et al. 2016	Memorize, encode, and rehearsal of digital codes (24 Exp 1; 856 Exp 2)	fMIR Psychometric Mouse-tracking	Performed a multimethod NeuroIS study and showed how mouse cursor tracking and psychometric measures could be used to validate some of the findings.
Anderson et al. 2016a	Identifying image as new, similar, or identical to the things they have seen before (25)	fMIR Mouse-tracking	Performed a second study using mouse-tracking data to corroborate the findings of the fMRI study.
Anderson et al. 2016b	Identifying warning as new, similar, or identical to the things they have seen before (62)	Eye-tracking	Eye-tracking was the only method used in this study.
Hu et al. 2015	Decision making about security scenarios (21 Exp 1; 40 Exp 2)	EEG	Performed a multimethod NeuroIS study, both experiments leveraged EEG.
Teubner et al. 2015	Decision making in auction (120)	ECG	ECG was the only method used in this study.
Wang and Hsu 2014	Computer-based instruction for e-learning of excel (189 Exp 1; 20 Exp 2)	EEG Psychometric	They demonstrated the correlations between EEG measures and psychometric measures obtained from the same experiment.
Vance et al. 2014	Security warning disregard (62)	EEG Psychometric	Showed that psychometric measures are ineffective and used EEG as an alternative to the solution. Predictive validity of EEG and psychometric tools were compared.
Tams et al. 2014	Game like computer-based task (64)	sAA Psychometric	Psychometric and sAA were used. Both were used to measure stress; thus, one performed the role of corroborating the findings of the other one.
Riedl et al. 2014b	Trust game in the investment (19)	fMRI	fMRI was the only method used in this study.
Leger et al. 2014	Reading industry report with interruption (24)	EEG	EEG was the only method used in this study.
Gregor et al. 2014	Reacting to emotionally stimulating photos (41 Exp 1; 21 Exp 2 which was EEG)	EEG	EEG was used as an additional data collection method to test some hypotheses that needed insights from users' real time cognitive activities.
Li et al. 2014	Playing a game on a smartphone (48 Exp 1; 44 Exp 2)	EEG Psychometric Interview	Performed multimethod NeuroIS experiments by collecting EEG, psychometric, and a qualitative study to triangulate and support EEG findings.

Table 11. Summary of multimethod and non-multimethod NeuroIS studies (Cont.).

Study	Study	Study	Study
Ortiz de Guinea et al. 2014	Completing a task using Microsoft Access and an educational gaming software (24)	EEG Psychometric	Performed multimethod NeuroIS experiments by collecting EEG and psychometric simultaneously. The EEG measure was used in the structural model analysis along with psychometric measures of other concepts.
Kuan et al. 2014	Evaluating group buying deals (18)	EEG Psychometric	Psychometric and EEG were used, but no statistical evidence in showing a connection between the methods or how one complements, corroborates, or undermines the other's findings.
Minas et al. 2014	Hidden profile decision making about admitting applicants to the university (44)	EEG	EEG was the only method used in this study.
Astor et al. 2013	Decision making in the auction game (36 Exp 1; 68 Exp 2)	ECG Psychometric	ECG used along with psychometric tools. Psychometric tool used as a checkpoint for users' emotions.
Riedl et al. 2010	Decision on the trustworthiness of eBay offers (20)	fMIR Psychometric	Psychometric test used in a pretest and later they compared and contrasted its results with the main fMRI study and tried to interpret/reconcile the results and draw conclusions.

Notes: Exp = Experiment.

The use of neuro and psychometric measures in the study of immersion

Immersion

In this study, we define immersion as the extent to which an individual performing IT-facilitated activity becomes oblivious to other attentional demands. This definition is consistent with prior definitions that associate immersion with user attention and ignoring irrelevant attentional demands to the primary task (Lee et al. 2012; Lowry et al. 2013). In our review, we identified several definitions that mentioned the role of neglecting/ignoring other attentional demands. For example, Lee et al. (2012) defined immersion as “an experience of total engagement, where other attentional demands are rather ignored.” Hou et al. (2012) defined immersion as “experience of a complete focus on the game environment and an appealing engrossment free from distraction.” Likewise, Soutter and Hitchens (2016) defined immersion as “the sense of being wholly absorbed in an activity to the complete loss of awareness of the real world”. Last but not least, Cairns et al. (2013) defined player’s experience of immersion as “the sense of being “in the game” by which is meant being wholly involved or absorbed in the activity of playing to the neglect of the real world around the player.” In conclusion, obliviousness (or negligence) to the other attentional demands is the core criteria for the users' experience of immersion which is the common recurring theme across many proposed immersion definitions.

Users' experience of immersion is among other important topics in IS use or continued use. In this study, we selected the concept of immersion because: (1) it has ties to user attention and there is a long history of studying and measuring attention and suppression in neuroscience literature (Posner, 1995; Sarter et al. 2001), and 2) This concept is not alien to IS literature, since there are several studies on immersion and immersive technologies such as virtual reality, which highlight their importance to IS research (Jennett et al. 2008; Lee et al. 2012). Besides, scholars have recently called for further research on immersive technologies to realize their capabilities for businesses and organizations (Cavusoglu et al. 2019); 3) there are exiting subjective measures in IS literature for measuring immersion, which minimizes our effort in measurement development (Lowry et al. 2013), when our objective is to compare the neurophysiological measures with psychometric measures.

Our literature review on the concept of immersion indicates that immersion is a graded experience, such that a user might experience different degrees of immersion depending on the context, technology, and nature of the task (Brown and Cairns 2004); this implies that immersion is a complex and potentially multilevel construct. Therefore, using neurophysiological and psychometric immersion measures could potentially help us capture different pieces of a holistic construct known as immersion (Riedl et al. 2014a).

Cognitive and affective engagement

Our literature review on the antecedents of immersion led to two widely studied forms of engagements that are cognitive and affective (Björk and Holopainen, 2004; Jennett et al. 2008; Lowry et al. 2013). Cognitive engagement refers to a form of a self-conscious mental engagement with IT that requires thinking, processing, or other forms of mental calculations (Csikszentmihalyi 1990; Greene and Miller 1996; Greene et al. 2004; Zhu 2006; Walker et al. 2006; Dimoka 2012;). Affective engagement refers to any forms of emotional exchange between IT and the user (Picard 1995). As mentioned, the objective is to measure immersion using multiple techniques and then test the structural model in a nomological network of antecedents and consequences. Therefore, we selected the two mentioned antecedents of immersion that help with this objective.

Attention is a limited resource, so the human brain could allocate its’ attention to process information until it runs out of available capacity to process incoming information (Marois and Ivanoff 2005). Any activity requiring thinking and mental calculations takes away a part of the user's attention to process this information, making the user oblivious to other attentional demands (e.g., environmental distractors). Hence, cognitive engagement is positively associated with immersion. Similarly, suppose a user decided to selectively allocate part of their attention to emotionally interact with IT (e.g., listening to music). In that case, as emotional processing increases, less capacity is left to be allocated to other attentional demands; thus increase in affective engagement leads to an increase in the level of immersion.

User performance and satisfaction with technology

In this study, we also examine two consequences of immersion—performance and user satisfaction with IT. As aforementioned, one of the gaps that we try to address pertains to building and testing a structural model in which antecedents and consequences of the focal concept are present. Therefore, showing the effect of immersion on performance and user satisfaction with technology helps us achieve this goal. Prior works have shown that immersion positively influences user satisfaction with IT (Reychav and Wu, 2015; Ozkara et al. 2016). In fact, user satisfaction in virtual settings has been frequently studied as the dependent variable of interest

(Chan et al. 2014; Bormann and Greitemeyer, 2015; Guo et al. 2016). The underlying logic is that if a technology can help the user focus their attention on the activity of interest and ignore distractors, the user is happier and more satisfied with the technology, largely due to the technology's capacity in helping the user to achieve more by focusing on the primary activity and becoming immersed. For instance, consider an individual who would like to play a game and prefers not to be distracted while in the game, because breaking their focus could hurt their performance. If a pair of headsets or virtual goggles can minimize other attentionally distractive stimuli in the environment, the user would be more satisfied with their use of the VR goggles or headsets because it can unlock their potential to perform better.

Moreover, given that user satisfaction with IT is generally assessed as a psychometric measure prone to self-report biases (e.g., social desirability), this study utilizes objective measures of performance in addition to perceived user satisfaction with IT. By extension, we consider task completion time and user error rate, both of which are traditional objective measures of user performance (Card et al. 1980). As immersion increases, the subject focuses their attention on the primary activity and ignores other attentional demands in the environment (e.g., distractors). Consequently, as focused attention on the primary task increases, the user can complete the task in less time and make fewer errors. In summary, Figure 9 demonstrates the research model.

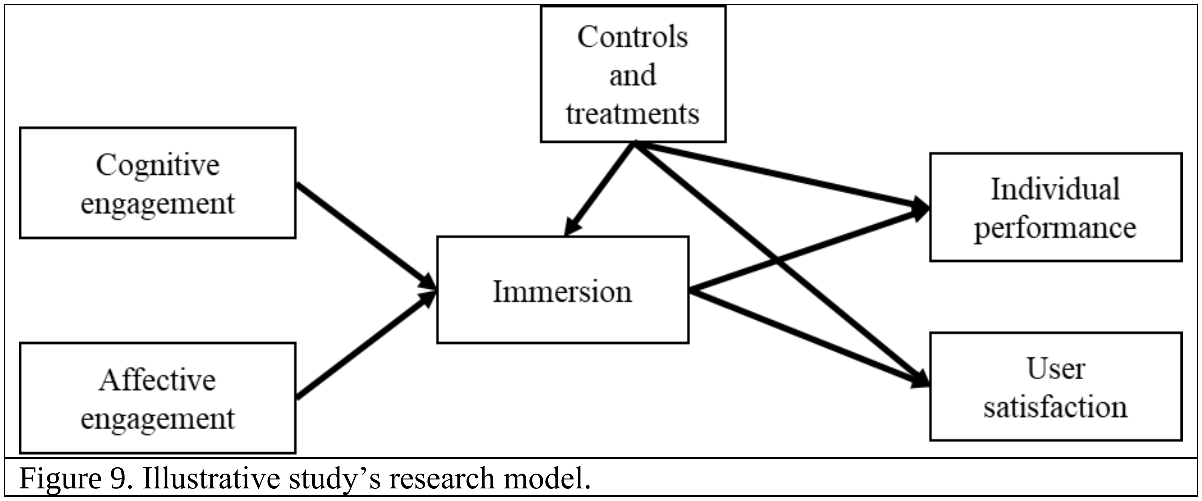

Figure 9. Illustrative study’s research model.

