Computers in Human Behavior 29 (2013) 1054–1064

Contents lists available at SciVerse ScienceDirect

Computers in Human Behavior

journal homepage: www.elsevier.com/locate/comphumbeh

Lost in space? Cognitive fit and cognitive load in 3D virtual environments

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ARTICLE INFO

Article history:
Available online 7 November 2012

Keywords:
3D virtual environment
Cognitive fit
Cognitive load
Individual understanding
Shared understanding
Group decision making

ABSTRACT

In this paper, we explore how visual representations of information in 3D virtual environments (3DVEs) supports both individual and shared understanding, and consequently contribute to group decision making in tasks with a strong visual component. We integrate insights from cognitive fit theory and cognitive load theory in order to formulate hypotheses about how 3DVEs can contribute to individual understanding, shared understanding, and group decision making. We discuss the results of an experiment in which 192 participants, in 3-person teams, were asked to select an apartment. As proposed by *cognitive fit theory*, our results indicate that 3DVEs are indeed more effective in supporting individual understanding than 2D information presentations. Next, in line with *cognitive load theory*, the static presentation of 3D information turns out to be more effective in supporting shared understanding and group decision making than an immersive 3DVE. Our results suggest that although the 3DVE capabilities of realism, immersion and interactivity contribute to individual understanding, these capabilities combined with the interaction and negotiation processes required for reaching a shared understanding (and group decision), increases cognitive load and makes group processes inefficient. The implications of this paper for research and practice are discussed.

1. Introduction

In 2006, Starwood Hotels was one of the first chains to establish a hotel in the 3D virtual world *Second Life* (Jana, 2006). The purpose of this 3D visualization was to gain feedback from potential customers about the hotel's design features. This feedback could then be incorporated in the physical design of the hotel, reducing the costs of building a prototype in real life. Currently, 3D modeling techniques for the design, construction and purchase of physical objects are becoming increasingly popular in different sectors, from real estate agents to IKEA (Morrisson & Skjulstadt, 2010), construction firms (Li et al., 2008) and architects (Boland, Lyytinen, & Yoo, 2007), manufacturers in the automotive and aerospace industry (Regenbrecht, Baratoff, & Wilke, 2005) and many others. While the product of interest may differ between these companies, the main implications of using a 3D tool is to help visualize the physical end results, be it a prospective IKEA kitchen, a newly built or renovated house, a car or an airplane. Basically, the idea is that visualization in a 3D virtual space helps provide a better *understanding* of what a product will look like in a physical space, how it will function, and what its most important design parameters will be.

Besides this *individual understanding* of the specifics of an object or environment, 3D visualization can also affect the *shared understanding* among members of groups, teams or innovation networks (Boland et al., 2007). The emergence of collaborative 3D virtual environments such as Second Life, Active Worlds and Teleplace has also made 3D visualization available for team work (Wirth, Feldberg, Schouten, Van den Hooff, & Williams, 2011). Group decision making in virtual teams can be enhanced by using 3D virtual environments because they offer a higher sense of social presence and provide multiple cues which, in turn, creates a higher degree of immersion in the environment (Schouten, Van den Hooff, & Feldberg, 2010).

In this paper, we explore how a 3D virtual environment can enhance group decision making by influencing both individual and shared understanding. Based on accepted definitions of "understanding", we define individual understanding as an individual's ability to perceive and comprehend the nature and significance of an object, task or situation (Anderson, 2000). Shared understanding refers to reaching a common comprehension of an object, task or situation, and an understanding of each other's viewpoints (Weick, 1985). Despite the growing business interest in, and use of, 3D visualization technologies, little empirical research has investigated how information presented in 3D virtual environments influences individual and shared understanding (Suh & Lee, 2005).

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http://dx.doi.org/10.1016/j.chb.2012.09.006

Previous research on consumer decision making in 3D virtual environments, for instance, showed that individuals tend to understand products better, prefer them to other products, and are more inclined to buy products when they are presented in 3D rather than in 2D (Daugherty, Li, & Biocca, 2008). Other studies investigate to what extent and under what conditions 3D virtual environments may support shared understanding and group decision making (Huang, Kahai, & Jestice, 2010; Kohler, Fueller, Stieger, & Matzler, 2011; Schouten et al., 2010). To the best of our knowledge, however, research has not yet addressed how *both* individual and group processes may be affected by 3D visualizations.

This is a relevant theoretical omission since group decision making is largely determined by the interaction between individual and group processes (Dennis, Fuller, & Valacich, 2008; Kwok & Khalifa, 1998). Although there has been a steady line of research on the social and emotional aspects (e.g. trust, group identification) impacting group decision making (Jarvenpaa & Leidner, 1999; Walther & Bunz, 2005), the scope of the present study is on cognitive processes. More specifically, there is an interesting difference in the cognitive processes required for individual understanding and shared understanding (Dennis et al., 2008; Weick, 1985). Generating individual understanding involves gathering a variety of information from a variety of sources, information which is subsequently subjected to slow retrospective examination to find patterns and draw conclusions. Reaching a shared understanding, however, requires examining others' individual understandings, and negotiations about these understandings so as to arrive at a mutually agreed-upon meaning (Weick, 1985). This requires a faster transmission and exchange of "distilled" information; information which has already been processed at the individual level (Dennis et al., 2008). Hence, the requirements placed upon the cognitive processing of information for individual or shared understanding are different, and the question is raised how the capabilities of 3D virtual environments relate to these requirements. Consequently, the scope of the present study is on these cognitive processes.

Two theories that can provide insight into the influence of 3D virtual environments on these processes are cognitive fit theory and cognitive load theory. Central to both these theories is the human mind and the limitations of working-memory capacity. The relevance of both these theories for this study is that they propose different strategies to present information (multiple representations) in a way that the information can easily be processed, and hence promote learning (Kirschner, 2002). On the one hand, *cognitive fit theory* poses that a match between the way information is presented and users' tasks enhances task performance (Goodhue & Thompson, 1995; Vessey & Galletta, 1991). Thus, in tasks where the visual element is important (such as designing or choosing a building, a kitchen or a car) a 3DVE may support understanding of the task at both the individual and the group level.

