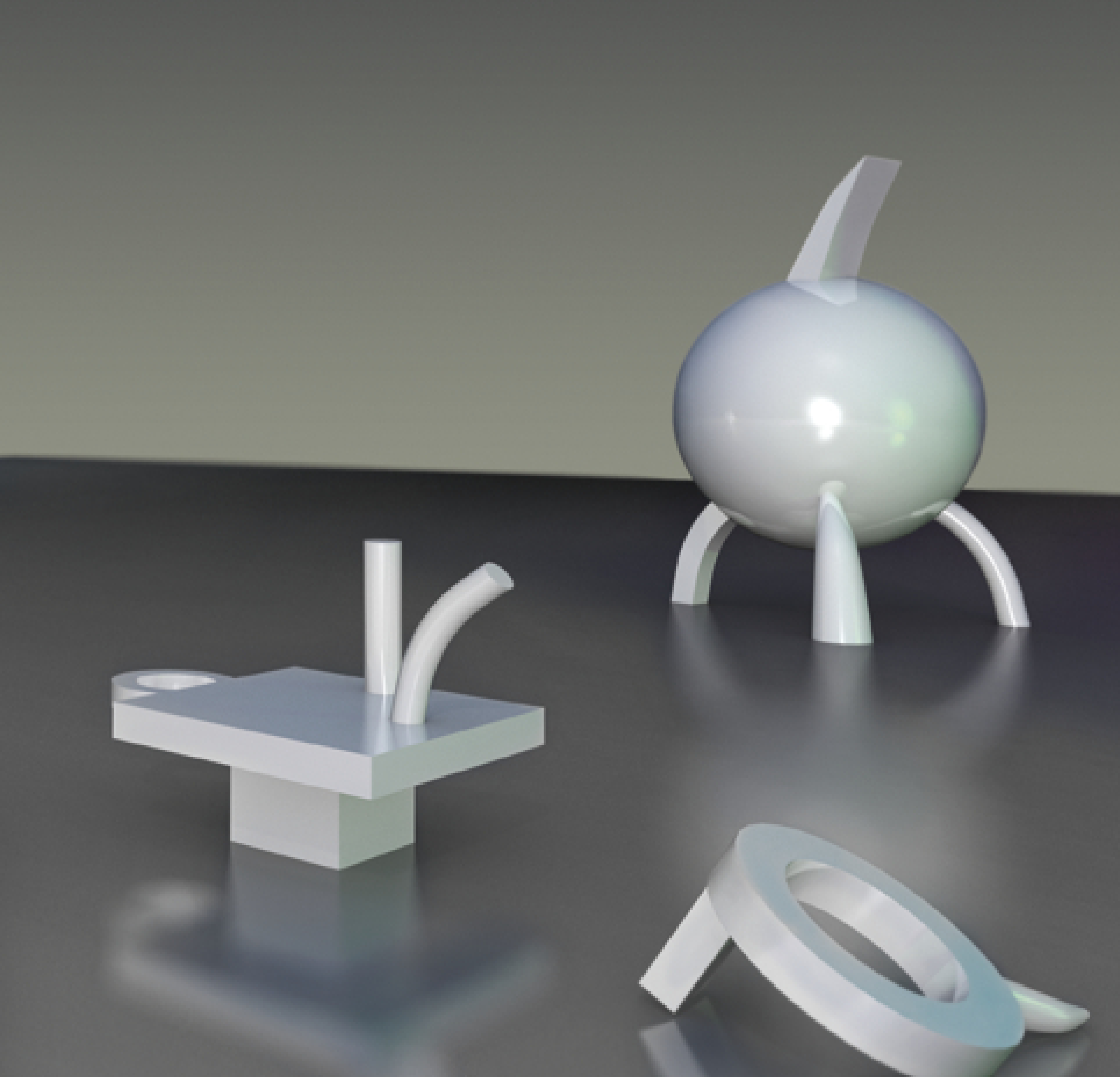
Spatial Cognition in Synthetic Environments



F. Meijer

SPATIAL COGNITION
IN
SYNTHETIC ENVIRONMENTS

DISSERTATION

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General Introduction

INTRODUCTION

One of the many challenges a design team faces during the design process of products is reaching consensus. Often, not only designers amongst each other have to reach an agreement on product specifications, they also have to take into account other stakeholders who are involved in the design process, such as managers, customers, and end-users (Lawson, 2005). This is not an easy task because different stakeholders often have different ideas about product design. For example, product designers emphasize the importance of creativity, managers strive for efficiency of the production process and marketability, and end-users expect a maximum of user comfort in the design. The different perspectives on how a product should be designed can lead to miscommunication among these stakeholders, thus obstructing the design process. Not surprisingly, much effort is put into developing new technologies to support communication between stakeholders and to test the effectiveness of the different product ideas (Wang et al., 2002).

In the past decades, Virtual Reality (VR) has become a powerful tool to support communication and collaboration between the different stakeholders in the design process (Bruno & Muzzupappa, 2010). VR refers to a computer-mediated environment, which is presented in such way that people have the illusion of participating in it rather than observing it externally (Earnshaw, Gigante, & Jones, 1993). The term Virtual Environment (VE) is often interchangeably used with VR and refers to the same concept. VR is already applied in a large number of professional fields, such as medicine, military, and product design (Burdea & Coiffet, 2003). In these professional fields, VR is mostly used to support education, improve training of skills, and enhance human communication. For product design, a product can be simulated in VR so it can be evaluated. Stakeholders are able to perform realistic interactions with a virtual product, which will not only increase their insight in the product’s practical options and limitations, but also stimulate them to discuss their ideas with each other (Landman, Van den Broek, & Gieskes, 2009). This will improve the effectiveness of the selected design solutions and eventually will increase the final product’s chance for success when it enters the market.