Experimental design

We designed an experiment in which the primary objective is to capture users’ immersion experience using neurophysiological and non-neurophysiological measures. The concept of immersion is mostly studied with virtual reality (VR), games, or interface design (Brown and Cairns 2004). Therefore, in this experiment, we implemented a few treatments that are associated with immersion. First, we selected a hedonic task (video game) because immersion is studied in relation to games. However, to make the study relevant to business problems, we also included a utilitarian task (virtual house tours). Second, immersion is associated with virtual reality. In this experiment, we use Oculus rift S VR goggles because the selected contents for the experiment were available on the desktop computer. We used both VR and desktop computer in the experiment. In addition to these two treatments that are associated with task type and technology type, a third treatment – task difficulty – was used because prior works suggest that it influences immersion (Jennett et al. 2008). Thus we accounted for task difficulty by designing easy and difficult versions of the utilitarian and hedonic task. In conclusion, this is a 2 (VR vs. PC) x 2 (Game vs. House tour) x 2 (Easy vs. Difficult) design. Appendix M presents details of the selected tasks for the experiment.

Moreover, we implemented some natural distractors in the room that played as the user interacted with the technology while completing the primary task[14]. The concept behind using distractors stemmed from the definition of immersion; as proposed earlier, it accounts for an individual’s obliviousness to other attentional demands. Thereby, we created artificial distractors to manipulate other ‘attentional demands’ in the experiment room. The details of the distractors and their purpose are discussed in Appendix I. Afterward, the subjects completed a short survey to obtain the demographic information and psychometric measures.

Measurement

Neurophysiological measures

Neurophysiological equipment

For the neurophysiological measures in this study, we used the MyndPly EEG headband with the NeuroSky ThinkGear microchip for capturing waves at 512 Hz. This is one of very few commercialized and affordable dry sensor devices on the market that is compatible with the VR goggles[15] , which was the primary motivator for investing in this device. Prior EEG experiments have validated this single electrode device's reliability by comparing it to conventional expensive EEG equipment with over 16 reference points, and found it to have adequate quality and reliability (Rogers et al. 2016; Rieiro et al. 2019). Because the device is a dry sensor, prior to their appointment with the lab, we asked subjects to avoid wearing makeup or face cream on the experiment day to allow the sensors to come into direct contact with the subject’s skin. The EDA

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[14] Subjects performed a baseline task before the primary task, which was watching a relaxing video clip for three minutes.

[15] The VR device has big and tight straps on top and around the head to hold it firmly in front of the user’s eyes. We predicted that it would put pressure on and dislocate the electrodes if we were to attach electrodes on the scalp to F7-F8, T3,T4, Cz, Pz, O1, O2, T5, and T6 in the traditional 10–20 system.

in this study was recorded using Empatica E4, which is a biosensor that gets attached to the subject's wrist. The EDA was sampled at 4 Hz, and the unit of analysis is microSiemens.

In parallel to measuring EEG in real time while the user is working with the IT, we administered a short questionnaire survey (post-experiment) in which demographic and psychometric measures were included.

EEG measure of immersion

In this study, we adopted a beta to alpha plus theta ratio, which is an index that accounts for both attention allocation on an activity and attention control/suppression (Freeman et al. 2004). This measure captures the described aspects in the definition of immersion, in which an increase in obliviousness equals the focused attention to the IT-facilitated activity. Beta oscillation captures focused attention on the IT-facilitated activity, while theta and alpha oscillations are associated with a decrease in attention (Scerbo et al. 2003; Foxe and Snyder, 2011). The theoretical idea is that if a user is not oblivious to other attentional demands in the room because something in the users' surroundings distracts them, they shift attention to those stimuli, which should be captured through a decrease in the beta and an increase in the alpha plus theta. Equation 1 represents the EEG measure of immersion index:

Eq1.

$$Immersion\ index = \frac{beta}{theta + alpha}$$

EEG measure of cognitive engagement

For cognitive engagement, the relative power of gamma-band is used as the measure of cognitive engagement. A few prior studies found that cognitive activities (e.g., mental calculation) augment EEG gamma power (Fitzgibbon et al. 2004). Another benefit of using Gamma to represent cognitive engagement is that it does not have an overlap with the proposed EEG measure of immersion.

EDA measure of affective engagement

Some works have suggested autonomic innervation of sweat glands is reflected in measurable changes in skin conductance at the surface, defined as electrodermal activity (Critchley, 2002). EDA is another NeuroIS tool that has been adopted and promoted by recent IS studies and has been used as a tool to measure emotional arousal and engagement (Minas et al. 2014). Therefore, we used EDA to objectively measure emotional engagement.

Psychometric measures

Perceived immersion

Given that measures for perceived immersion already exist in the IS literature, we adopted the measures from the works of Agarwal and Karahanna (2000), Jennett et al. (2008), and Yoo et al. (2018). We used three items: adaptations from the mentioned sources and measured on a 7-point Likert scale (1 = Strongly Disagree to 7 = Strongly Agree). These items are: 1) while performing the activity, my attention was not diverted very easily; 2) I become unaware of my surroundings while performing the activity; and 3) while performing the activity, I was oblivious to other attentional demands[16]. Against this backdrop, one might argue that a user could not provide his/her correct judgment of their obliviousness because they are engaged with the task. If a user is mindful about their obliviousness to distractors, they must be focusing on both the task and distractors, which is counterintuitive. Therefore, there is a need for an alternative approach that does not suffer from this critique.

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[16] We slightly reworded one of the items to capture obliviousness to surroundings.

Observational (spatial) measure of immersion

The proposed definition of immersion ties this concept to becoming oblivious to the other attentional demands as a result of performing an IT-based activity. However, the current psychometric measure for perceived immersion in the previous section does not conclusively reflect the degree of obliviousness to other stimuli. Perhaps this is because the human brain, voluntarily and involuntarily, processes sensory stimuli in the environment, but human "perceptions" are biased towards realizing the most salient stimuli in the environment (Kayser et al. 2005), meaning that the background audiovisual noises, while being processed and internalized involuntarily in the user's brain, are not "fully perceived" by the user himself (Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977; Kayser et al. 2005). In short, the existing perceptual measures do not fully capture the immersion construct based on the proposed definition, which has ties to obliviousness. Thus, there is a need for a set of measures to bridge this gap by asking specific questions that can reveal to what extent the user paid specific attention to the irrelevant stimuli in the experimental room. Given the discussed argument, presumably, more obliviousness to the stimuli reciprocates the higher degrees of immersion because the user allocates all of their available attention to the main activity, and thus little capacity is left for allocation to the distractors.

Since the VR tasks were pre-developed, and we had no internal control to create visual distractors (due to the inherent nature of the user interface) in Oculus Rift S, we focused on creating auditory distractors instead, which could be externally manipulated. We developed some day to day natural auditory distractors that one could face at home or workplace, such as iPhone text-sound or irrelevant news about the weather, stock market, oil prices change, and such (see Appendix I for details about the distractors). "To be ignored sounds" (distractors) were created based on the suggestions of the prior literature (Hughes et al. 2013; Addas and Pinsonneault 2015, 2018). To create irrelevant news voices, we used two males, two females; each with unique accents (American English accent, Middle-eastern accent, Kenyan accent, Chinese accent), and each person read five sentences that are shown in Appendix I, totally making 20 sentences with unique attributes of gender and accent.

Furthermore, to correctly tap the domain of the construct based on the proposed definition of immersion, and to understand the available strategies for measurement development that captures auditory distractions, we reviewed the extant literature and found some approaches for measuring the effect of distractors and found some strategies in “phonemic awareness studies”. Phonemic awareness, defined as awareness of the sound structure of words, consists of knowledge of rhyme, sound categorization, phoneme blending, phoneme segmentation, and phoneme manipulation (MacDonald et al. 2013). Given the nature of the text sound and the recorded voices, we adopted some of the approaches similar to the phonology literature in which we asked subjects specific questions about attributes of the sounds they heard during the activity as a way to assess the amount of attention they paid to the primary activity. If they could not recall many specific attributes of the distractive sounds, they were immersed in the primary activity and oblivious to other attentional demands . Although all subjects receive and process distractors in their mind, the extent to which these auditory distractive sounds are kept at a noise level (ignored) or become salient (perceived and captures selective attention) should be different for participants. Therefore, we looked at the questions at three levels, and ask questions that targeted to assess the subject’s short-memory (Banburry et al. 2001) in recalling frequency and segments of the distractive sound/sentences they heard during the experiment (Yopp 1988):

- Shallow immersion: Conceptually recognizing a gender's voice is expected to be relatively easy to process and differentiate for users, given that women generally speak at a higher pitch. We asked two separate questions. 1.) How many male voices did you recognize? and 2.) How many female voices did you recognize? There were two males and two females who were recorded in the voices, so the answer ranged from 0–2 for each question.
- Middle immersion: Theoretically, the tracking frequency might require a higher level of attention, so we asked two questions: 1.) How many text message sounds could you hear? and 2.) How many times did you hear voices in the room? We played ten text message sounds and 20 voices with few-second gaps between them.