On the other hand, *cognitive load theory* states that learners' cognitive capacity may be overloaded by the richness of 3D virtual environments (Paas, Tuovinen, Tabbers, & Van Gerven, 2003). Being immersed in an information-rich environment (providing multiple cues about various aspects of the task), while at the same time discussing possible solutions in a team, may create too much cognitive input to be able to effectively process information and come to an understanding (Schrader & Bastiaens, 2011). Thus, for tasks with a strong visual component, cognitive fit theory and cognitive load theory seem to lead to diverging assumptions with respect to the possible contribution of 3D virtual environments to understanding and performance.

This paper contributes to the literature by empirically investigating how visual representation of information in 3D virtual environments supports both individual and shared understanding, and consequently contributes to group decision making in tasks with a strong visual component. In doing so, this study does not focus on the process of learning and learning outcomes, concepts which are traditionally related to cognitive load theory (van Merriënboer & Sweller, 2005). Instead, based on cognitive fit theory, we assume that 3D virtual environments may support individual understanding since these environments are able to provide the visual cues that help individuals comprehend the nature and significance of various elements of the tasks. At the same time, however, cognitive load theory leads us to assume that 3D virtual environments could impede the reaching of a shared understanding since the richness of information provided in these environments distracts too much from the communication process. The realism, immersion and interactivity of the visual cues that characterize a 3D virtual environment are likely to enhance the individual processing of visual information. Nevertheless, they are likely to slow down the sharing and transmitting of that information. We investigate this in an experimental setting in which the central task is one where the visual element is indeed important: the selection of an apartment. The participants face a task of selecting an apartment in three different conditions: a 2D condition (a floor plan), a 3D static condition (bird's-eye view from different angles) and a 3D immersive condition (in which they can navigate through virtual replicas of the apartments).

This study makes three contributions to research and practice. First, we seek to clarify the contradictory findings on the influence of 3D technology on individual and shared understanding (e.g., Beale, Kato, Marin-Bowling, Guthrie, & Cole, 2007; Schrader & Bastiaens, 2011) by integrating insights from cognitive fit theory and cognitive load theory. Secondly, we empirically investigate how 3D virtual worlds contribute to individual and shared understanding, and group decision making, by focusing on tasks with a strong visual component. This is an important contribution given the relative scarcity of experimental research on collaboration in 3D virtual environments and the impact of these environments on individual and shared understanding (Davis, Murphy, Owens, Khazanchi, & Zigurs, 2009; LaFrance, 1982; Walsh & Pawlowski, 2002). Thirdly, this study generates design guidelines for effective virtual team collaboration. Guidelines yielded from our findings will enable practitioners to have a more informed understanding about which tasks are most conducive for virtual team collaboration.

This paper is organized as follows. First, we review the relevant literature on how the visualization of information in 3D virtual environments may support individual and shared understanding, and team decision making. Subsequently, hypotheses are established and tested empirically in an experiment conducted among 192 participants. Finally, we discuss our research findings and provide implications for research and practice.

2. Theory and hypotheses

Three-dimensional virtual environments or 3DVEs are defined as "online electronic environments that visually mimic complex physical spaces, where people can interact with each other and with virtual objects, and communicate via avatars – a digital representation of themselves" (Bainbridge, 2007, p. 472). Based on Suh and Lee's (2005) analysis of the role of virtual environments in enhancing consumer learning about products, three specific capabilities of such environments have been distinguished which are likely to affect information processing: realism, immersion and interactivity.

2.1. 3DVE Capabilities: Realism, immersion and interactivity

First of all, *realism* refers to the extent to which one believes the virtual environment is real (Davis et al., 2009) – the degree to which one feels the virtual space represents the actual physical space. The extent to which a virtual environment is experienced as being similar to a non-virtual environment for which an actual decision is to be made, is expected to be relevant for its contribution to understanding and decision making. Davis et al. (2009) argue that representation and rendering are important technological capabilities of 3D virtual worlds, both of which refer to the process of creating lifelike images on screen as well as to how realistic objects are represented in the three-dimensional space. These capabilities are closely related to the concept of presence, which is defined as the perceptual illusion of non-mediation (Blascovich, 2002; Lombard, 2000). For instance, in a virtual environment one can virtually experience physical locations that do not (yet) exist in real life, for example, a virtual representation of an architectural design. Compared to 2D representations, 3D virtual environments offer more cues and provide a higher degree of reality, which may positively affect information processing (Daft & Lengel, 1986; Scaife & Rogers, 2001).

Secondly, 3D virtual environments are *immersive*. Immersion is the extent to which one feels perceptually surrounded in the virtual environment rather than one's physical surroundings (Guadagno, Blascovich, Bailenson, & McCall, 2007; Witmer & Singer, 1998). In a 3D virtual world, users are represented in the environment by means of their avatars, enabling them to move around and interact with the 3D virtual environment. This creates a higher level of stimuli and experiences in 3D virtual environment than in other, less rich environments, which leads to a stronger feeling of being immersed in the environment (Witmer & Singer, 1998; Verhagen, Feldberg, Van den Hooff, Meents, & Merikivi, 2012). This immersion, in turn, may lead to users paying more attention to relevant stimuli in the environment, aiding information processing (Kim & Biocca, 1997).

Thirdly, 3D virtual worlds offer a high degree of *interactivity*, which is the capability to interact with and control the environment (Fox, Arena, & Bailenson, 2009). Interactivity refers to the ability to move and navigate through a virtual environment in contrast to examining static 2D or 3D images of the environment (Bishop, Wherrett, & Miller, 2001). Because 3D virtual environments are highly interactive, users are active, rather than passive in their engagement with the information, which may lead to more effective information processing (Pimentel & Teixeira, 1994).

2.2. 3DVE Capabilities and individual understanding

As argued above, the 3DVE capabilities of realism, immersion and interactivity are likely to positively influence information processing. Such information processing is often perceived as an antecedent to learning (MacInnis & Jaworski, 1989), or individual understanding. The way in which individuals process information is primarily determined by the amount of attention they are willing to devote to the source of information (Lamme, 2004; Ledoux, 1998). Most dual-processing models (Fazio & Towles-Schwen, 1999; Petty, Gleichter, & Jarvis, 1993) claim that deliberate cognitive processing only occurs if a person is motivated and has the opportunity to engage in the effort of thoroughly analyzing the information content. When motivation and opportunity are lacking, information processing is assumed to take place on a more implicit, tacit and unconscious level (Petty et al., 1993). Because 3D virtual environments are highly realistic, immersive, and interactive, this is likely to have a beneficial effect on the extent to which users are engaged and to which they pay their attention to the information they are processing, which leads to a greater individual understanding of the presented information than in less immersive environments.