The current dissertation investigates the influence of VR on the stakeholders' understanding of design issues. The goal of the present research is to determine the constraints for an efficient and effective use of VR for product design. For this purpose the effect of various aspects of VR on human cognitive processing is investigated. In particular, the influence of two typical aspects of VR on cognition will be the topic of research: interaction and visualization. This introductory chapter will first introduce the problem and solution space paradigm in product design and explain how VR can aid this process. Next, the concept of Synthetic Environment (SE) will be introduced and its application to product design will be explained. Subsequently, important factors that designers have to take into account when using an SE for product design will be discussed. Next, the importance of human cognitive processing for the implementation of SEs is explained. Finally, an overview of the remaining dissertation will be provided.

PROBLEMS AND SOLUTIONS IN PRODUCT DESIGN

Product design is about solving problems. Whether the problem is to find the right materials or to invent a smart mechanism, the designer's task is to come up with clever solutions. These design problems are often roughly described at the beginning of a product's design process. As the design process advances these problems become more precise, alter, and may lead to new problems. Therefore, designers constantly have to redefine the design problems and come up with new solutions during a design process. This section will briefly describe the different stages of product design and will focus on the process of solving design problems. Subsequently, a possible role of VR in the design process will be discussed.

In general, product design processes are divided into several design stages, in which designers perform a number of design activities (Cross, 2000). These stages of product design are illustrated in the model of French (1985). This is shown in Figure 1. The first design activity is to analyze the problems that have to be solved to fulfill specific needs from the market. Analyzing the design problems is an important part of the overall design process, which results in a formal statement of the design problem. According to French this statement comprises three elements: a description of the design problems, the limitations of the design solutions, and the quality of the product's design to be achieved. These elements determine the goals, the constraints, and the criteria to be worked with in the design process. The second design activity is to generate solutions in the form of concepts on basis of the stated design problem. This is referred to as conceptual design. During conceptual design, different types of knowledge are brought together, such as engineering science, practical knowledge, production methods, and commercial aspects. In this phase there is feedback to the problem analysis phase to evaluate to what extent a concept actually solves the initial design problems. The third activity is to work out the concept in greater detail and, if there is more than one concept to make a final choice between them. This is referred to as the embodiment of concepts. In this phase there is feedback to the conceptual design phase to evaluate whether concepts are effective and feasible. The last design activity is to decide about the remaining number of small but essential design issues. This is referred to as detailing of the design. The final output of the design process is a technical drawing or CAD (i.e., Computer Aided Design) model, which is used for manufacturing the product.

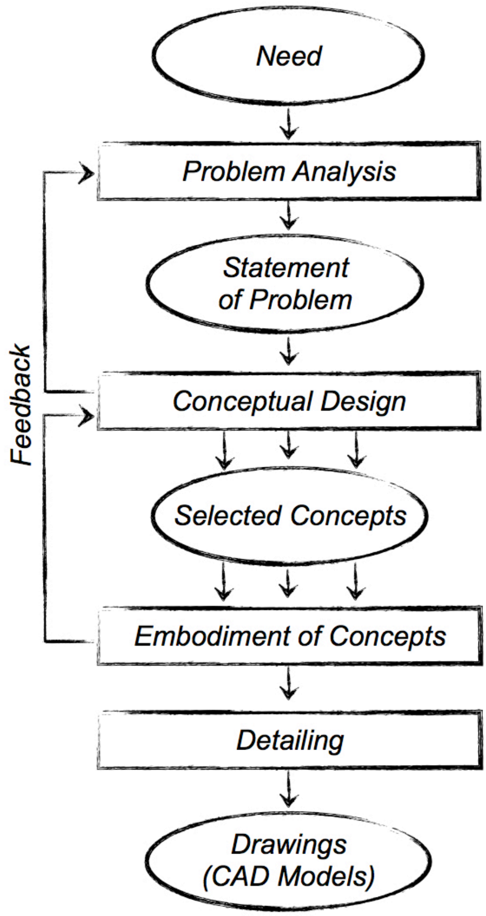

Figure 1. French's model of the design process (1985). Design activities are illustrated in the squared boxes, whereas the rounded boxes depict the design stages.

For an effective and efficient design process, it is essential that the designers do not overlook important aspects of the design problems and that they find suitable solutions (Cross, 2000). There is a number of prescriptive models that describe a systematic procedure to find design solutions. In general, this procedure starts with analyzing and understanding the overall design problem as fully as possible. Next, the problem is divided into sub-problems, to which suitable solutions have to be found. Finally, the various solutions found are combined into an overall solution. Although this suggests that there is a logical progression from problem to sub-problems and from sub-solutions to solution, Cross (2000) argued that there is also a direct relationship between the overall problems and solutions as well. Problems and solutions are explored and developed concurrently. This is illustrated in Figure 2.

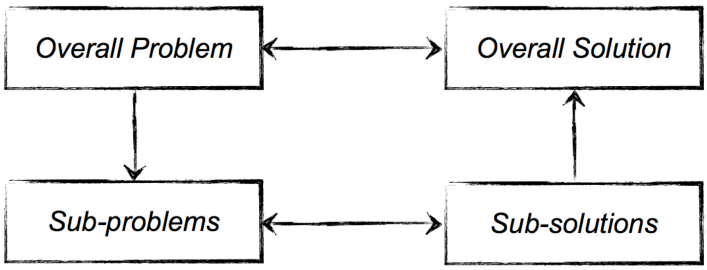

Figure 2. The symmetrical problem/solution model of Cross (2000).

The interdependency between design problems and solutions is also described by Maher and Poon (1996), who stressed the development of problem and solution over time. According to Maher and Poon, product design is divided into two separate “spaces”: the *problem space* and the *solution space*. Problem space refers to the potential design problems in a design process as defined by the designers, who are creating a new product. Solution space refers to the potential solutions that designers generate to overcome these problems. Usually, designers jump between problem space and solution space more than once, because a certain design solution refocuses the original problem such that new solutions are often needed. In other words, design problems and their solutions evolve during product design. This process is referred to as *co-evolution of problem-solution*. Figure 3 shows the co-evolution model of Maher and Poon. In this model, the downward arrows represent the process of finding solutions to certain design problems at different moments in time. The upward arrow represents the process of refocusing the original design problem when a solution is found. The horizontal arrows represent the evolutionary process of the design problems and solutions over time.