  Deep immersion: Finally, we asked two questions that required a deeper level of attention to the stimuli in the room: 1.) If you recall the male or female voices, could you please list what they were saying? and 2.) How many different accents did you recognize? The voices repeated five sentences (See Appendix I), and based on how accurate subjects could write them in the survey, we scored them based on their accuracy. For each sentence in the appendix, we scored 0 = if they were not listed, 0.5 = if they were half right, and 1 = if they could be recalled correctly. We also asked about the accents of the voices. Conceptually, we expected that recognizing accents requires higher attention compared to, for example, recognizing the gender of the voice, or roughly the number of iPhone text sounds they could hear. Our reasoning is that it takes time for the subject to comprehend the accents from the voices in the room. They need to hear a few sentences, then think and match this accent with the ones they have heard before, requiring more attention. There were four accents among the distractors in the room.

Perceived cognitive and affective engagement

Cognitive engagement was measured using four items (Ben-Eliyahu et al. 2018; Smiley and Anderson, 2011; Rotgans and Schmidt, 2011): 1) I put in a lot of mental effort while performing the activity; 2) The activity required me to actively think; 3) When performing the activity, I planned out or strategized about what to do next; and 4) During and after the activity I tried to reflect on how I was doing. For affective engagement, we used the following four items in the survey (Skinner et al. 2009; Fredricks et al. 2005; Ben-Eliyahu et al. 2018): 1) The activity was fun; 2) I felt happy while performing the activity; 3) I felt excited while performing the activity; and 4) I liked being in the environment of the activity. Both concepts were measured on a seven-point Likert scale.

Perceived user satisfaction and objective performance

To measure user satisfaction, we used the following five seven-point scales, ranging from 1 to 7, informed by Wixom and Todd (2005) and Hsieh et al. (2012): 1) I am very pleased to use this technology for this task; 2) It is absolutely delightful to use this technology for this task; 3) All things considered, interacting with this system is satisfactory.

Objective performance

Completion time and error rate are frequently studied performance measures in the field of human-computer interaction (Card et al. 1980). Therefore, for subjects who were randomly assigned to the house tour task, we used their time to completion in minutes as their measure of performance. For subjects who were randomly assigned to the gaming task, we used their average time to complete each level and the number of levels completed as the objective measures of performance.

Experiment protocol

We recruited 132 students (61 females and 71 males) from business and psychology majors. Subjects with pre-existing conditions were excluded from the study. Each participant completed a short demographic survey before the experiment. We selected a small room large enough to have space for Oculus Rift S, as recommended by the manufacturer. The subjects went through seven phases after arriving at the lab. During Phase 1, upon arrival, the operator greeted the participant, guided them to the room, and explained the purpose of the study with a briefing about their task. The lab operator attached the EEG headband and helped the subjects to place the biosensor wristband on their left or right hand, depending on whether they were left-handed or right-handed. In Phase 2, subjects received a brief explanation about the activity and received the scenario sheets (See Appendix J). In Phase 3, after they read the scenario and asked clarification questions, the lab operator trained the subject to work with the VR goggles and their controllers or showed them how to use a keyboard and mouse for completing the task (depending on the platform that the subject was assigned to). In Phase 4, the lab operator helped subjects to put on the VR goggles or sit behind a computer in the right position, then started a three-minute video clip of a waterfall (we used this as the baseline task for comparison against the main task) and asked them to watch and relax. The operator left the room and returned after three minutes. In Phase 5, the lab operator closed the relaxing clip and launched the game or house tours. The operator left the room as soon as he instructed the subjects to start the task and began monitoring the situation. The operator used a virtual connection to the user’s computer as well as two cameras in the room to observe the subject’s behavior to ensure that the procedure was being followed accurately and interfered if the subject encountered any issue[17]. In Phase 6, after the subject was one minute into the task, the operator started playing the aforementioned distracting sounds and voices (see the previous section for details). In Phase 7, after finishing the task, the operator detached all devices from the user and guided them to another room to immediately complete an online questionnaire about their experience.

Analysis and results

Analytical agenda for this study

This study's analytical agenda is mostly informed by Tams et al. (2014) and Riedl et al. (2014a), who provided suggestions for ways to analyze multi-measured constructs and structural models. In particular, we perform tests to (a) reveal the relationship among different measures of immersion, and (b) show whether these measures together represent the whole construct of immersion. Additionally, this study investigates the effects of antecedents and consequences of immersion in a broader structural model. Therefore, we focus on intra-construct relationships, then inter-construct relationships.

Convergent validation

Convergent validation suggests that multiple methods should be used in the measurement validation process to help ensure that explained variance results from the constructs under investigation rather than the method used. Convergent validation presumes that different measures assess the same dimension of a construct, and to establish that, one needs to show they have extensive overlaps such that a significant and large positive correlation exists between them (Jick, 1979; Strube and Newman, 2007; Tabachnick and Fidell, 2007). If the measures neither correlate at a statistically significant nor at a high level, the measures do not have a common core and do

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[17] An independent researcher watched the recorded videos to make sure that the protocol was being followed correctly.

not assess the same dimension of a construct. However, in their review, Tams et al. (2014) do not present a cut-off threshold to indicate how high/large the correlations need to be.

Holistic representation

Holistic representation becomes relevant when there is no significant correlation between different construct's measures suggesting that each measurement might be capturing dissimilar but complementary dimensions of the construct (Jick, 1979). Tams et al. (2014) emphasize that the absence of correlation between measures should be interpreted carefully. It does not mean that there is a divergence between measures; one needs to perform additional empirical analysis to show whether the measures are complementary if used together, and they could explain a significant portion of the variance in an outcome. Simply put, the measures of the same construct could combine to predict complementary parts of the variance in a dependent variable and achieve a higher level of the explained variance than the use of any one measure alone (Tabachnick and Fidell, 2007).

Structural model analysis

As described earlier, this study goes beyond the intra-construct analysis and investigates immersion in a nomological network of antecedents (cognitive and affective engagement) and consequences (performance and satisfaction with IT). Therefore, not only the variance explained in the different measures of immersion will be presented, but also the predictive capability of each measure of immersion against two different forms of outcomes will be evaluated. Riedl et al. (2014a) stated the need for more utilization of structural equation modeling (SEM) in NeuroIS research because they can generate new knowledge and add new insights to the field's methodological conversations. In short, the third approach focuses on inter-construct relationships of (a) Neurophysiological measure on the psychometric measure; (b) psychometric measures on the neurophysiological measure; (c) psychometric measures on the psychometric measures, and (d) neurophysiological measures on the neurophysiological measures.

EEG and EDA analysis

The EEG data that were used in this study were obtained during the baseline activity (relaxing video clip) and the primary activity (game or house tour). A five-second time window before start time and end time was excluded for each subject to avoid lab operator's walk-ins and walk-outs interference with the subjects' attention on the activity. Next, the obtained EEG waves were filtered for eye-blink using the manufacturer's software plug-in. Furthermore, the software filtered data at low pass of 0.1 Hz and high pass of 100 Hz, then we obtained delta (0.1 Hz–3 Hz), theta (4 Hz–7 Hz), alpha (8 Hz–12 Hz), beta (12 Hz–30 Hz), and gamma (30 Hz–100 Hz) that were generated through a standard Fast Fourier Transformation (FFT) from the software. We log normalized the extracted EEG data and used average band power to estimate an "immersion index," which allowed us to obtain two separate immersion indexes for each participant based on their experience during the primary or baseline activity. For cognitive engagement, we used the relative power of gamma, which was obtained after applying the same filtration and proxies as the immersion index.

For the EDA, we followed a similar approach in that we first excluded time windows that were not part of the primary activity + a five-second window in the opening and closing of the activity; then we used the average number of the output for EDA.

Reliability and validity of psychometric measures

Psychometric measures were tested for reliability and validity. Results are provided in Appendix L. All psychometric measures passed standard reliability and validity measures of

Cronbach's alpha above 0.70, composite reliability above 0.70, with average variance extracted above 0.50 (Fornell and Larcker, 1981; Hair et al. 2006).

Full model analysis

We used PLS-SEM for analysis. PLS-SEM is a suitable tool when the analysis involves a combination of formative and reflective constructs, which is the case in this study. Table 12 summarizes the results of the analysis. By extension, we examined the theoretical model using 12 combinations of immersion measures and outcomes while keeping antecedents of immersion consistent across all models. Therefore, two measures of cognitive engagement (subjective and objective) and two measures of affective engagement (subjective and objective), consistently used as the independent variables of immersion, while we rotated immersion measures and outcomes for each model. Twelve models were tested: four combinations of immersion (EEG, psychometric, observational, and formative) multiplied by three measures of satisfaction and performance. In the analysis, we controlled for the effects of treatments, age, gender, session hour (time of the day when the experiment started to account for the fatigue), and the number of days since the first experiment (to account for the possibility of participants informing each other about how to excel in the experimental task). This section is organized as follows: First, we report the correlation of different construct's measures. Second, we report the effects of cognitive and affective engagement on immersion. Third, we report the results for the effect of immersion on performance and user satisfaction with IT. Finally, we report the structural model analysis results using the formative (aggregate) measure of immersion (EEG, perceived, and observational).

Correlation analysis (convergent validation)

The descriptive statistics (mean, standard deviation) and correlations among all constructs are presented in Appendix L (Table L2). We compared the correlations between different measures of the same construct. We found a non-significant correlation between objective and subjective measures of cognitive engagement ($\rho = 0.06$, $p = 0.43$). Likewise, we found no statistically meaningful correlation between measures of affective engagement ($\rho = 0.11$, $p = 0.30$). On the other hand, we found a significant correlation between the objective (EEG) and perceptual measures of immersion ($\rho = 0.19$, $p < 0.05$).