Cognitive fit theory posits that if a match is realized between the users' tasks and visual presentation of information, this will lead to greater individual understanding (Vessey, 1991). Vessey and Galletta (1991) have shown that 3D representations aid spatial recognition, which is essential for sense making of physical spaces. Moreover, 3D graphs outperform 2D graphs in terms of understandability (Kumar & Benbasat, 2004). Therefore, cognitive fit theory would suggest that representing a physical space in a 3D virtual environment would lead to more effective information processing concerning the space compared to 2D representations, subsequently resulting in a better understanding of the physical space (Goodhue & Thompson, 1995; Vessey & Galletta, 1991).

Realism, immersion and interactivity have been shown to be positively related to depth and effectiveness of information processing, which is related to understanding (Grigorovici, 2003; Scaife & Rogers, 2001). We therefore argue that the capabilities of 3D virtual worlds in terms of realism, immersion and interactivity, can enhance individual understanding about the object to be investigated, namely the apartment in this study (Kim & Biocca, 1997; Li, Daugherty, & Biocca, 2003). Building on that, we expect that participants in the 3D immersive condition in our experiment (expected to score highest in terms of realism, immersion and interactivity) will show the highest level of individual understanding. This then leads to the following hypotheses:

H1. Realism, immersion and interactivity will positively influence individual understanding.

H2. Compared to the 2D floor plan condition, individual understanding will be higher in the 3D static condition, and it will be the highest in the 3D immersive condition.

2.3. 3DVE Capabilities and shared understanding

During the past decade, a broad line of research has devoted attention to how groups, teams and networks gain an understanding of phenomena that is not merely grounded on the individual level, but also *shared* among group members (Cannon-Bowers, Salas, & Converse, 1993; Klimoski & Mohammed, 1994; Swaab, Postmes, Neijens, Kiers, & Dumay, 2002; Wegner, 1987). This broad scholarly interest in notions of shared understanding in groups has resulted in an equally broad conceptualization. For example, the terms mutual understanding (Postrel, 2002), intersubjectivity (Plaskoff, 2003), team mental models (Klimoski & Mohammed, 1994) transactive memory stystems, (Wegner, 1987), and shared mental models (Canon-Bowers et al., 1993) have all been concepts that are closely related to an understanding of phenomena that is grounded in individual cognition as well as shared among members of groups. The difference between, for instance "intersubjectivity" and the concept of "transactive memory systems", is that intersubjectivity refers to "shared meanings" achieved through interactions between people, whereas transactive memory systems commonly refers to "knowing who knows what" (Wegner, 1987).

In this study, shared understanding refers to *reaching a common comprehension of an object, task or situation, and an understanding of each other's viewpoints* (Weick, 1985). This definition has been chosen as it explicitly acknowledges that shared understanding requires the examination of others' individual understandings, as well as coming to a mutually agreed-upon meaning among team members. In other words, the greater the extent to which team members envision the problem in a similar way and are on par with each other about a possible solution, the greater the degree of shared understanding they will experience (Swaab et al., 2002). Such shared understanding, in turn, is often found to be positively related to team performance and decision making (Cannon-Bowers, Salas, & Converse, 2001). In order to relate the 3DVE capabilities of realism, immersion and interactivity to shared understanding, we turn to cognitive load theory.

Cognitive load theory is concerned with "the manner in which cognitive resources are focused and used during learning" (Chandler & Sweller, 1991, p. 294). The importance of cognitive load theory in relationship to shared understanding lies in the fact that the theory can provide insight into ways of presenting information that enhances performance. Cognitive load theory is especially relevant in light of the fact that, as argued above, reaching a shared understanding requires the rapid transmission and exchange of less detailed information (interaction), as opposed to the slow, in-depth processing required for individual understanding. At the centre of cognitive load theory is the human memory system, in particular the relationship between limited working memory and unlimited long-term memory (Anderson, 2000). This implies that learning depends on the efficiency of the use of available, but also the limited cognitive capacity that learners bring to learning task (Schrader & Bastiaens, 2011). Cognitive load is determined by the relationship between such cognitive capacity on the one hand, and the amount of cognitive processing required for a task on the other.

The triarchic theory of cognitive load (Sweller, 1999, 2005) argues that there are three kinds of cognitive processing that can contribute to cognitive load: (a) *extraneous processing*, referring to processing that does not support the task objective but results from inappropriate task design (for instance, providing too few or too many cues), (b) *intrinsic processing* which is essential for task understanding and is related to task complexity, and (c) *germane processing* which refers to deep cognitive processing such as mentally organizing task elements and relating this to prior knowledge, influenced by motivation and prior experience. The 3DVE capabilities of realism, immersion and interactivity are likely to influence the cognitive load experienced when conducting tasks, especially in terms of extraneous processing since they are related to the *design* of the task, and not to its inherent characteristics or to the participants' motivation or experience. As argued above, these characteristics lead to the processing of more cues (realism), and stimuli (immersion), in a more active way (interactivity). On the one hand, it could be argued that the simultaneous presence of team or group members in a 3DVE will contribute to reaching a shared understanding – members are simultaneously interacting with each other and the environment, which may lead to a convergence of their understandings of the environment. On the other hand, reaching a shared understanding requires not only information processing to create an individual understanding of tasks and objects, but it also requires communication in order to share these individual understandings and converge them into a shared understanding (Dennis et al., 2008; Van der Land, Schouten, Van den Hooff, & Feldberg, 2011). Thus, in reaching a shared understanding, extraneous cognitive load is increased by the 3DVE capabilities of realism, immersion and interactivity that lead to more active processing of more cues and stimuli. This increase in cognitive load does not mean that reaching an individual understanding is hampered, since this requires rich, yet slow information processing (Dennis et al., 2008). Reaching a shared understanding, does however, require processes of interaction, adjustment and negotiation, which are supported by leaner and faster information transmission (Dennis et al., 2008). This leads to the assumption that the combination of realism, immersion and interactivity in 3DVEs supports individual understanding, but that it creates an extraneous cognitive load which is too high to effectively support the process of reaching a shared understanding.