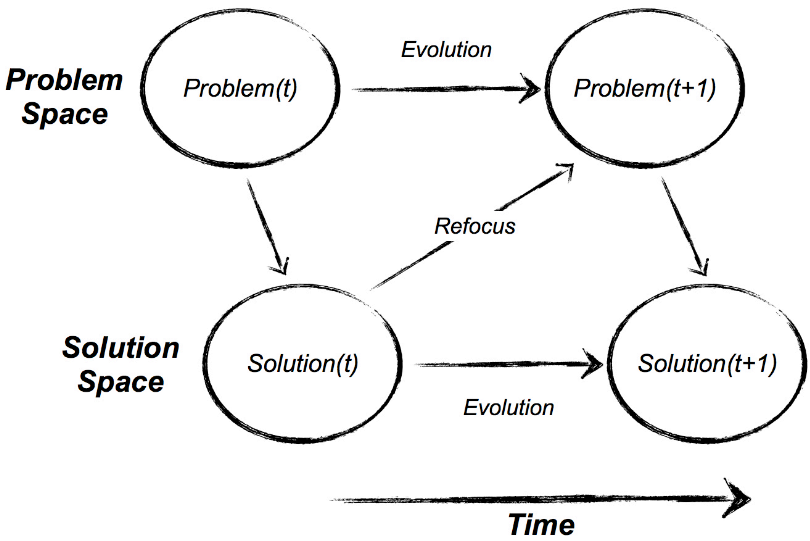

Figure 3. The co-evolution model of Maher and Poon (1996) illustrating the relationship between problem and solution space in the design process. Note that (t) stands for a given moment in time, (t+1) for a later moment.

The process of solving design problems is particularly difficult when designers have to develop complex products, operate in multi-disciplinary design teams, or experience extreme pressure to create products within a limited time (Cross, 2000). Various methods lie at hand to improve the designers' ability to analyze design problems and to find suitable solutions. One method that has proved to be helpful is the use of design scenarios; i.e., explicit descriptions of hypothetical events concerning a product during a certain phase of its lifecycle (Tideman, Van der Voort, & Van Houten, 2008). A design scenario can be a written or spoken storyline, but it also may be visualized by for example images, movies, or animations. In addition, a scenario can contain product prototypes with which people can interact in simulated environments. These prototypes and environments can be physical, virtual, or augmented (i.e., combination of both physical and virtual). Design scenarios enable designers to explore all kinds of practical design issues and test the effectiveness of the solutions found, which further increases the designer's ability to uncover new design problems and find more suitable solutions (Tideman, Van der Voort, & Van Houten, 2008). With the recent technological development of computer systems, designers are able to implement scenarios in VEs so that prototypes can be tested in their future context in the earliest stages of the design process. The next section will further discuss how design problems and solutions can be made explicit by using VR technology.

SYNTHETIC ENVIRONMENTS

Currently, companies operate in an increasingly demanding environment to create new products (Burdea & Coiffet, 2003). The demand for innovation has increased and the average life cycle of products decreased. Furthermore, products have become more and more complex and an increasingly large number of people is involved in designing and building them. Therefore, companies feel the necessity to use new methods and technologies to make their product design processes more effective and efficient. One technology that has proved to be particularly useful for product design is VR (Chitescu et al., 2003). VR can be used throughout the entire product design process. A number of studies showed a successful application of VR to rapidly test prototypes, support production planning, and evaluate the effectiveness of manufacturing processes (e.g., Dangelmaier et al., 2005; Mujber, Szecsi, & Hashmi, 2004; Weyrich & Drews, 1999). Until recently, VR typically demanded expensive technology and extensive human expertise (Burdea & Coiffet, 2003). As a result, the use of VR was mostly confined to larger companies that could afford this type of technology and expertise. With current technological developments, however, VR has become within reach of medium and small companies as well. In this dissertation, a specific use of VR for product design is proposed: VR including affordable technology that is applied in the earliest stages of the product design process. This specific use of VR will be referred to as the use of *Synthetic Environments* (SEs).

In the literature, SEs are generally defined as artificial environments in which people can interact with (virtual) prototypes as if they were in a real environment (Innocentit & Pollinit 1999; Kalawsky, 1999; Lu & Conger, 2007; Ma & Kaber, 2006; Ressler et al., 2001; Rudolph, 2007). Often, SEs are realized by VR technology. However, an SE may contain not only virtual elements, but physical elements as well (Wang et al., 2008). In this dissertation, the term SEs will be used specifically in relation to the first stages of product design: problem analysis and conceptual design. In an SE, a product prototype can be simulated together with its possible future environment. Accordingly, a scenario can be created, in which designers can test their concepts on for example usability issues. Figure 4 shows a model that illustrates how design problems and solutions are applied to SEs. After a design team has defined the initial design problems, these are applied to an environment (either physical or virtual). This process is represented in the model by the left downward arrow. Next, when design solutions are found, these are applied to a prototype (physical or virtual). This process is represented in the model by the right downward arrow. After the SE is realized, designers are able to test the prototype in an environment. The experience in the SE is then used to refocus the original design problems. This is represented in the model by the upward arrow. Because designers have experienced the practical implications of their design solutions, they increase their ability to refocus design problems. Applying problems and solutions to SEs is an iterative process, so that the SE is adjusted repeatedly to the designers' needs and interests as the design process advances. This process is represented in the model by the curved arrows.