The observational immersion measures are based on different scales and capture non-overlapping aspects of users' obliviousness (Petter et al. 2007). Each type of immersion (Shallow, Middle, and Deep) captures the level of a user's attention through their obliviousness to the distractors. We estimated the user error in responding to the questions. The more errors participants made in responding to the questions, the higher the level of immersion. It is a sign that they are focusing on the main activity and becoming oblivious to the distractors. The observational immersion was estimated as a formative construct (formed by deep, shallow, and middle levels). After the estimation, we compared the correlation between observational and the other two measures. Results yielded a significant correlation between perceived immersion and observational measure of immersion ($\rho = 0.20$, $p < 0.05$). However, results did not show any significant correlations between EEG measure and the observational measure of immersion ($\rho = 0.05$, $p = 0.55$). Figure 10 provides a schematic diagram of the constructs and overlapping space between the measurements. By extension, Figure 10 represents the idea of different measurement tools capturing overlapping (or non-overlapping) pieces of a construct using a Venn diagram. The circles with names above them are constructs, while the circles with names under them are measures of that construct. Where the correlations are statistically larger, the inter-measurement overlaps are illustrated as bigger, and where the correlations are statistically small, the overlapping space is presented as smaller. For example, if the correlation between the two measures were zero, then there would be no overlapping space between different measures, meaning that each measure is capturing a totally unique part of the construct.

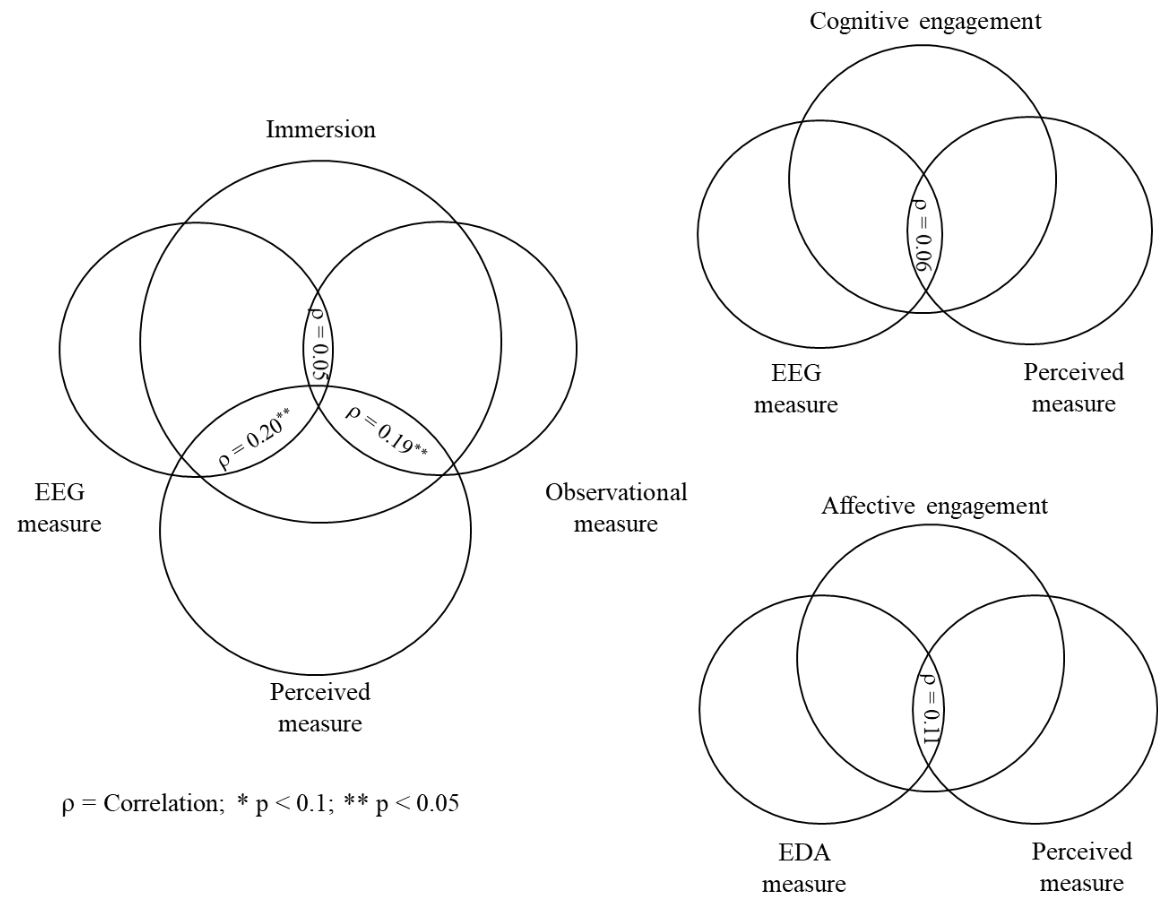

Figure 10. Venn diagrams illustrating overlapping variance.

Antecedents analysis

In this section, we focus on the effects of cognitive and affective engagement on EEG, psychometric, and observational measures of immersion. While table 12 presents the results for the full model analysis, the part that pertains to the antecedents of immersion are shown in the bottom-half of the table, where the first column lists the independent variables, and column M1 to M12 represents one out of four measures of immersion as the dependent variable for antecedents. We found that subjective measure of cognitive engagement ($B = 0.31$, $p < 0.01$) only influences perceived immersion, while objective cognitive engagement only influences the EEG measure of immersion ($B = 0.24$, $p < 0.01$). Furthermore, we found similar results for the effects of subjective affective engagement on perceived immersion ($B = 0.17$, $p < 0.05$) and objective affective engagement on EEG immersion ($B = 0.15$, $p < 0.10$).

Consequent analysis

The top-half of table 12 represents the effects of immersion, controls, and treatments on satisfaction and performance, where the first column lists the independent variables and column M1 to M12 are the dependent variables. Performance 1 (models 5-8) is a standardized combination of the completion time for the house group, and the total number of levels passed for each subject in the hedonic group. On the other hand, Performance 2 (models 9-12) combines the completion time for the house tour group with the average completion time to pass a level for the gaming group subjects. Regarding performance and satisfaction, we found that perceived immersion positively influences user satisfaction with IT ($B = 0.26$, $p < 0.01$), while other forms of immersion had no influence on this DV. However, for objective measure of performance, we found that the observational measure of immersion positively influences users' Performance 1 ($B = 0.17$, $p < 0.10$) and Performance 2 ($B = 0.15$, $p < 0.10$). Figure 11 illustrates the immersion measures' capability in predicting satisfaction and performance; in this figure similar to figure 10, the overlaps between different measures of immersion are presented, and the variance explained in the DV's are show with a smaller black and white circle within each DV.

Formative (aggregate) measure analysis

Moreover, when we created a formative (aggregate) measure of immersion that includes all three measures of immersion (EEG, perceived, and observational). The idea was to investigate whether these measures could be aggregated into a higher-order as Tams et al. (2014) suggested about ‘holistic representation’. We found that the combined formative measure of immersion positively influences perceived satisfaction with IT ($B = 0.28$, $p < 0.05$), but we did not observe such an effect on Performance 1 or Performance 2.

Cross effect analysis

In addition, we performed some cross-effect analysis[18] to see whether there is a statistically meaningful difference between the coefficients of the different measures (See Table 13). The results suggest that in almost all cases, the effects of subjective or objective measures of cognitive engagement differed across all forms of immersion. We found mixed results about the difference in the effects of perceived affective engagement and objective measure of affective engagement across immersion measures. Per Table 14, the most statistically meaningful relationship that we found was for the difference in the beta coefficient of perceived immersion on satisfaction versus on Performance 1 and Performance 2 ($\Delta B = 0.32$ and 0.29, $p < 0.01$). Further insights and implications are discussed in the next section.

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[18] We adopted Paternoster et al. (1998) approach for coefficient comparisons using this equation: $Z = \frac{b1-b2}{\sqrt{SE_{b1}^{2}+SE_{b2}^{2}}}$; where, b = standardized beta coefficient, and SE = Coefficient’s variance.

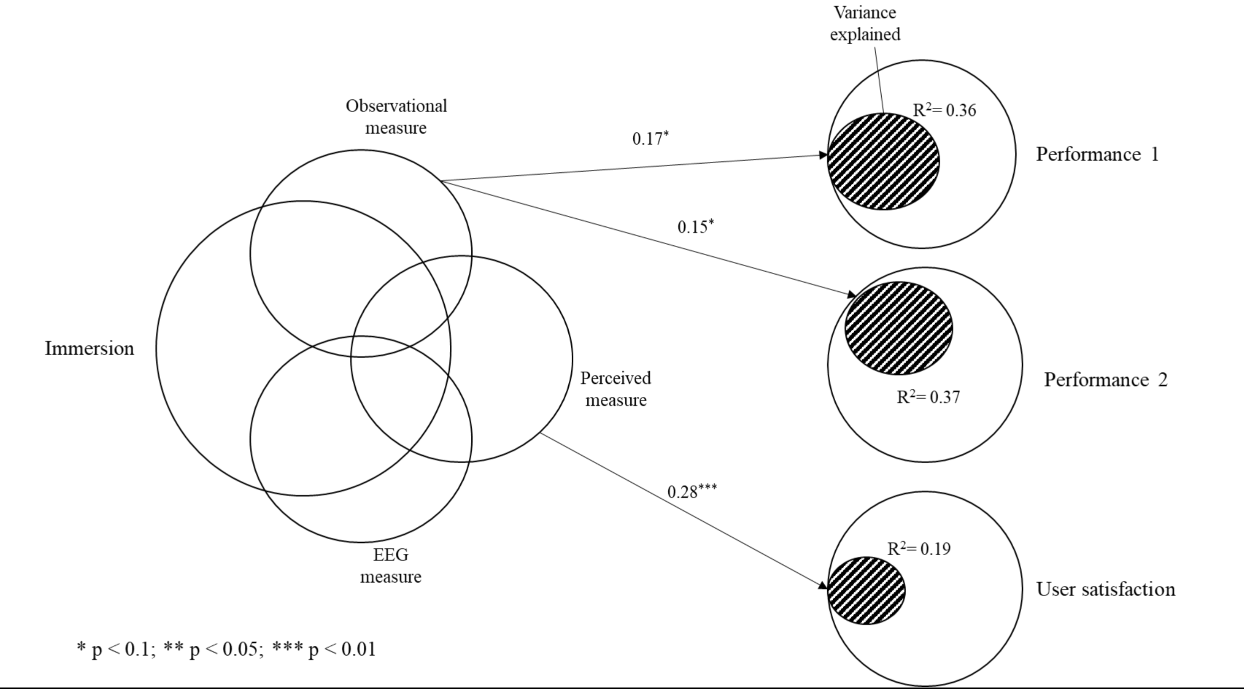

Figure 11. Predictive abilities of immersion measures.