At the same time, however, it can be argued that extraneous processing is increased when the task design provides insufficient information about the task. As Münzer and Holmer (2009) argue, extraneous working memory load is increased when information is presented in an incoherent, or disparate way. Therefore, if the environment in which the task is to be conducted provides only very *limited* information about the actual space on which the task focuses, uncertainty will increase and participants will have to integrate information from other sources (their own assumptions, other participants' opinions, external sources) into their processing effort. The split-attention effect (Kalyuga, Chandler & Sweller, 1999) argues that such integration efforts indeed lead to a higher extraneous cognitive processing load.

In conclusion, we expect that the combination of 3DVE capabilities and the requirements in terms of interaction and negotiation will result in a higher extraneous cognitive load in a 3DVE than in other conditions. We also expect that the limited information in the 2D condition will require more extraneous processing of external information, subsequently leading to a higher cognitive load. As higher extraneous cognitive load has been found to negatively influence performance (Chandler & Sweller, 1991), and shared understanding has been found to positively influence team decision making (Cannon-Bowers et al., 2001), we expect decision performance to be higher where cognitive load is lower. In a decision making task in which there is no correct answer (such as the one in our experiment), appropriate measures for team performance include consensus about the group decision (Swaab et al., 2002), and the time needed to reach a decision (Adams, Roch, & Ayman, 2005; Hinds & Weisband, 2003).

Consequently, we expect the extent to which a shared understanding is reached to be highest in the 3D static condition compared to both 2D and 3DVE, and we expect that team performance (in terms of consensus and decision time) will also be higher in the 3D static condition than in the other two conditions. In other words, we expect the 3D static condition to represent an "optimal cognitive load", combining the advantage of 3D representation in terms of information processing with the advantage of not overloading team members so as to hamper reaching a shared understanding. Therefore, we pose the following hypotheses:

H3. Cognitive load will be lower in the 3D static condition than in the 3D immersive condition and the 2D condition.

H4. Compared to the 3D immersive condition and the 2D condition, (a) shared understanding and (b) consensus will be higher in the 3D static condition, and (c) decision time will be lower in the 3D static condition.

3. Method

To test our hypotheses, we conducted a laboratory experiment in which the central task was the joint choosing of an apartment in teams of three participants. We compared three experimental conditions which differed in the degree of realism, immersion and interactivity: (1) a 2D condition in which the participants saw a 2D floor-plan of the apartments, (2) a 3D static condition in which participants had a bird's-eye view of the apartments and were able to view the apartments from four different angles, and (3) a 3D immersive condition in which the participants could navigate through virtual replicas of the apartments from a first-person perspective in a 3D virtual environment. A visual presentation of these conditions is provided in Fig. 1.

2D 3D static 3D immersive

Fig. 1. Visual presentation of the apartments in the three conditions.

3.1. Participants

Participants were students who were enrolled in an undergraduate course in Business Administration. A total of 192 students participated in the experiment (68.80% male), with a mean age of 19.88 (SD = 1.55), ranging between the age of 18 and 28 years old. Most of the participants considered themselves to be experienced with text-based CMC (5.85 on a 7-point scale) and most participants had experience with instant messaging (84.9%). 36 participants were familiar with virtual worlds, most notably *World of Warcraft* (n = 13). Participants received course credits for participating in the experiment.

3.2. Task

Participants were given a situation in which they had to select one of three apartments that were to be shared with two other students. This apartment selection task is a common task in behavioral decision making research (e.g. Payne, 1976) as well as in IS research (e.g. Todd & Benbasat, 1992, 1999). Other research on decision making support in the context of spatial planning employed a similar set up (e.g., Chu & Eric, 2000; Payne, 1976; Swaab et al., 2002). Moreover, the task reflects a real life situation for most students.

Participants first viewed each of the three apartments (A, B, and C) individually, after which they made a choice regarding one of the three apartments and filled in a short questionnaire about their decision processes. Subsequently, the participants were teamed up in groups of three. They were told that the three of them were to share the apartment together and that they should decide which of the three apartments would be best for them to share. After the team made a final decision regarding one of the apartments, participants were again asked to fill out a short questionnaire. In this way, both individual information processing and group decision making could be studied.

The three apartments differed in terms of seven characteristics, all of which could be represented visually: the size of one's own room, the window size, the outside view, the kitchen, the communal space, the outdoor space, and the bathroom facilities (see Table 1). These characteristics were distributed evenly among the apartments so that there was no obvious best alternative. The apartments were similar in all other ways. They were all part of the same apartment block and cost the same rent and has the same amenities. The floor plan of the apartments is shown in Appendix A.

The experimental task matches our research goals in that the successful completion of the task relies on assessing the valence and the importance of the apartments' characteristics based on the visual information provided. The task consists of an individual phase and a team phase, both representing the individual understanding and shared understanding elements of a team task. First, the participants are to individually form an understanding based on new information. Then afterwards, they need to reach a shared decision concerning one of the apartments with their team members.

3.3. Experimental design and procedure

Sixty-four 3-person teams were randomly assigned to one of the three experimental conditions: 2D condition (n = 60), 3D static condition (n = 63), and 3D immersive condition (n = 69). In the 2D condition, participants were shown a two-dimensional floor plan of the apartments on a computer screen. The 3D static condition showed a three-dimensional model of the apartments on a computer screen so that the participants had a bird's-eye view of the apartments. The participants could rotate the 3D models so that the apartments could be viewed from different angles, allowing for more depth and detail. The virtual world *Second Life* was used to create the 3D immersive condition in which the participants could navigate through virtual replicas of the apartments from a first-person perspective that allowed them to investigate the spatial and visual dimensions of the apartments.

One week before the experiment, participants were asked to enroll for a specific time slot. Precautionary measures were taken to

Table 1
Apartment characteristics.