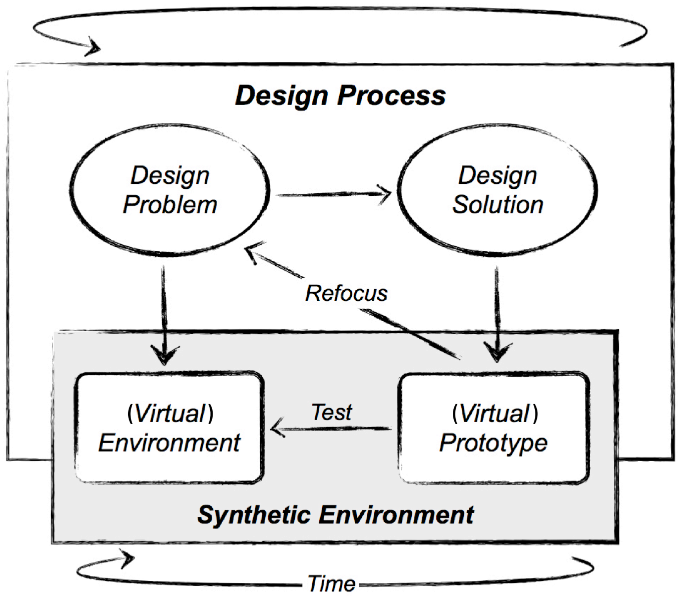

Figure 4. Adaptation of the co-evolution model of Maher and Poon (1996), in which design problems and solutions are implemented in an SE.

Using SEs does not only support designers to refocus design problems, but there are a number of other benefits as well. First, making the problems with their solutions explicit in SEs allows all stakeholders in a design process to experience a virtual prototype's practical use in a similar manner. This experience stimulates the stakeholders to form similar ideas about the product despite their different backgrounds. In other words, SEs facilitate stakeholders to form shared mental models (Landman, Van den Broek, & Gieskes, 2009). A shared mental model will prevent miscommunication and motivates stakeholders to discuss the product's potential with each other. This will increase the number of creative solutions and, eventually, lead to a better product. Second, SEs make it possible to involve end-users at an early stage of the design process when important decisions still have to be made (i.e., the fuzzy front end of design; Smulders, Van den Broek, & Van der Voort, 2007). Usually, the design team invites end-users in the final stages of the design process to test the usability of a product. At this moment, most of the product's design is almost definite and it is difficult to change the design according to the end-users' feedback. By proactively involving the end-users in the design process it is more likely that the final product will correspond to their expectations and needs (Tideman, Van der Voort, & Van Houten, 2008). Third, SEs enable designers to make changes in their design that can immediately be evaluated. Design modification tools can be implemented in SEs, with which designers can intuitively change a product's design and immediately test its effectiveness (Wang et al., 2008). This will increase the number of iterations in the design process and decrease the time to create effective product solutions.

In conclusion, an SE can improve the design process because it supports designers to refocus design problems, it increases communication between the stakeholders, it involves end-users at an early stage, and it facilitates fast design modifications. After a design team decides to use a SE in their design process, the next step is to actually implement the SE. There are various important factors that designers have to take into account when implementing an SE for product design. These factors will be discussed below.

IMPLEMENTATION OF SYNTHETIC ENVIRONMENTS

When a design team decides to use an SE, the main question they probably will ask is how to implement it. There are a number of factors that designers have to take into account when implementing an SE, such as the technology, the time, and the budget available to develop an SE. Another important factor is which people will interact with the SE; i.e., the users of the SE. Designers can involve different types of users, such as mechanical engineers, artists, managers, and product end-users. It makes a large difference what kind of user will interact with the SE. For instance, end-users will establish other design problems than expert-designers. The first group will probably identify usability issues, whereas the latter will identify mechanical issues. These user groups require different types of SEs. End-users probably need an SE that contains a high level of realism whereas expert-designers need an SE that is easily changed according to their design solutions. Thus, the potential users play an essential role in the implementation of an SE. When an SE is used, the designers' set of tasks in a design process changes (Tideman, Van der Voort, & Van Houten, 2008). With SEs designers acquire a number of additional tasks.

The first two tasks concern the implementation and evaluation of the SE. After the product designers have specified their needs and wishes, the SE developers start implementing these in the SE. Based on the requirements of the product designers and the restrictions of the design process, they implement a) the virtual aspects, such as 3D models, b) the physical aspects, such as display and interaction devices, and c) the simulation model, such as programming code that describes how the SE reacts to the users' interactions. During the design process, the design team repeatedly evaluates whether the design problems and solutions are sufficiently represented in the SE. If design problems remain unresolved or new ones arise, then the SE needs to be redefined and the technical configuration of the SE modified. Furthermore, these evaluations help the design team to improve the quality of the SE as the design process advances.

The next two tasks of the design team concern the supervision and evaluation of the users of the SE. A design team starts to determine what kind of user to involve. To select the users, designers look at the type of design problems they want to solve. For example, if a design team wants to assess the usability of a product, they should invite end-users for a test session in an SE. However, if they want to test whether the product is safe, they should invite safety experts. When the users are selected, designers decide how to give them supervision during the test session. Supervising the users is important to ensure that they provide useful feedback about the product's design. Before a test session starts in an SE, designers give instructions about the purpose of the SE and about their tasks. During the session, feedback may be given about the users' actions and discussions held afterwards about the users' experience with the SE. Furthermore, the personal characteristics of the users, such as gender, age, nationality or computer experience, potentially have a large influence on the interactions with the SE (for a review see; Chen, Czerwinski, & Macredie, 2000). Designers need to take these characteristics into account to be able to understand the users' interactions more accurately.

The last task of a design team is to evaluate the users' interactions with the SE. This evaluation is used to assess the effectiveness of the designers' solutions and to refocus the design problems. The evaluation of user interactions can be done with various methods (for an overview see; Preece, Rogers, & Sharp, 2004). One method the designers can use is to ask the users directly for their subjective experience with the product. This can be done with an interview or questionnaire. Both of these measures provide the designer with qualitative information about the product. Another method that can be used is to observe the users by documenting or recording their actions. This method is more laborious, but provides rich information about the users' interactions. Finally, feedback can be acquired by measuring task performance in an experimental setting (Loomis, Blascovich, & Beall, 1999). With this method, the SE becomes an experimental environment. The feedback gathered, such as time to complete task or accuracy rate, provides the designer with quantitative information. This type of information is precise and suffers less from the fact that people may in practice behave in another way than when you would ask them about their opinions. Designers select one method or a combination of these methods depending not only on their needs, but also on the time, expertise and technology available in the design process.