Table 12. Results of the analyses for the combinations of different NeuroIS and psychometric tools on performance and satisfaction.

Independent variable:	Dependent variable:											
	M1	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	**M12**
	Satisfaction				**Performance 1**				**Performance 2**			
Age	-0.04	-0.06	-0.07	-0.10	0.06	0.06	0.01	0.03	0.03	0.03	-0.01	0.01
Gender	-0.04	-0.06	-0.06	-0.04	-0.10	-0.10	-0.10	-0.12	-0.10	-0.10	-0.11	-0.10
SesH	0.04	0.02	0.05	0.04	0.02	0.03	0.04	0.02	0.04	0.04	0.05	0.04
SesD	-0.04	-0.01	-0.04	-0.03	0.12	0.11	0.13	0.13	0.10	0.10	0.10	0.11
ED	-0.15*	-0.14*	-0.015*	-0.14*	-0.48***	-0.48***	-0.50***	-0.49	-0.50***	-0.50***	-0.51***	-0.49***
HG	0.01	-0.04	-0.05	-0.14	0.25***	0.26***	0.15*	0.20**	0.25***	0.25***	0.17*	0.20**
VP	-0.29***	-0.23***	-0.30***	-0.240**	0.06	0.03	0.10	0.10	0.01	-0.01	0.03	0.03
EImer	0.06				0.01				0.01			
SImer		0.26***				-0.06				-0.03		
OImer			0.10				0.17*				0.15*	
CoImer				0.28***				0.10				0.10
R^2	0.13	0.18	0.13	0.19	0.34	0.35	0.36	0.36	0.35	0.35	0.37	0.37
	EImer	**SImer**	**OImer**	**CoImer**	**EImer**	**SImer**	**OImer**	**CoImer**	**EImer**	**SImer**	**OImer**	**CoImer**
SCog	0.12	0.31***	-0.01	-0.001	0.12	0.31***	-0.01	-0.001	0.12	0.31***	-0.01	-0.001
OCog	0.24***	0.12	-0.01	0.001	0.24***	0.12	-0.01	0.001	0.24***	0.12	-0.01	0.001
SAff	0.05	0.17**	-0.01	0.001	0.05	0.17**	-0.01	0.001	0.05	0.17**	-0.01	0.001
OAff	0.15*	-0.01	-0.02*	0.001	0.15*	-0.01	-0.02*	0.001	0.15*	-0.01	-0.02*	0.001
Age	0.01	0.06	-0.02*	0.01	0.01	0.03	0.01	0.01	0.01	0.04	-0.02	0.01
Gender	-0.10	0.06	0.01	-0.01	-0.10	0.06	0.01	-0.01**	-0.10	0.06	0.01	-0.01
SesH	0.05	0.07	0.01	0.01	0.05	0.07	0.02	0.01	0.05	0.07	0.01	0.01
SesD	0.02	-0.14	0.02	-0.01	0.02	-0.17*	0.01	-0.01	0.02	-0.16*	0.02	-0.01
ED	-0.06	0.06	0.01	-0.01	-0.06	-0.05	-0.01	-0.01**	-0.06	0.06	-0.01	-0.01
HG	-0.05	0.10	0.01	0.01*	-0.05	0.10	0.01	0.01***	-0.05	0.10	0.01	0.01
VP	-0.35***	-0.26	0.01	-0.01	-0.35***	-0.27***	0.01	0.01*	-0.35***	-0.27***	0.01	0.01
R^2	0.31	0.29	-	-	0.31	0.29	-	-	0.31	0.29	-	-

Notes: N= 132;* $p < 0.10$. ** $p < 0.05$; *** $p < 0.01$. M = Model
SCog = Subjective cognitive engagement; OCog = Objective cognitive engagement (relative power of gamma); SAff = Subjective affective engagement; OAff = Objective affective engagement (EDA); SesH = Session hour; SesD = Number of days since start date; ED = Easy vs. difficult; HG = House vs. game; VP = Virtual reality vs. PC; EImer = EEG measure of immersion; SImer = Perceived immersion; OImer = Observational immersion; CoImer = Combined formative measure of immersion.
R^2 for M3, M4, M7, M8, M11, and M12 were 0.99 due to them being a formative measure with repeated-indicator analysis, thus not reported here.
Performance 1 = Completion time in minutes (multiplied by -1) for the utilitarian group and total number of levels passed for the hedonic group.
Performance 2 = Completion time in minutes (multiplied by -1) for the utilitarian group and average time in minutes (multiplied by -1) to pass a level for the hedonic group.

Table 13. Cross effect comparisons of the antecedents of immersion.

	EImer Vs. SImer	**EImer Vs. OImer**	**EImer Vs. CoImer**	**SImer Vs. OImer**	**SImer Vs. CoImer**	**OImer Vs. CoImer**
ΔSCog	-0.18^{**}	0.13^{**}	0.12^{**}	0.32^{***}	0.31^{***}	-0.01^{*}
ΔOCog	0.11	0.26^{***}	0.24^{***}	0.15^{***}	0.13^{**}	-0.01^{*}
ΔSAff	-0.13	0.07	0.05	0.19^{***}	0.17^{***}	-0.02^{***}
ΔOAff	0.16^{*}	0.17^{***}	0.15^{**}	0.010	-0.01	-0.02^{***}

Notes: N = 132;* p < 0.10. ** p < 0.05; *** p < 0.01; Δ = Coefficient differences (Z – test was used for comparisons).

SCog = Subjective cognitive engagement; OCog = Objective cognitive engagement (relative power of gamma); SAff = Subjective affective engagement; OAff = Objective affective engagement (EDA); EImer = EEG measure of immersion; SImer = Perceived immersion; OImer = Observational immersion; CoImer = Combined formative measure of immersion.

Table 14. Cross effect comparisons of the immersion measures.

	Satisfaction Vs. Performance 1	**Satisfaction Vs. Performance 2**	**Performance 1 Vs. Performance 2**
ΔEImer	0.05	0.05	0.001
ΔSImer	0.32^{***}	0.29^{***}	-0.03
ΔOImer	-0.07	-0.05	0.02
ΔCoImer	0.16^{*}	0.17^{*}	0.005

Notes: N = 132;* p < 0.10. ** p < 0.05; *** p < 0.01; Δ = Coefficient differences (Z – test was used for comparisons).

SCog = Subjective cognitive engagement; OCog = Objective cognitive engagement (relative power of gamma); SAff = Subjective affective engagement; OAff = Objective affective engagement (EDA);

Discussion

Multimethod studies are cherished in IS research (Venkatesh et al. 2013); they can greatly contribute to our understanding about complex IS- and IT-related phenomena. In addition, several NeuroIS studies have encouraged future researchers to not rely on a single measurement tool and data collection approach (Dimoka et al. 2011; Riedl et al. 2014a). Performing a multimethod NeuroIS study can enrich our understanding of complex phenomena. In this study, we attempted to address two identified gaps concerned with (a) the relation of neurophysiological and psychometric tests and (b) the possibility of aggregating them into a higher-order construct with the goal of providing a superior explanation for the phenomenon of interest. We conducted an extensive lab experiment with 132 human subjects and collected data using EEG, ECG, and psychometric tools. We found both interesting and conflicting results about the nature of the relationship between measurement tools of immersion.

Insights into measurement convergence

We found perceived immersion to be significantly correlated with both EEG measure of immersion and the observational measure of immersion, thus showing the value of the perceptual measure as an alternative to both EEG and observational measures of immersion, and the complementary (non-related) nature of EEG and observational measures relative to each other. Additionally, the result yielded a non-significant correlation between objective and subjective measures of cognitive engagement, and we did not find any significant relationship between objective and subjective measures of affective engagement. These findings together show the complementary nature of engagement measures in relation to their respective constructs. As Riedl et al. (2014) stated: "failure to find a relation between measures is—often wrongly—interpreted as a missing relationship between constructs" (p. xv), thus not finding a significant correlation could mean these measures are capturing part of the construct (also known as incomplete representation of a construct; Straub and Newman, 2007). Moreover, the lack of a significant correlation between neurophysiological and psychometric tools is not uncommon (Tams et al. 2014).

Insights into holistic representation and measurement aggregationAntecedents of immersion

After exploring correlations, we tested several combinations of immersion measures and performance measures in which immersion was positioned at the center and examined against antecedents and consequences. Again, we found some insightful and contrary results. In terms of antecedents, we found that, for the most part, subjective engagement measures only influence subjective immersion, while objective measures influence EEG immersion. For example, perceived cognitive engagement and perceived affective engagement positively influenced perceived immersion. However, only the objective measure of cognitive engagement positively influenced the EEG measure of immersion. One theoretical explanation for not finding a cross effect between neurophysiological and non-neurophysiological measures is the consistency in bias within the tool. For example, assuming psychometric tools are suffering from social desirability and leniency effects (Podsakoff et al. 2003), then this effect is present in perceive engagement and perceived immersion. The consistency of bias within the tool could homogenize measurement errors of each construct and possibly lead to inter-construct correlations and finding statistically significant causal relationships between psychometric measures (or between neurophysiological measures). However, the EEG data bias could be due to physiological factors (Melnik et al. 2017), not social desirability nor leniency (or any other biases in psychometric tools). Inconsistency between the nature of biases in the tools would influence the causal effect of one on the other—leads to finding no statistically meaningful correlations or causal effects. An alternative view is that the EEG measure we adopted did not fully capture the essence of immersion, which ties to obliviousness. By extension, we theorized that attention suppression represents the attention shift from the primary activity to distractors, thus accounts for the obliviousness if beta decreases and alpha plus theta increases; however, results did not confirm this conceptualization.