	Apartment A	Apartment B	Apartment C
Own room's size	Three rooms of 12 m^2 each	Three rooms of 16 m^2 each	Three rooms of 20 m^2 each
Window size	Small window in student rooms (42 × 50 cm)	Door + large window in student rooms (130 × 190 cm)	Window bay with three large windows (250 × 190 cm)
View	A great view over a canal	Small garden and balconies of other apartments	A busy road
Kitchen	Shared simple open kitchen of 5 m^2 in the communal space	Shared luxurious closed kitchen (10 m^2), with room for a dinner table	Shared closed kitchen of 10 m^2
Communal space	Shared communal space of 15 m^2 (including kitchen)	No communal space	Separate communal space of 15 m^2
Outdoor space	Shared rooftop terrace of 15 m^2	Student rooms have a small private balcony (1 × 2.5 m)	No outdoor space
Bathroom facilities	Shared toilet and bathroom	Sinks in student rooms, shared toilet and bathroom	Private shower and toilet in each room

avoid that subjects who were acquainted with one another enrolled in the same session. Nine participants were scheduled during a single time slot. These nine participants were randomly spread across three teams, so the participants would not know with whom they would be interacting. After the participants had signed a non-disclosure statement, they received written and oral instructions related to the experimental procedures and the decision making task. After receiving the general instructions, the participants were distributed among three different computer rooms, so that all of the participants of a team were physically separated from one another. Each computer room was supervised by an instructor. During the experiment, all instructions were provided on-screen.

The experiment consisted of two phases. In the first phase of the experiment, which was aimed at the individual decision making process, participants viewed the apartments individually, after which they individually chose for an apartment, followed by a short questionnaire. In the second (team) phase of the research, the participants teamed up in 3-person groups and had to reach a shared decision about which apartment to choose. All of the groups interacted using a text-based chat application similar to an Instant Messaging application. Team members were identified by generic nicknames that were assigned to them by the chat application based on the participant's gender. Participants were asked to enact their roles as being a student on the lookout for a shared apartment. They were asked to use their nicknames consistently and to not ask for each team member's real names. The teams had 30 min to make the decision about the apartment. All of the teams managed to reach a decision within this time limit.

In the 2D and 3D static conditions, the groups interacted using text-based chat that was provided in a browser window using a java-based chat applet. The groups could also view the apartments while chatting, in a similar fashion as during the individual phase. In the 3D immersive condition, participants virtually met up with their "future roommates" in the hallway connecting the three apartments. From the hallway they could walk to the three apartments to view these again when needed. The groups interacted using the text-based chat function available in *Second Life*. The team members were identified with avatars which were of average attractiveness and who were uniformly dressed wearing a T-shirt and jeans. Participants were assigned a male or female avatar depending on their gender. After a team's choice was recorded, a post-experiment questionnaire opened automatically.

3.4. Measures

3.4.1. Manipulation checks

Unless otherwise indicated, all items were measured on a 7-point scale ranging from 1 (*completely disagree*) to 7 (*completely agree*). All scales and items employed in this study are listed in Appendix B. Cronbach's alphas are listed in Table 2. As a manipulation check, realism, immersion, and interactivity were measured. These scales were also used as independent variables in the testing of hypothesis 1. Realism was measured with six items based on the naturalness scale by Witmer and Singer (1998) and assessed the extent to which the participants thought that the apartments had been displayed realistically and accurately. We used five items to measure immersion based on the scales by Kim and Biocca (1997) and Nichols, Haldane, and Wilson (2000). The items in this scale measured the extent to which participants experienced a feeling of "being there" whilst being in the virtual environment. Interactivity was measured with three items based on the scale by Sundar and Kim (2004) and the involved/control subscale by Witmer and Singer (1998). The items investigated measured the extent to which the participants felt that the system allowed them to interact with, and control, the environment.

3.4.2. Outcome variables

Individual understanding was adapted from Zigurs, Buckland, Connolly, and Wilson (1999). The seven items assessed the extent to which participants thought they had been able to collect all the information they would need in order to make a correct decision regarding the apartments. Cognitive load was assessed with a single item which asked the extent to which participants experienced the decision making process as difficult (Paas, van Merrienboer, & Adam, 1994). The scale ranged from 1 (*not difficult at all*) to 7 (*very difficult*). Shared understanding was measured with four items measuring the extent to which group members understood each other's viewpoints and had a shared perception of the decision task (Swaab et al., 2002). Consensus was measured with five items that asked the extent to which participants had agreed with the decision made by the group and how convinced they were that the best solution had been chosen (Green & Taber, 1980; Jarvenpaa, Rao, & Huber, 1988). Finally, the time the teams took to reach a shared decision was automatically recorded by the system.

4. Data analysis and results

4.1. Correlations and manipulation checks

The correlations between the constructs in our analyses are shown in Table 2.

For manipulation checks and the testing of hypotheses 2, 3 and 4, we conducted one-way ANOVAs with Tukey B correction for post hoc tests. Table 3 compares the means of all outcome variables across the three conditions. The results of our manipulation checks showed that the three conditions were found to differ in realism, $F(2,189) = 6.46$, $p = .002$, $\eta^2 = .064$, immersion, $F(2,189) = 16.88$, $p < .001$, $\eta^2 = .152$, and interactivity, $F(2,189) = 61.83$, $p < .001$, $\eta^2 = .396$. Post-hoc analyses showed that the 2D condition was seen as less realistic and interactive than the 3D static and 3D

Table 2
Correlations between variables.

		1	2	3	4	5	6	7	8
1	Realism	.87							
2	Immersion	.48**	.87						
3	Interactivity	.52**	.47**	.75					
4	Cognitive load	−.05	−.04	.11	–				
5	Individual understanding	.71**	.43**	.55**	−.03.	87			
6	Shared understanding	.01	−.02	.01	−.07	.48**	.82		
7	Consensus	.01	−.08	.01	.03	.39**	.65**	.93	
8	Decision Time	.10*	.16*	.18*	.14*	−.33**	−.21**	−.20**	–

Values on the diagonal are the Cronbach's alpha's of the scales.
* $p < .05$.
** $p < .01$.

Table 3
Variable means across the three conditions.