In summary, designers implement the technical configuration of the SE, evaluate it, supervise potential users in the SE, evaluate their characteristics, and evaluate the users' interactions with the SE. It is essential that the technology of an SE matches the users who interact with it. In case of a mismatch, users will experience their interactions with an SE as unrealistic. This could impair the quality of their feedback about the product's design. To facilitate effective and realistic user interactions, designers are not only required to understand the possibilities and limitations from a technological perspective but also from a user's perspective. Designers should understand the relationship between the technology used in the SE and the users' capacity to process the information presented by the SE. Below, we will focus on how users process information from their environment, referred to as human cognitive processing, and the implications it may have for the implementation of SEs.

A COGNITIVE APPROACH TO SYNTHETIC ENVIRONMENTS

To understand the effect of the technology used in an SE on the users' behavior and opinions, it is essential that designers understand how the users process information from their environment. There are various distinct cognitive processes that determine for example how people reason, remember, make decisions, and perform actions (Ashcraft & Radvansky, 2009). The most notable cognitive processes are visual, auditory, and haptic perception. However, processes like attention, memory, and spatial cognition are important as well. Each of these cognitive processes imposes constraints on the implementation of SEs. The current section will give a brief introduction of some prominent processes that are assumed to be relevant for the implementation of SEs. Furthermore, some notable constraints for SEs are discussed in relation to these cognitive processes.

Visual perception

The first stage of human information processing is the perception of visual, auditory and/or haptic information. The most dominant of these perceptual systems is visual perception, which therefore imposes the most important constraints on the implementation of SEs. Because people normally rely so much on their ability to see, an accurate presentation of visual information is crucial for realistic user interactions in SEs. The human visual system is sensitive to small variations in color, shape, and lighting in the environment. Users experience an SE as more realistic when it is presented with more visual detail in accordance with a natural environment. This is referred to as visual realism (Slater et al., 2009). Visual realism can be achieved by providing more detailed 3D models, textures, natural colors, shadows, and reflections (for further reading see; Möller, Haines, & Hoffman, 2008).

An important characteristic of visual perception is the ability to perceive depth. Depth perception arises from a variety of visual cues, which are generally divided into monocular and binocular cues. Monocular cues require the visual input from only one eye and are derived from parallel lines that converge towards the horizon, and decreasing motion, size, texture gradient, luminosity, contrast, saturation, and shadows of objects at greater distances (Wickens, 2003). Binocular cues provide depth information from using both eyes. On each retina of the eye an image is projected from a slightly different angle. If an object is far away the disparity between these images is small, if it is close the disparity is large. This disparity is used to estimate distances towards objects in an environment. Binocular cues can be provided in the SE by using stereoscopic displays (for further reading see; Javidi, Okano, & Son, 2009). Depth perception improves the users' experience of realism in the SEs (IJsselsteijn et al., 2001). Furthermore, binocular cues are mainly used to estimate distances inside the space directly surrounding the user, which is called personal space (Cutting & Vishton, 1995). Therefore, binocular cues are important when interacting with objects in the users' personal space is an essential part of the task.

Auditory perception

Another important sensory system is auditory perception: the sense of hearing. The auditory system identifies a sound by specific qualities of the sound waves and how the sound waves develop over time (Wickens, 2003). Sounds can be implemented in an SE by using recorded sounds (i.e., sound samples), but can also be "engineered" with a synthesizer (for further reading see; Viers, 2008). The latter requires more expertise, but also provides more control over the specific characteristics of the sounds. In general, sounds provide users with feedback of their interactions in an SE, which makes these interactions more realistic (Kim, 2005). Furthermore, adding sounds in a SE increases the users' experience of realism (Stanney et al., 2003). Sounds that correspond with a natural environment will often further improve this experience. However, in some cases exaggeration of sound effects can also increase the users' subjective experience of realism in SEs (Cohen & Wenzel, 1995). This is widely applied by the film industry and their principles may well be adopted for the development of SEs. For example, exaggerating the intensity of low frequencies can increase the users' sensation of being physically close to large objects moving through the SE.

Haptic perception

A third important perceptual system is haptic perception. Haptic perception is important for people to receive feedback about their physical interactions with the immediate environment. Haptic perception includes proprioception and kinesthetics (Wickens, 2003). Proprioception refers to the sense of the limb positions. Some differentiate the kinesthetic sense from proprioception by excluding the sense of equilibrium or balance from kinesthesia. Proprioceptive and kinesthetic feedback can be simulated in an SE by implementing haptic devices, such as a Phantom Device or Haptic Master (for further reading see; Burdea, 1996; McLaughin, Hespanha, & Sukhatme, 2002). The use of these haptic devices is relatively expensive and the implementation of this type of feedback is complex. Therefore, designers may be tempted to ignore haptic feedback in the SE. However, the absence of haptic feedback can have a negative impact on the users' interactions with an SE (Robles-De-La-Torre, 2006). Providing haptic feedback in SEs can be important for a number of purposes. First, haptic feedback enables users to feel their physical movements and positions in relation to the SE, which facilitates more realistic interactions. Second, haptic feedback enables users to perform precise and fast movements, which is important to manipulate for example an object's shape in the SE. Third, haptic feedback enables users to learn motor skills in the SE, which is important for designers when they want to assess the users' capacity to learn how to operate products.

Multimodal perception

Multimodal perception occurs when perceived information from different modalities, such as visual, auditory, or haptic information, is integrated into a unified perceptual experience. Implementing and synchronizing different modalities in an SE requires additional effort and often more than one computer is used to present the modalities (for further reading see; Popescu, Burdea, & Treffiz, 2002). One of the most important benefits of multimodal presentation of information in SEs is that it increases the users' experience of realism (Slater et al., 1999). However, if multimodal SEs are used, then the coherence between the modalities becomes crucial. When users detect a (e.g., temporal) mismatch between the modalities they will experience the SE as less realistic (Stanney et al., 2003). A mismatch between the modalities can have serious implications for the users' interactions with an SE. For example, including large visual displays in SEs without providing realistic physical feedback can cause cyber-sickness. When the users see that they are moving through an SE but do not feel it, they may experience dizziness, fatigue or nausea (Benson, 2002; Bonato & Bubka, 2004). With large visual displays, the visual cues are stronger and the difference between what users see and feel increases.