Consequences of immersion

Much like the effects of antecedents on immersion, for the effects of immersion on performance, we found that psychometrically measured constructs influenced the other psychometrically measured constructs (perceived immersion positively influences perceived satisfaction with IT). While we did not find any effects for EEG measure of immersion on satisfaction and performance, we found that the observational measure of immersion positively influences both objective measures of performance. During the experiment, if users paid more attention to the distractors, their task completion time and error rate increased. This has a few implications for theory and practice. First, it confirms our conceptualization about the obliviousness aspect of immersion, which could not be captured using the existing psychometric measures of immersion . For example, a user may "believe" or think they were paying attention to the primary activity (reporting high score on perceived engagement) and were oblivious to other attentional demands, but in fact they were not oblivious to all background noises and underperformed as the empirical results depicted.

These finding opens up the discussion about the limitations of self-report measures, one being self-report bias (Dimoka et al. 2011). Second, the non-significant effects of the EEG measure of immersion and the significant effects of the observational measure of immersion together indicate the importance of the observational measure over the EEG measure. Not finding any effects from EEG on the three outcome variables raises questions about this measure. Considering the (i) low effect size correlation between immersion measures; (ii) insensitivity of perceived immersion to user's obliviousness; and (iii) the inability of EEG measure of immersion to show predictive validity, we conclude that the observational measure of immersion is the most representative measure of the immersion construct. Besides, one could argue that the neurophysiological measures are prone to bias, similar to psychometric tools (common method bias). Melnik et al. (2017) investigated the effects of systems (EEG devices), subjects, and sessions on the EEG data and found that systems[19] are producing a relatively small variance in the data, but subjects are the primary source of creating a variance in the outputs such that they could account for over 30% of

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[19] They used two standard research-grade EEG systems, one EEG system designed for mobile use with dry electrodes, and an affordable mobile EEG system with a lower channel count.

the variance. Thereby, EEG data is not completely liberated from bias. This bias could affect content validity—increasing the error in covering the construct domain. In summary, although immersion index (EEG measure of immersion) has been adopted in attention and distraction studies (Freeman et al. 2004), further research is needed to validate this measure's capabilities.

Aggregated immersion

Not finding correlations and conflicting results about the effects of psychometric and EEG measures on performance motivated us to explore whether these three measures form a higher-order concept, which we decided to put into a statistical test. We found that the aggregated (third-order formative) construct of immersion positively influences users' satisfaction with IT, and slightly contributed to the R^2. However, no such effect was found for the effect of formative measure of immersion on performance. Exploring aggregating measures has been encouraged by recent NeuroIS studies (Riedl et al. 2014a; Tams et al. 2014), but we did not find strong statistical and considerable results for such a relationship among different measures of immersion; only a marginal improvement (in terms of R^2) for the effects of the aggregated measure on perceived satisfaction. One theoretical explanation could be that once the measures are aggregated to represent a construct holistically, their errors are aggregated as well. Therefore, if any of the measures are inefficient in capturing the domain of immersion as defined, the aggregated measurement error within the construct would be high, and the construct would be unable to predict an outcome accurately.

Contributions and implications

This study collected data during the experiment through EEG, EDA, objective performance measures, and psychometric tools to test a theoretical model of engagement, immersion, and performance in a nomological network of antecedents and consequences. In light of our findings, this study contributes to the methodological research convergence and relationships of neurophysiological and psychometric tools. First, this study highlighted the importance of realizing that the neurophysiological measures are not liberated from bias. The subject's physiological and psychological conditions can introduce biases to both psychometric (Podsakoff et al. 2003) and neurophysiological data (Melnik et al. 2017), such that the variances could minimize the overlapping domains between the different measures of the same construct (e.g., EEG immersion and observational immersion), and subsequently between the construct and every single measure (Immersion construct and EEG measure of immersion; see figure 10).

Second, there are a myriad of analytical approaches for analyzing neurophysiological data, as diverse as any other statistical tool in IS research. However, leveraging structural equation modeling to investigate complex models has been encouraged as being informative and insightful in shedding light on the phenomenon of interest (Riedl et al. 2014a). This study is one of the few that adopted PLS-SEM in analyzing a complex model that integrated EEG, EDA, and psychometric measures as another small step to bring new insights to NeuroIS literature. The structural equation modeling enriched our knowledge about the predictive ability of neuro measures beyond other neuro measures. Accordingly, several models were tested to reveal a causal relationship between (a) neurophysiological measure on the psychometric measure; (b) psychometric measure on the neurophysiological measure; (c) psychometric measure on the psychometric measure, and (d) neurophysiological measure on the neurophysiological measure.

Third, the findings highlight the potential importance of observational measure, suggesting the need to examine it, and its antecedents, further. By extension, our observational measure of immersion was developed based on the assumption that when someone is focused on an activity, they should ignore distractors, and if they are asked about them, they should not remember if immersed. The perceived measure of immersion does not account for the fact that the human brain processes environmental stimuli involuntary and sometimes with delays; therefore the subject may believe they were focused on the attention while in fact, their brain was processing the distractors. This effect was demonstrated by showing an increase in immersion as the result of ignoring distractors, leading to the increase of objective performance (shorter task completion time and passing more levels in the game).

Fourth, this study showed different measures of the same construct might not collectively represent the construct entirely. In particular, by formatively combining neurophysiological and psychometric measures, in addition to combining the capability of each measurement in capturing a piece of the construct, the different sources of bias from each tool are aggregated. The aggregated biases within the aggregated construct could prevent it from predicting an outcome variable. Future studies need to pay attention to the issues regarding aggregated biases of different natures (e.g., physiological and psychological). Table 15 summarizes the most important implications for future studies.

Table 15. Summary of the findings and implications for measurement

	Results	Implications	Future studies considerations
Intra construct measurement	➢ Small correlation (low effect size) between different measures of immersion. ➢ Aggregated (formative) construct of immersion did not represent the concept as a whole. Results did not show any statistically superior predictive validity of the aggregated immersion.	✓ Different measures of the same construct might not collectively represent the construct entirely.	• Use consistent measures of the same kind for a construct. • Diversify inter construct measurements instead of intra construct measurements where possible.
	➢ The observational immersion measure was the only measure that was sensitive to other attentional demands (aural noises in this study), given the low correlations between observational immersion and other measures of immersion. ➢ Observational immersion measure was the only immersion measure that influenced performance. ➢ Existing psychometric measures of immersion were unable to fully capture the "obliviousness to other attentional demands," which is an integral part of immersion.	✓ The observational immersion is the most logical representative operationalization of the immersion, given its sensitivity to distractors and showing an effect on performance. ✓ The psychometric measure of immersion should be revisited since it was not very sensitive to the distractors used in this study (logically, attending to distractors should lower both performance and immersion).	• The proposed observational measure of immersion should be used instead of the existing psychometric measure because it is more sensitive to the distractors.
Inter construct	➢ There are causal relationships between measures of the same kind. ➢ Psychometrically measured IV influenced psychometrically measured DV. ➢ Neurophysiologically measured IV influenced neurophysiologically measured DV.	✓ This study highlighted the importance of realizing that the neurophysiological measures are not liberated from bias. ✓ The consistency of bias within the tool could homogenize measurement errors of each construct and possibly lead to inter-construct correlations and finding statistically significant causal relationships between variables of the same kind.	• In the research design phase implement ways to account for neurophysiological measurement bias. • Perform tests to mitigate measurement bias.

With respect to engagement, immersion, and performance, our findings contribute to the discussion of how cutting-edge technologies influence user performance and behavior. Immersive technologies are some of the few that have shown great potential for resolving business problems (Morris, 2020), and one of the implications of our findings is that distraction is harmful to user performance since users sometimes do not perceive that they are distracted. A managerial implication of our finding is that, while through self-reports an employee, user, or customer might claim they are focusing on their activity, more objective measures can put their self-reports in check, which favors businesses. Distractions and interruptions in the workplace are challenges to performance (Addas and Pinsonneault 2015, 2018), and our research design highlights the impact of distractors on user performance. Another implication for NeuroIS researchers is that the objective measures may potentially present a similar explanation to a phenomenon as does psychometric measures. An empirical parallelism in the effects of subjective measures on the subjective outcomes and objective measures on the objective outcomes highlighted this potential capability in providing parallel explanations if used. Therefore, possibly if the psychometric studies in IS are replicated using objective measures, the results should be consistent.

Limitations and future studies

This study should be seen in light of its limitations. First, finding applications that work across platforms (VR vs. desktop computer) was an arduous task since there are limited utilitarian and hedonic apps available that work across platforms. This limitation itself minimized the pool of applications that were available to be used in the experiment. Second, this study used a single sensory EEG device. While the device's accuracy has been compared to 10–20 traditional systems and found to be of high quality and accuracy, there are still inherent limitations to using one sensor, as it does not inform the study about how other areas of the brain function. Third, we only asked subjects to complete a baseline task and a primary task, which limited our resulting data collection about different conditions under which EEG waves reflect the brain activity.

We encourage future studies to explore the possibility of (a) parallelism between results if a model is tested using fully objective or fully subjective measures; (b) non-linear relationships between neurophysiological and psychometric measures. A basic scatter plot of our data suggested that some effects could be curvilinear, and this needs to be investigated further with sound and solid theoretical justifications; (c) forming an aggregated (second- or third-order formative) measure certainly has benefits, and future studies should explore this possibility.

Conclusion

In conclusion, NeuroIS is very young compared to neuroscience studies and is evolving rapidly. Against this backdrop, there is a dearth of studies on methodological triangulation between neurophysiological and psychometric tools, which we investigated. This study's findings offered two broad implications for measurement and future methodological NeuroIS studies, as depicted in Table 15. These could be discussed in two categories: Intra construct measurement and inter construct measurement.

First, for intra construct measurement, we found small correlations between the immersion measures and that the aggregated immersion measures did not offer any statistically superior predictive capability compared to each measure alone. Therefore, one implication of these findings is that different measurement approaches for the same construct might not collectively represent the construct as a whole. We encourage future NeuroIS studies to use consistent measures of the same kind for a construct and instead try to diversify inter construct measurements (e.g., psychometric measures for construct A and neurophysiological for construct B in the theoretical model).