	2D ($n = 60$) Mean (SD)	3D static ($n = 63$) Mean (SD)	3D immersive ($n = 69$) Mean (SD)
Realism	4.36[a] (1.03)	4.88[b] (0.92)	4.95[b] (1.03)
Immersion	2.74[a] (1.05)	2.99[a] (1.12)	3.83[b] (1.20)
Interactivity	3.20[a] (1.09)	4.76[b] (1.06)	5.03[b] (0.82)
Cognitive load	4.42[a] (1.77)	5.68[b] (1.32)	4.54[a] (1.55)
Individual understanding	4.72[a] (1.14)	5.09[ab] (0.83)	5.15[b] (0.96)
Shared understanding	5.43[a] (1.17)	6.01[b] (0.94)	5.17[a] (0.98)
Consensus	6.32[ab] (1.04)	6.56[b] (0.81)	6.10[a] (0.86)
Decision time	9:36[a] (5:46)	8.16[a] (3:34)	15:22[b] (5:33)

Note. Different superscripts indicate significant differences among the three conditions with p < .05 with Tukey's B correction. Decision time displayed in minutes:seconds.

immersive conditions (see Table 3). There was no difference between the 3D static and 3D immersive condition in how realistic or interactive the apartments displays were perceived. The 3D immersive condition was judged to be more immersive than the 3D static and 2D conditions. In conclusion, the results showed that the 3D static and 3D immersive conditions differed only in how immersed the participants felt while viewing the apartments. Both 3D conditions were seen as more realistic and interactive than the 2D condition.

4.2. Hypotheses testing

To test whether realism, immersion and interactivity predict individual understanding, we performed a regression analysis. Results show that realism, $\beta = .565$, $p < .001$, and interactivity, $\beta = .232$, $p < .001$, significantly predict individual understanding, explaining 54% of variance in individual understanding, adj. $R^2 = .542$, $F(3,188) = 76.43$, $p < .001$. Immersion was not a significant predictor of individual understanding, $\beta = .048$, $p = .410$. This partly confirms hypothesis 1 which states that higher perceptions of realism and interactivity positively affect individual understanding.

Hypothesis 2 posed that individual understanding would be the lowest in the 2D condition, higher in the 3D static condition and the highest in the 3D immersive condition. This hypothesis was partially supported. The analysis showed that there was a significant main effect between the three conditions for individual understanding, $F(2,189) = 3.50$, $p = .032$, $\eta^2 = .036$. Post-hoc analyses (Tukey B) only revealed a significant difference between the 3D immersive condition and the 2D static condition, with the 3D static condition not differing from either of the other two conditions. However, since the difference between the mean scores in the 2D and 3D static conditions is considerable (.37), we also checked other post hoc tests to explore the differences between these conditions. Both Least Square Differences ($p < .05$) and Tukey HSD ($p < .10$) indicate that these conditions do differ (at least at the $p < .10$ level), whereas Bonferroni ($p = .12$) shows the difference to not be significant. Hence, our conclusion is that the 2D and 3D static conditions differ considerably, but not at a consistently significant level.

Hypothesis 3 predicted that cognitive load would be lower in the 3D static condition than the 3D immersive and the 2D condition. This hypothesis was supported, $F(2,189) = 12.78$, $p < .001$, $\eta^2 = .119$.

Finally, hypothesis 4 formulated the expectation that shared understanding and consensus would be higher in the 3D static condition than in the 2D condition and the 3D immersive condition, and that decision time would be lower in the 3D static condition than in the 2D condition and the 3D immersive condition. The results mostly supported this hypothesis. First, the shared understanding was higher in the 3D static condition than in the 2D condition and the 3D immersive condition, with the latter two conditions not differing on this variable, $F(2,189) = 11.44$, $p < .001$, $\eta^2 = .108$. Consensus also differed between conditions, $F(2,189) = 4.27$, $p = .015$, $\eta^2 = .043$. Post-hoc analyses revealed that the 3D static condition resulted in a higher consensus than the 3D immersive condition, with the 2D condition in between. Finally, decision time was higher in the 3D immersive condition than in the other two conditions, which did not differ between themselves, $F(2,189) = 36.80$, $p < .001$, $\eta^2 = .280$. All in all, the results showed that the performance in the 3D immersive and 2D condition was lower than in the 3D static condition.

5. Discussion

By integrating insights from both cognitive fit theory and cognitive load theory, our study provides clarification into the mechanisms underlying the contribution, (or lack thereof, of 3D virtual environments to individual and shared understanding, as well as group decision making.

The results of the experiment indicate that 3D virtual environments contribute to the individual understanding for those tasks which include a visual component (e.g. selecting an apartment). The mechanisms underlying this contribution are the 3DVE's capabilities of realism and interactivity. Contrary to our expectations, it appeared that immersion was not of influence on individual understanding as anticipated by previous research (Suh & Lee, 2005). Next, although we do see a clear trend in terms of both 3D conditions scoring higher than the 2D condition, the difference in increasing individual understanding was only significant between the 3D virtual environment and the 2D condition. These findings are largely in line with cognitive fit theory which proposes that in order to generate individual understanding for a task which involves visual representations of physical spaces, a rich environment, such as a 3D virtual environment is more effective.

The results of the experiment's group decision making phase, however, showed that the 3D static environment contributed to a greater shared understanding among team members than a 3D virtual environment did. In the 3D static condition the participants significantly reported to be "more on par with each other about the group's final decision" and shared "more similar views of the problem" while conversing with their team members via the chat-application than in the other conditions. This finding supports the notion of cognitive load theory which states that shared understanding was higher in the condition in which the participants experienced an optimal extraneous cognitive load (e.g. 3D static), whereas a higher cognitive load was reported in the 3D immersive environment and the 2D condition. Finally, when it comes to performance, the condition with the lowest cognitive load (3D static) outperformed the 3D immersive condition in terms of consensus and decision time.

5.1. Theoretical implications

This study contributes to theory in numerous ways. First of all, this one of the first studies to empirically investigate how *both* individual and shared understanding are affected by 3D visualizations of information for group decision making tasks. This is an important contribution due to the relatively scarcity of this research in the field of virtual team collaboration (Davis et al., 2009; LaFrance, 1982; Walsh & Pawlowski, 2002) and consumer learning (Suh & Lee, 2005).