Attention

Attention is the cognitive process of selectively concentrating on certain aspects of an environment while ignoring other aspects. Attention plays a central role in human cognition, controlling what people see, hear, or feel, and what to remember (for a review see; Pashler, 1995). Attention is typically divided into bottom-up and top-down selection of information. Bottom-up guided attention refers to the situation when attention is automatically captured by salient information from an environment. Top-down guided attention refers to the situation when attention is driven by the individual's inner goals or expectations. People tend to search for information where they expect to find it, but also detect information more rapidly that they beforehand judge as valuable (Wickens, 2003). For the implementation of SEs the following issues concerning attention should be taken into account. First, presentation of salient but irrelevant information in an SE, such as too much visual detail or background noise, may divert attention. Second, clear instructions and task descriptions are important to guide the users' attention to the relevant information, particularly in a large-scale or complex SE. Third, people are able to keep a high level of attention for only a limited amount of time, depending on factors like task difficulty, an individual's motivation, and ability (DeGangi & Porges, 1991). Sustained attention can be stimulated in an SE by adopting techniques that are also used in computer games, such as providing incentives (e.g., game points), competitiveness with other people, and storylines (for further reading see; Adams, 2009).

Memory

After information is perceived, it is further processed and stored in memory. Human memory refers to the ability to store, to retain and recall perceived information at a later moment in time. Human memory is traditionally divided into sensory memory, short-term memory and long-term memory (Baddeley, 1990). Whereas sensory memory and short-term memory have a limited storage capacity and are temporary, long-term memory can hold large amounts of information up to several decades. Information in long-term memory is structured according to specific patterns in so-called mental models. A mental model is a coherent idea about something in the surrounding environment; about what it is, how it works, and how it is organized (Johnson-Laird, 1980). In SEs, users build up mental models about the product's design, its functionality, and how to operate it. The accuracy of the users' mental model of a certain product affects their feedback about a product's design to the designers. Furthermore, the extent to which various users have comparable mental models determines, at least partly, their ability to communicate and the quality of the discussions about a product's design (Landman, Van den Broek, & Gieskes, 2009). Various methods can be used to support the development of accurate mental models in an SE, such as emphasizing important design aspects with for example a distinctive color, or using clear instructions to guide users towards important information (for further reading see; Wickens, 2003). Finally, as not all knowledge in memory is accessible to consciousness, products requiring excessive human-machine interaction should be tested by assessing performance rather than asking for (conscious) opinions.

Spatial Cognition

Another relevant aspect of cognitive processing for the implementation of SEs is spatial cognition. Spatial cognition is concerned with the acquisition, organization, utilization, and revision of knowledge about the relative locations in and attributes of a spatial environment (Hart & Moore, 1973). This knowledge is stored in memory mostly in the form of mental maps or 3D object representations. Cognitive maps are used to navigate through large-scale environments (Spence, 1999), whereas object representations are used to recognize and manipulate objects (Peissig & Tarr, 2007). Users often experience difficulty to maintain knowledge of their location and orientation while navigating through an SE (Chen & Stanney, 1999). They easily get lost. Therefore, users may devote much of their attention trying to find out the spatial layout of an SE, which distracts them from their main tasks in the SE. To improve the users' ability to navigate and to construct mental maps, the interaction methods (e.g., interaction devices) should allow the users to move effortlessly through an SE so they can obtain as much views of the SE as possible (Bowman, 1999). Navigation and the construction of mental maps can be further improved by implementing landmarks (i.e., easily recognizable objects and structures) (Darken & Sibert, 1996a, b), paths with a clear structure (Charitos & Rutherford, 1996) or assistants offering advice and suggestions (Van Dijk et al., 2003). Object manipulation (i.e., the ability to reposition, reorient, or query objects) has a profound impact on the efficiency and effectiveness of interactions in SEs as well (Stanney et al., 2003). The users' ability to freely manipulate objects improves spatial processing of objects (James, Humphrey, & Goodale, 2001). The users' ability to realistically interact with objects can be improved by providing haptic feedback (Richard et al., 1996). Spatial processing of objects can be further improved by providing stereopsis in the SE (Luursema et al., 2006).

Conclusion

For the implementation of SEs it is important that designers understand the relationship between the technology used and human cognitive processing. If the technology matches the users operating it, then the feedback from user opinions and behavior relevant for a product's design will be more reliable and valid. Some technologies are relatively easily implemented in the SE, while others are complex and require extensive human expertise. Cognitive processes such as visual, auditory, haptic perception, and memory impose important implications for the implementation of SEs. In relation to the implication of these cognitive processes, two typical characteristics of SEs are important for SE implementation: the level of interactivity and the actual (visual) realism. These two characteristics distinguish an SE from for example a technical drawing or an animation. For the implementation of SEs, designers have to determine how much interactivity and realism they should provide to obtain valid and reliable feedback from the users. In general, interactivity and realism improve the users' subjective sense of realism (Slater, 1999) and cognitive processing of, mainly, spatial information (Mania et al., 2006). However, the latter effect may vary across different groups of people (Cornoldi & Vecchi, 2003). Therefore, to determine the level of interactivity and realism in an SE, more knowledge is needed about the relationship between these characteristics and spatial cognition.

OVERVIEW OF THE DISSERTATION

The current dissertation is the result from a collaborative project with academic partners from industrial design and companies interested in the potential of (low fidelity) SEs for product design. The studies in this dissertation focus on the influence of two typical characteristics of SEs on human cognition: interactivity and visual realism. Implementing interactivity and visual realism in SEs takes a substantial amount of expertise and effort. Therefore, it is important to determine if and how users benefit from interactivity and visual realism. The dissertation is divided into two parts describing different types of studies, in which the influence of interactive and visual realistic SEs was investigated on performance and on the sense of realism that human users experienced.