Furthermore, the newly proposed observational measure of immersion represented a more theoretically sound approach in capturing immersion as a concept, which is the obliviousness to other attentional demands and showing its effect on performance. One immediate implication is that the newly proposed measures of immersion should be used instead of the psychometric measures, because logically, being distracted should show an effect on the user performance, but the psychometric measure is insensitive to that. However, existing psychometric measures of immersion did not show any effects on user performance, which highlights the fact that they did not fully capture the obliviousness aspect. We encourage future studies to develop new and more robust psychometric measures of immersion.

Second, with respect to inter construct measurement, in testing the causal effects between constructs, we found measures of the same kind only influence each other (e.g., psychometrically measured IV influences psychometrically measured DV). The implication for future methodological studies is that neurophysiological measures are not free of bias like the psychometric measures, but the source of bias is indeed different. We found no study in NeuroIS that raises concern about bias in neurophysiological measures or ways to address and mitigate that in the analysis perhaps because such model testings are rare and there is room for further investigations. Hence, we need future studies to find ways for addressing measurement bias in neurophysiological measures similar to the existing ones in psychometric tools (e.g., common method variance). This should be done in the study design and subsequently in the analytical phase. As Melnik et al. (2017) mentioned, the sources of bias could be identified for EEG studies, and then the researcher can adopt ways to diagnose.

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Appendix

Appendix I: Distractors

In order to create realistic distractors that employees deal with in their day to day activities, we reviewed the literature on interruption and distraction. In particular, we focused on IT-based distractors and used Hughes et al. (2013) and Addas and Pinsonneault (2015, 2018) guidelines to develop our distractors. We selected two forms of audio noises to be played in the room in the form of internal and external sounds a minute after the subject started doing the main task. To have business relevancy and/or replicate the natural environment of the user, we selected the most representative day to day distractors at the workplace and user environment. For example, iPhone text sound is so distractive that if someone's phone is not on silent mode and receives a text, others would start checking their phones as well because they might think the sound was theirs. Or perhaps hallway chitchats of colleagues passing by and talking about things that are irrelevant to you or your job.

The first distractor that we selected is the iPhone text message sound. We created a sound file with 10 iPhone text sounds and played it every 15 seconds on the user VR goggle or computer desktop. The second one is a series of irrelevant pieces of information, each of which is played every 15 seconds. We recruited four students and recorded their voices reading the following five sentences:

1. Todays' weather is 75^{o} Fahrenheit.
2. United Nations will have a meeting for climate change.
3. Super Bowl game will be delayed.
4. The Dow Jones index increased by 1%.
5. Oil price has increased by 1%.

Then we created a set of five, and played each set of five sentences with different gender and accent combinations every 15 seconds. We used a separate pair of speakers that were installed in the corner of the room away from the user to convey the externality of the sound to the desktop or VR goggles. It should be mentioned that the desktop computer had its own pair of speakers that were in front of the monitor. Also, the Oculus Rift S (VR goggle) that we used in this research comes with 3D environmental headphones that wrap around the user's heads but does not cover their ears to block environmental sound factor. Therefore, there was no technological obstacle on the way of distractor sound to reach out to the user.

Appendix J: Experiment scenarios

Table J1. House hunting scenario for difficult group (Easy group presented with House A - D).

You will perform a house hunting task. In the house hunting task, your goal is to buy a house based on your preferences. The cost of the houses does not play a role and you can select any houses that you like to buy! Try to spend enough time to select the house that matches with your preferences from the available options on the second page. So, your objectives are:

1. Review the available options on the second page and select one house that you like. Complete the task carefully. Try to be quick but spend necessary time to learn about details of the available options.
2. Inform the person in charge about the option that you selected.
3. On the score column in the table (page 2) rank the importance of each option to you by distributing 100 points between the available options, but the total sum of the scores for all options must be hundred so try to spend necessary times in distributing scores based on importance (e.g. if cabinet color is more important to you than number of floors in the house then you should give cabinet color more points).
4. After giving scores to these options inform the person in charge.
5. You have to visit the same houses using 3D technology and then find the house that you selected on the paper from the available options in page 2 (this will be the house that you want to buy)!

I addition, you will be asked a couple of questions about the details of each house if you answer them correctly, you will receive an extra $2 on this task. So do your best to learn about each house and their differences.

Please select one of the houses that matches with your preferences. Select the one that you like the most from the table on the second page!

Score	**Factor**	**House A**	**House B**	**House C**	**House D**	**House E**	**House F**	**House G**	**House H**
	Average Room sizes (Sq/ft)	150	250	250	200	250	300	250	200
	# of Bathrooms	4.25	5	4	4	4	6	5	3
	Floors	2	2	2	3	3	2	2	2
	Decoration level	Half-furnished	Full furnished	Half-furnished	Full furnished	Full furnished	Full furnished	Full furnished	Full furnished
	Living room	Small; no TV	Large; has TV	Medium; no TV	Average; has TV	Large; has TV	Large	Large; has TV	Small; has TV
	Kitchen Size	Small	Large	Small	Large	Medium	Large	Medium	Small
	Kitchen style	Island open	Island open	Island open	Open	Island open	Island open	Island open	Open
	Pantry	Yes	No	No	Yes	No	No	No	No
	Kitchen window	1	2	0	1	1	1	0	1
	Laundry room	Small; 2nd floor.	Large; 2nd floor.	Small; 2nd floor.	Small; 3rd floor	Small; 1st floor; part of bathroom	Large; 2nd floor.	Medium; 2nd floor.	Small; 1st floor.

Table J1. House hunting scenario for difficult group (Easy group presented with House A – D; Cont.).

Score	Factor	House A	House B	House C	House D	House E	House F	House G	House H
	Living room sunlight	Great day light penetration	Great day light penetration	Great day light penetration	Average day light penetration	Average day light penetration	Great day light penetration	Great day light penetration	Weak day light penetration
	Dining room/area	Has one large that is near the kitchen	Has two: one large separate from kitchen; one small close to kitchen	Has one large that is near the kitchen	Has one large that is near the kitchen	Has one large that is near the kitchen	Has two: one large separate from kitchen; one small near the kitchen	Has two: one large separate from kitchen; one small near the kitchen	One large separate from kitchen
	# of Bedrooms	5	4	5	3	3	5	4	4
	BBQ	Yes	Yes	No	No	No	Yes	1	1
	Balcony	2 (Front and rear)	None	1	3	2	1	1	1
	Patio	1	2	1	1	1	1	3	2
	Backyard size	Very Small	None	Very Small	None	None	None	Average	Small
	Pool	No	No	No	No	No	No	No	Yes
	Kitchen cabinets	White	Dark brown	Brown	White tile	Dark brown	Brown	White	Dark brown
	Exterior color theme	White	Brown	Cream / Brown	cream / orange	White	Yellow / cream	Beige	White / brwon
	Interior decoration color theme	Blue	Dark brown / blue	White	Light grey	White	White / light grey	White	Mixed
	Floor material	Light brown parquet	Dark brown parquet	Brown parquet	White tile	Cream parquet	White tile	Dark brown parquet	Brown tile

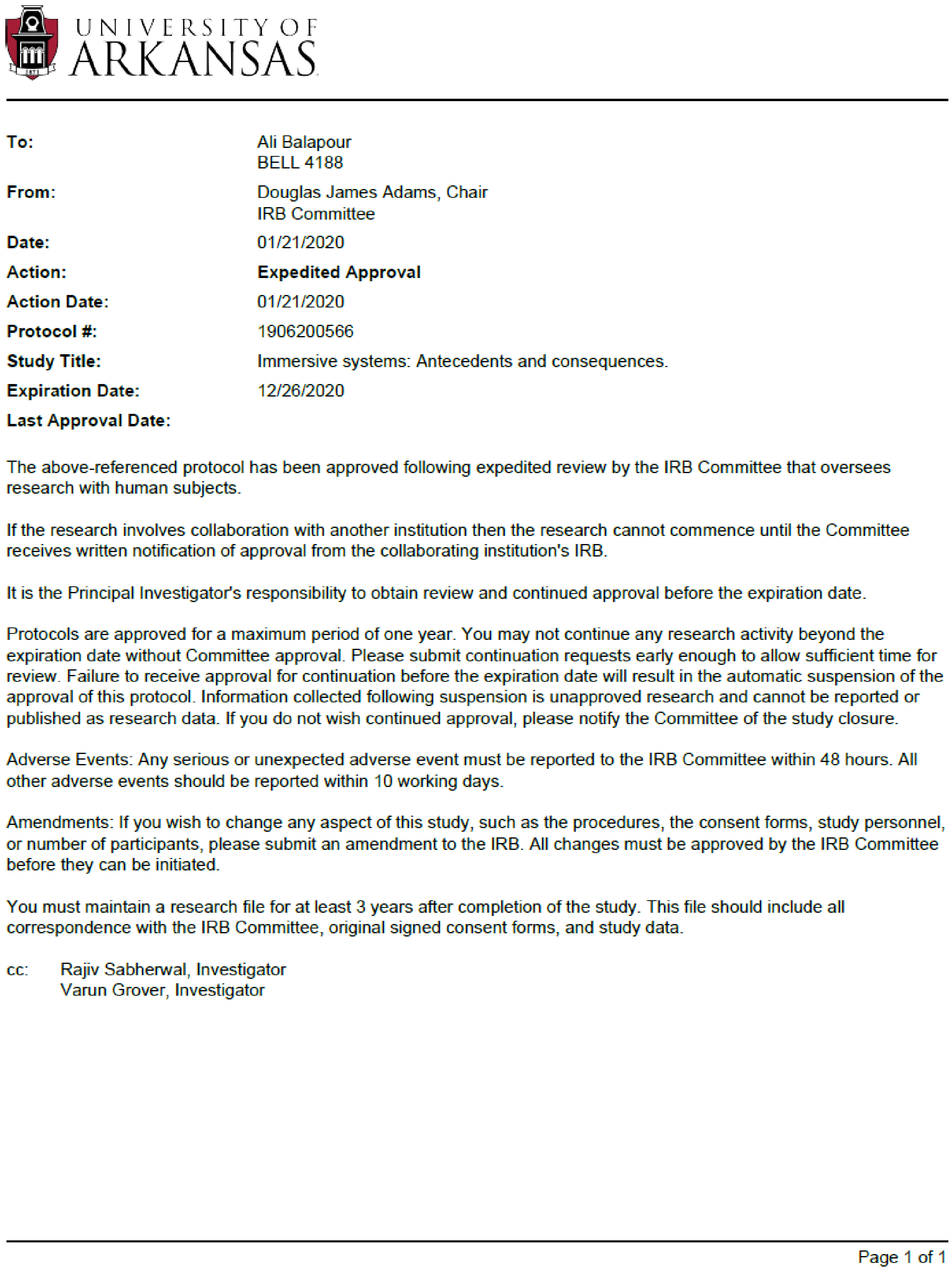
Table J2. Game scenario.