Secondly, we have integrated both cognitive fit theory and cognitive load theory in order to explain the contribution of a 3D virtual environment to group decision making tasks on physical spaces. With this theoretical integration, our study helps to clarify the contradictory results that were found in earlier research (e.g., Beale et al., 2007; Schrader & Bastiaens, 2011). For instance, cognitive fit theory explains how 3D representations can aid spatial recognition, which supports individual understanding in tasks in which the spatial element is relevant (Schrader & Bastiaens, 2011; Suh & Lee, 2005). Cognitive load theory, on the other hand, explains how the combination of realism, interactivity and immersion can create an extraneous cognitive load that, in combination with the cognitive processing required for group processes, in the end negatively influences group processes (Paas et al., 2003).

Drawing on cognitive fit theory (Vessey & Galletta, 1991), our results show that greater individual understanding is reached when information is presented in 3D virtual worlds. This finding corresponds to previous research on consumer learning in 3D virtual environments (Suh & Lee, 2005). Another reason why this individual understanding was greater in the 3D virtual environment might be attributed to the virtual experience of the participants navigating through a rich, immersive environment. This "virtual experience" could have generated greater emotional and motivational engagement, which may have lead to greater information processing and learning as earlier research pointed out (Li et al., 2003; Grigorovici, 2003; Scaife & Rogers, 2001). In this way, our findings can have theoretical implications for theories on the self-regulation of learning, motivational and emotional processes in 3D virtual environments.

In terms of cognitive load theory, our findings on group decision making are somewhat less straightforward and have interesting implications. Our findings demonstrate that the mechanisms which create a higher extraneous cognitive load are vastly different in the 3D immersive condition than in the 2D condition. Where *uncertainty* is the main driver for cognitive load in the 2D condition, *overload* would seem to be the main driver in the 3D immersive condition. In the 3D immersive condition, the extra cues and stimuli that a rich environment offers only seem to distract from the group process, leading to decreased performance. Where individual understanding requires the slow processing of rich information, the interaction and negotiation required for shared understanding build on the fast exchange of leaner information (Dennis et al., 2008). Hence, we conclude that the combination of realism, immersion and interactivity in 3DVEs supports individual understanding, but the interaction and negotiation requirements raise the extraneous cognitive load, which in turn appears to undermine the process reaching a shared understanding.

In the 2D condition, however, the lean information provided by the 2D floorplan in itself is insufficient to fully understand the task (hence the low score on individual understanding). This necessitates that the participants turn to other sources of information (their own assumptions, others' understandings, external sources) and that they integrate these sources into their processing. In that sense, the situation can be compared to a split-source format (Cierniak, Scheiter, & Gerjets, 2009), in which information that is needed to conduct a task is dispersed across different sources. The processing required to integrate this information (from different sources, in different formats) creates a higher extraneous cognitive load (Chandler & Sweller, 1996; Kalyuga et al., 1999). This corresponds to the inverted U-shaped relationship between information load and performance: beyond a certain optimum cognitive load, more information leads to less performance (Schroder, Driver, et al., 1967).

The results from this study also have implications for Daft and Lengel's Media Richness Theory (1987). Our study did not provide support for Media Richness Theory's assumption that rich media is more efficient when performing equivocal tasks (such as group decision making). This research suggests another decision rule for group decision making: when task performance relies on both group communication and task-information processing, media which requires lower cognitive demands should be selected (e.g. a 3D static environment). Our finding is in line with prior research which demonstrates that Media Richness Theory has difficulty predicting the efficiency of new media usage (Dennis & Kinney, 1998).

Finally, our findings are in line with a central assumption regarding Media Synchronicity Theory or MST (Dennis et al., 2008). According to this theory, any task that requires team collaboration (e.g., decision making, knowledge sharing or negotiation) consists of two fundamental communication processes (Weick, 1985). The first is conveyance, which is viewed as the transmission of new information that is primarily related to individual understanding. The second process is convergence, which refers to the discussion of preprocessed information contributing to shared understanding. Our findings in terms of cognitive fit and cognitive load echo the assumptions that conveyance (i.e., reaching an individual understanding) requires an in-depth processing of a variety of information, whereas convergence (i.e., coming to a shared understanding), is characterized by the faster transmission of more abstract information. Moreover, by using cognitive fit and cognitive load theory as a framework for the analysis of these processes, our study provides a new and more in-depth explanation (relative to MST) for the differences between conveyance and convergence.

5.2. Practical implications

From our findings the following implications and contributions to practice have emerged. Firstly, practitioners who seek to design a virtual environment which fosters individual understanding should first determine how to present the relevant information attributes of the product or task as clearly as possible. For instance, if an architect seeks to convince a client of the end results of a rather radical and controversial design solution for his/her home (e.g. sacrificing a bedroom to become a kitchen), the architect will be more likely to do so by using a 3D virtual world representation. When a person can virtually navigate through this new kitchen, and see and "feel" how this positively affects the dimensions in his/her own house, the personal experience will be greater, leading to a greater impact on the person's understanding of the design solution. Translating this into concrete design guidelines, it is imperative for practitioners to comprehend that the features implemented in the design should directly aim at enhancing participants' understanding. This will improve individual understanding and foster decision making.

However, as for group decision making, our study results suggest that using a 3D virtual environments does not necessarily improve decision making. For instance, for tasks in which a decision needs to be made regarding different options by a team or group (e.g. a comparison between different products), it is more efficient and effective to use 3D static representations. In such representations, an overview and images of relevant spaces and objects from different angles can be provided (such as a 3D static representation), which also allows participants to discuss their opinions.

Our results also suggest that teams need to employ different technologies in different phases of the group decision making process. In phases involving a group process in which creating an individual understanding of a space or object is primarily important, an immersive 3D virtual environment can be very valuable. In phases of the group process in which negation processes are important, technology support should be aimed at team interaction rather than further information processing. These technologies should mainly provide communication support with only a few possibilities for information processing, because this could distract from effective team interaction (Zigurs & Buckland, 1998).

5.3. Limitations and further research

This study has several limitations. First, college students were used as a convenience sample. Although these were students of Business Administration, they do not represent the professionals who are currently using virtual environments for dispersed work. Hence, we should be cautious when generalizing these findings to practice. On the other hand, this research is more focused on understanding the processes involved in group decision making than on generalizability. Moreover, given that the task of collectively selecting an apartment as future flat-mates is a rather common task among students, we are less concerned with using students as a sample. Still, future research is needed to confirm our findings using different samples and tasks.