In the first part, two basic studies are described. These studies encompass five experiments addressing how people process information in an SE situation. The focus of these studies is on determining the significance of interactivity in SEs for the users' ability to learn spatial information. The users' performance on spatial tasks after interactive exploration of virtual 3D objects is compared with their performance after passive observation of these objects. These basic studies investigate the cognitive processes that are affected by interactive exploration of virtual 3D objects, as are often used in SE. Based on the insights gained by these experiments, the conditions for an effective use of interactivity in SEs can be better determined. These conditions are important for designers to decide whether or not they should use SEs in their product design process. In the second part of this dissertation, two case studies are described. These studies encompass two experiments, in which the knowledge obtained from the basic studies is validated in SEs. In these studies, the significance of interactivity and visual realism in SEs on the users' ability to learn spatial information is investigated. The design cases used are provided by companies that participated in this project, who are interested in SEs for product design. These design cases enabled to verify whether or not the results obtained with the basic studies could be generalized to practice, to the use of SEs; in other words, the ecological validity of the basic studies was assessed.

Chapter 2 specifically discusses the effect of interactivity on memory, while taking the users' ability to memorize visual spatial information into account. Stakeholders may well vary in this ability. For example, expert-designers are probably better at memorizing 3D objects than the product's end-users, as they are skilled in working with spatial information. In an experiment, participants first either interactively or passively explored 3D objects. Afterwards, they were tested on a mental rotation task to assess to what degree they had memorized the objects in either condition. To assess individual differences among people, the participants were divided into different groups varying in their visual spatial ability. This study was conducted to determine whether or not the designers' decision to use SEs for their design process should depend on the type of users they want to include in their design process.

Chapter 3 further discusses the effect of interactivity on memory performance. First, the effect of interactivity on motoric processes in memory (i.e., memorizing actions) was investigated. Participants studied 3D objects interactively or passively and were then tested on a mental rotation test. Subsequently, the effect of interactive exploration on visual memory was investigated. Participants were tested on an object recognition test. Next, the extent to which interactivity affects memory was investigated. The recognition of degraded and intact objects was compared in both interactive and passive conditions. Last, the role of attention in the interactive exploration of objects was investigated. This study was conducted to provide more insight in the precise benefits of interactivity for mental representations in visual spatial memory.

Chapter 4 describes the effect of visual realism on memory performance in an SE. A virtual supermarket was created that participants interactively explored. The participants' performance on several spatial tasks in a photo-realistic SE was compared with a visually non-realistic SE to determine the importance of visual realistic SEs for human memory. First, participants navigated through either the photo-realistic or the non-realistic SE. Subsequently, they were tested to what degree they had memorized the spatial lay-out of the SE.

In Chapter 5, the effect of interactivity was investigated on the users' subjective experience of realism in SEs, their ability to identify design problems, and their ability to solve these problems. A virtual airplane cabin including a galley was created. Participants either explored an interactive SE of the airplane cabin or watched movies or images of the airplane cabin. Subsequently, the user's experience and spatial memory of the airplane cabin were tested. Finally, the conclusions of the research in this dissertation were summarized in Chapter 6.

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PART I Basic Studies

Chapter 2 Representing 3D virtual objects: Interaction between visuo-spatial ability and type of exploration

ABSTRACT

We investigated individual differences in interactively exploring 3D virtual objects. 36 participants explored 24 simple and 24 difficult objects (composed of respectively three and five Biederman geons) actively, passively, or not at all. Both their 3D mental representation of the objects and visuo-spatial ability were assessed. Results showed that, regardless of the object's complexity, people with a low VSA benefit from active exploration of objects, whereas people with a middle or high VSA do not. These findings extend and refine earlier research on interactively learning visuo-spatial information and underline the importance to take individual differences into account.

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INTRODUCTION

The ability to imagine objects three-dimensionally is crucial for object recognition. In the past decades, the underlying mechanism of object recognition is thoroughly studied. A wide variety of research fields ranging from neuro-physiology to computer vision has described how perceptions of objects lead to higher-level mental representations that support object recognition; for a review, see Peissig and Tarr (2007). It is generally theorized that mental representations of objects are the product of processing information in visual spatial working memory (VSWM). However, two important findings refine how three-dimensional (3D) mental representations are formed from two-dimensional (2D) images. First, constructing mental representations of objects is not merely a visual process. Manual interactions, both real and virtual (i.e., moving a mouse to control 3D shapes) during familiarization with objects increase to what degree mental representations are formed (Harman, Humphrey, & Goodale, 1999; James, Humphrey, & Goodale, 2001; James et al., 2002). Second, the efficiency with which 3D mental representations are formed is notably varied across groups of individuals; cf. Cornoldi and Vecchi (2003) and Voyer, Voyer, and Bryden (1995). The current paper puts these findings together and investigates individual differences in the effect of interactive exploration of objects.

Since Marr and Nishihara (1978) posed their idea how 3D object representations are formed from 2D retinal images, a large amount of empirical research is conducted on how these representations are used to recognize objects. Generally, building mental representations of objects is considered as a visual process. However, more recent studies have provided evidence that motoric processes as well play a significant role in the system underlying 3D object representations. In particular, research revealed the existence of a motoric component in imaginary object manipulations, such as mental rotations (e.g., Wexler, Kosslyn, & Berthoz, 1998; Wohlschläger & Wohlschläger, 1998; Wiedenbauer, Schmidt, & Jansen-Osmann, 2007). So, it is possible that the inclusion of this motoric component in 3D object representations facilitates better access to these representations at a later time. Thus, when a novel view of a familiar object is perceived, the object representation is more easily mentally rotated: for example, for comparison. Consequently, the object is better recognized.