You shouldplay a video game called SuperHot. Your goal in the gaming task is to:

- Kill enemies in each round in the shortest time possible and pass as many levels as you can.
- You are immortal in the game, but you have to redo each round when you die. Try to minimize the number of times you die by carefully assessing the situation of your enemies in each round. You will continue playing until the lab operator instruct you to stop (approximately for 10 minutes).

If you die less than three times (not more than that) throughout the whole task you will receive extra $2.

Appendix K: IRB approval



UNIVERSITY OF
ARKANSAS

To:	Ali Balapour BELL 4188
From:	Douglas James Adams, Chair IRB Committee
Date:	01/21/2020
Action:	**Expedited Approval**
Action Date:	01/21/2020
Protocol #:	1906200566
Study Title:	Immersive systems: Antecedents and consequences.
Expiration Date:	12/26/2020
Last Approval Date:	

The above-referenced protocol has been approved following expedited review by the IRB Committee that oversees research with human subjects.

If the research involves collaboration with another institution then the research cannot commence until the Committee receives written notification of approval from the collaborating institution's IRB.

It is the Principal Investigator's responsibility to obtain review and continued approval before the expiration date.

Protocols are approved for a maximum period of one year. You may not continue any research activity beyond the expiration date without Committee approval. Please submit continuation requests early enough to allow sufficient time for review. Failure to receive approval for continuation before the expiration date will result in the automatic suspension of the approval of this protocol. Information collected following suspension is unapproved research and cannot be reported or published as research data. If you do not wish continued approval, please notify the Committee of the study closure.

Adverse Events: Any serious or unexpected adverse event must be reported to the IRB Committee within 48 hours. All other adverse events should be reported within 10 working days.

Amendments: If you wish to change any aspect of this study, such as the procedures, the consent forms, study personnel, or number of participants, please submit an amendment to the IRB. All changes must be approved by the IRB Committee before they can be initiated.

You must maintain a research file for at least 3 years after completion of the study. This file should include all correspondence with the IRB Committee, original signed consent forms, and study data.

cc: Rajiv Sabherwal, Investigator
Varun Grover, Investigator

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Appendix L: Factor analysis, reliability and validity, and correlations.

Table L1. Factor analysis.

	Mean	**SD**	**Cognitive engagement**	**Affective engagement**	**Subjective Immersion**	**Perceived satisfaction**
CogEng1	5.75	0.99	0.881	0.282	0.316	0.139
CogEng2	6.04	0.95	0.869	0.140	0.373	0.155
AffEng1	6.17	1.09	0.203	0.826	0.245	0.618
AffEng2	5.49	1.43	0.184	0.916	0.254	0.615
AffEng3	5.49	1.36	0.259	0.878	0.295	0.546
AffEng4	5.56	1.34	0.199	0.844	0.271	0.414
OldImer1	5.23	1.33	0.220	0.214	0.734	0.296
OldImer2	4.70	1.62	0.338	0.241	0.785	0.212
OldImer3	5.52	1.25	0.367	0.273	0.847	0.270
Sat1	6.04	1.07	0.188	0.575	0.339	0.936
Sat2	5.62	1.32	0.184	0.644	0.304	0.932
Sat3	6.09	1.08	0.089	0.513	0.258	0.909

CogEng = Cognitive engagement; AffEng = Affective engagement; MedRich = Media Richness; OldImer = Subjective Immersion; Sat = Satisfaction with IT.

Table L2. AVEs, correlations, and reliabilities.

Construct	**Mean**	**SD**	**C.R.**	**C.A.**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1.Perceived cognitive Engagement	5.89	0.85	0.87	0.70	**0.88**									
2.Perceived affective engagement	5.68	1.13	0.92	0.89	0.24^{***}	**0.86**								
3.Objective cognitive engagement (RPG)	0.28	0.07	-	-	0.06	0.19^{**}	-							
4.Objective affective engagement (EDA)	1.75	1.87	-	-	0.01	0.11	0.04	-						
5.Objective immersion	0.48	0.20	-	-	0.18^{**}	0.21^{**}	0.29^{***}	0.23^{***}	-					
6.Perceived immersion	5.15	1.10	0.87	0.70	0.39^{**}	0.31^{***}	0.20^{**}	0.08	0.19^{**}	**0.79**				
7.Observational immersion	0.00^{+}	0.62	-	-	0.12	0.4	0.02	0.04	0.05	0.20^{**}	-			
8.Perceived satisfaction	5.91	1.07	0.91	0.94	0.17^{*}	0.63^{***}	0.28^{***}	0.18^{**}	0.21^{**}	0.33^{***}	0.07	-		
9.Performance 1	-0.31	1.10	-	-	-0.06	0.04	0.01	-0.01	0.05	0.03	0.20^{**}	0.14	-	
10.Performance 2	-0.30	1.12	-	-	-0.11	-0.01	-0.02	-0.03	0.02	-0.01	0.21^{**}	0.10	0.97^{***}	-

Note: N = 132; * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; $^{+}$ Standardized score; C.R. = Composite reliability; C.A. = Cronbach's alpha; diagonal is the square root of average variance extracted (AVE); RPG = Relative power of gamma; EDA = Electrodermal activity measure.

Appendix M: Task description.

We selected Superhot in this experiment, which is a widely played, easy to learn, first-person shooter game. The game was available on both VR and PC computer, which worked well with our experimental set up since we needed software that would be compatible with both VR and desktop computers. In addition, we identified level 1-5 as being easy enough for subjects to immediately play with limited training, but level 5+ was selected for the difficult group in which we knew the user is going to be challenged based on a few pilot tests. In addition, we selected a virtual house tour task in which subjects had to either visit four (easy) or eight (difficult) houses depending on their assigned group. The software used is called Transported, which is available both on VR and the web (PC). The difficulty levels of the house tour task were calibrated through a few rounds of pilots.

Chapter 4: Conclusion

The dissertation is motivated by contributing to two ongoing streams of research on immersive systems and NeuroIS. Business needs are evolving, and so is technology in response. Immersive technologies are one of the most rapidly evolving technologies in the business landscape. After a few decades of study on immersive technologies (Slater, 1999), IS scholars have only recently embraced their impact on individuals, businesses, and organizations (Cavusoglo et al. 2019), partly because they have not been as accessible and affordable as they are today. Our literature review revealed several gaps and research questions, which we tried to address in two essays.

Chapter 2 (Essay 1)

Essay 1 is primarily focused on reconceptualizing “immersion.” We argue that this concept has not received the attention it merits, and it has not been clearly defined (Suh & Prophet, 2018). Motivated to address this problem, we reviewed the literature on immersion. We identified six problems with existing definitions and provided a comprehensive definition to avoid common mistakes in conceptualization. Furthermore, past works on immersion informed us that there are several antecedents (and consequences) of immersion, which helped us in categorizing antecedents into three forms of sensory, cognitive, and affective engagements.

In this essay, we designed and conducted a lab experiment. In particular, we measured the concept of immersion, sensory engagement, cognitive engagement, affective engagement, and user performance through a combination of objective (EEG, ECG, log data) and subjective (survey-based) methods. In the experimental design, we implemented three treatments: technology type (VR vs. PC), task type (utilitarian vs. hedonic), and task difficulty (easy vs. difficult). Furthermore, we implemented naturalistic distractors that one could find in their day-to-day life that were central to measuring immersion per the newly provided definition.

The result yielded that immersion positively influences performance. The difference between the objective and subjective measure of immersion was that the objective measure showed a curvilinear (U-shaped) relationship with performance, meaning that immersion boosts performance exponentially from a certain point. Furthermore, we found that all three theorized forms of engagement positively influence immersion.

These findings have implications for reactionaries and contribute to the stream of literature on immersion. By extension, for developers or investors of immersive technologies, it is essential to calibrate the level of immersion to help with user performance. The immersion index in this study is one of the tools that serve this purpose. Additionally, the concept of immersion thus far has only been measured using traditional psychometric tools (seven-point Likert scale). Providing an index and trying to conceptualize and measure the concept could objectively be considered an advancement in theatrical developments around this topic.

Chapter 3 (Essay 2)

In Essay 2, we investigate the relationship between neurophysiological and psychometric tools. This study's findings suggest that, by and large, psychometric tools only affect each other, while in parallel, neurophysiological tools influence each other. In addition, neurophysiological psychometric tools are occasionally correlated, and these correlations were found to be weak.

This study contributes to the methodological studies on convergence and the relationships of neurophysiological and psychometric tools by: 1) investigating the phenomenon of interest using several data collection approaches. Accordingly, we collected data during the experiment through EEG, EDA, objective performance measures, and psychometric tools. Not only did we compare and contrast the relationship between EEG and psychometric measures, but we also explored the correlation and overlaps between EDA and its corresponding psychometric measures; 2) this study explored one of the areas in which future NeuroIS studies have been encouraged: measurement aggregation and a combination of psychometric, hybrid, and EEG measures; 3) leveraging structural equation modeling to investigate complex models has been encouraged as being informative and insightful to NeuroIS studies (Riedl et al. 2014a). Essay 2 is one of the few that adopted PLS-SEM in analyzing a complex model that integrated EEG, EDA, and psychometric measures as another small step to bringing new insights to NeuroIS literature.