Second, for the purpose of empirical testing, we selected and thus isolated the mechanism of processing task-related information as an outcome measurement. Hence, we did not explore the actual interaction processes between team members in the different conditions leading to their final choice in selecting an apartment interaction. In a future study, a content analysis of the chat conversations could be conducted to investigate how the process of sharing of experiences took place. Moreover, to fully understand effective group decision making and shared understanding, more social variables should be taken into account as well. It would be interesting, for instance, to study the interaction effects of social variables by focusing on the manipulation of avatar appearances. Subsequently, we could study which tasks would be the most useful to manipulate avatar appearance, such as e.g. negotiating or brainstorming.

Our study highlights three important issues for future researchers. First, more effort should be placed on examining the specific aspects of a task, and how 3D virtual environments can support this process. Second, we believe that 3D virtual environments should be studied more intricately by focusing on the capabilities of the medium. Third, since this study did not focus on the process of learning and learning outcomes in 3D virtual environments (concepts traditionally related to cognitive load), further research is encouraged regarding this particular aspect.

6. Conclusion

This study investigated how the presentation of visual information in 3D virtual environments affects collaborative decision making. As proposed by cognitive fit theory, our results indicated that 3D immersive environments are indeed more effective in supporting individual understanding than the 2D information presentations. Next, in line with cognitive load theory, the 3D static information presentation appears to be more effective in supporting group decision making than the 3D immersive environment presentation. The 3D static information presentation offers an optimal balance in supporting information processing and negotiation processes between team members. Our results suggest that teams need to employ different technologies during the different phases of the group decision making process. This can be achieved by focusing on efficient information processing when it comes to individual support, while at the same time focusing on efficient communication support when group processes are relevant. For tasks with a visual component, technologies should offer realistic and interactive presentation of the relevant information.

Acknowledgments

This work has been partly funded by the European Commission through the Metaverse1 project (Information Technology for European Advancement: ITEA2) and by Novay, the Dutch consortium on IT and open innovation.

Appendix A

See Fig. A1.

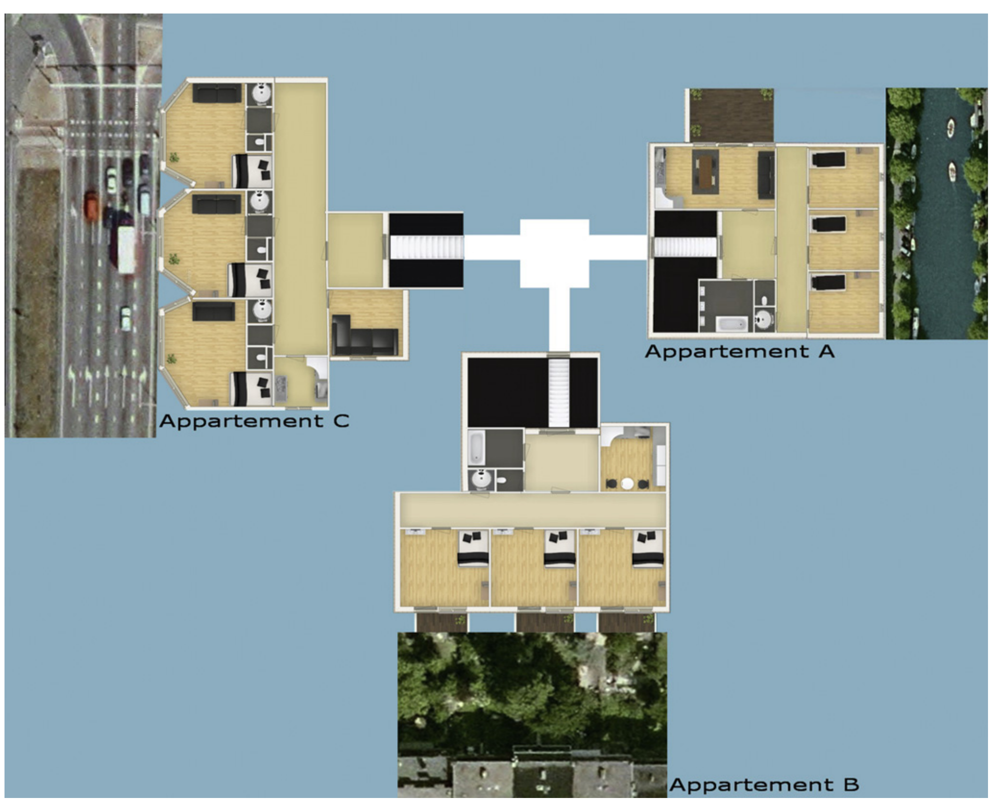

Fig. A1. 2D Overview of the three apartments.

Appendix B

Survey items.

Realism	I felt the apartments were presented realistically I got a good impression of the apartments I think my mental image of the apartments resembles how they really are I obtained a complete impression of the apartments I felt the apartments were realistically displayed Viewing the apartments this way resembled a real life visit
Immersion	During the presentations of the apartments, I felt like being present in the apartments During the presentations of the apartments, I felt I was in the world the system created During the presentations of the apartments, I had the sense of "being there" When I finished viewing the apartments, I felt like I had returned from a real life inspection To me, the virtual environment became a reality
Interactivity	I could control the presentation of the apartments I could view the apartments from many different perspectives How interactive would you rate the presentation of these apartments in terms of the ability to navigate through it? (*1* = non-interactive, *7* = very interactive)
Individual understanding	I was very well able to imagine the pros and cons of every apartment The way the apartments were presented allowed me to estimate how appropriate each apartment was for me I got a clear image of the pros and cons of every apartment The way the apartments were presented enabled me to thoroughly examine the apartments The way the apartments were presented helped me to collect the information necessary for the task The way the apartments were presented offered insight in which information was relevant and valuable The way the apartments were presented allowed me to choose the apartment that was most appropriate for me
Cognitive load	How difficult was it for you and your team mates to make a decision? (1 = very difficult, 7 = very easy)
Shared understanding	The members of my team were on par with each other The members of my team were at one about the decision The members of my team had the same view of the problem The members of my team have pretty much the same opinions
Consensus	I agree with my group's decision I accept the outcome of my group's decision I think we have made the right decision I am satisfied with the result of our group decision My team chose the best option

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