The importance of motoric activity for building mental representations in VSWM was also revealed by a study of Christou and Bülthoff (1999). These researchers compared active exploration of scenes to passive observation of an identical exploration. In their study, active explorers navigated through a 3D environment and passive observers watched a recorded movie of the active explorers. To ensure that active and passive observers attended the environment equally, they were required to respond to certain markers in the environment. Afterwards, all participants were tested on a recognition test, in which they had to identify images of familiar scenes (i.e., that they had encountered before) between images of novel scenes. Participants were able to identify unmarked familiar scenes after active exploration better than after passive observation, but there was no difference between the two conditions for marked scenes. From these results these researchers concluded that building mental representations is view dependent and that the ability to freely control viewpoints during active exploration facilitates more complete mental representations.

A similar effect of interactivity was found for the exploration of 3D objects. Harman, Humphrey, and Goodale (1998) suggested that interactive learning increases visual spatial storage of 3D objects, because it allows observers active control over their views upon which they can focus. These researchers showed that interactive exploration of objects in a virtual environment increases subsequent visual recognition of these objects. In this study, participants were instructed to study a set of novel 3D objects either interactively or passively. In the interactive condition they controlled the views of the objects manually, whereas in the passive condition they observed the same sequences of images of these objects. Next, they presented 2D images of objects on which decisions were made whether or not these objects were previously studied. Harman et al. found that performance was increased with interactively explored objects compared to passively observed objects. In addition, James, Humphrey, and Goodale (2001, 2002) showed that participants spend more time on plane views (i.e., “side” and “front”) of the objects during interactive exploration. This suggests that active control over this type of views is important for visual spatial storage of objects.

However, the studies of Harman et al. (1999) and James et al. (2001, 2002) did not take an important factor into account. Processing information in Visual Spatial Working Memory (VSWM) is strongly influenced by an individual's characteristics such as gender, age, or ability (Cornoldi & Vecchi, 2003; Stone, Buckley, & Moger, 2000; Voyer, Voyer, & Bryden, 1995). For example, Luursema et al. (2006) found that interactive learning of anatomical structures correlates with VSA. These researchers showed that especially participants with a low VSA increased their anatomical knowledge from interactive learning. These results suggest that interactive learning might trigger certain visuo-spatial processes in individuals with low VSA that aid the efficiency with which 3D information is represented.

The study described above suggested that individual differences play an important role in the formation of mental representations in visuo-spatial memory. However, the influence of VSA on interactive learning of 3D objects is not yet investigated. Therefore, in the present study we examined whether the effect of interactive learning of objects varies for groups with a different VSA. It was important to carry out this research for the reason that an effect of VSA on interactive learning can implicate the general assumption that the effect of interactivity is the same for all groups of people. Furthermore, studying the influence of VSA will further define under what conditions interactivity aids learning of visuo-spatial information, such as 3D objects.

In an experiment, we utilized a task comparable to that of Harman et al. (1999) and James et al. (2001, 2002). Participants first explored 3D objects passively or actively and, subsequently, performed a task in which the objects were tested. In addition to the previous studies, we intended to investigate whether the effect of interactively learning 3D objects was dependent on the participants' VSA. Based on the research of for example Cornoldi and Vecchi (2003) and Luursema et al. (2006), we expected that interactive learning will support those with low VSA, whereas those with high VSA perform similar under passive or active learning conditions.

The present experiment differed from the earlier studies of Harman et al. (1999) and James et al. (2001, 2002) on the following aspects. First, the participants were tested on a mental rotation task in contrast to the previous studies, in which either a recognition task or a perceptual matching task was used. A mental rotation task requires additional mental processing and the ability to mentally transform object representations in VSWM (Shepard & Metzler, 1978). Consequently, a mental rotation task is more difficult to perform than a recognition or perceptual matching task. We expected that a mental rotation task would reveal the difference in effect of interactive learning between participants with low and high VSA more evidently. Second, to determine the participants' VSA, they received a standard pen and paper test prior to the experiment. The results of this pen and paper test were then related to the performance in the test phase. Third, we were interested to what degree the participants formed mental representations after active and passive exploration and whether they used these representations on a subsequent test phase. Therefore, an extra condition was added to the experiment in which participants were not able to explore objects. Consequently, participants were not able to build up object representations and their performance in this condition formed a baseline for the test phase. Fourth, we added the object's complexity as a research variable. This was done to investigate whether the effect of interactive learning depended on the object's complexity. It is possible that participants with a low VSA benefited more from interactivity when they studied complex objects.

METHODS

Participants

36 University students (26 women and 10 men), age of 18-26 years (*M* = 20) participated in exchange for course credits. All participants had normal or corrected to normal visual acuity, had no known neurological or visual disorders, and were naïve concerning the purposes of the experiment.

Materials and apparatus

For the experiment, 48 novel non-symmetric three-dimensional objects were created with the 3D modeling program Art of Illusion (Free Software Foundation, Inc.). The objects were constructed from a set of 24 “geon-like” components (Biederman, 1987). Each object consisted of a big centre component with smaller components directly attached to it. In total, 24 “simple” objects, consisting of three components, and 24 “complex” objects, consisting of five components, were created. In addition, mirrored versions of the objects were created by removing one of the smaller components and by placing these on the opposite side of the centre component. The objects were gray scale and equal in their illumination and luminance. These 3D objects were used as both study and test objects (see for examples Figure 1 and Figure 2).

A desktop computer was used with a 17" Philips 107-T5 60 Hz monitor running Authorware 7.01 (Macromedia, Inc.) and the Cortona VRML Client 5.1 (Parallel Graphics, Inc.) plug-in, using the ActiveX option in Authorware that enabled the presentation of the study objects. E-Prime 1.1 (Psychology Software Tools, Inc.) presented the test objects and acquired the necessary response data through a standard keyboard and mouse.

Study and test objects were presented on a grey background (184.0 cd/m^2) at a viewing distance of 60 cm. Study objects were presented in the centre of the screen with a mean diameter of 20 cm. Test objects were presented in pairs, left and right on the screen, with a mean diameter of 10 cm. The left object was termed the “original" object, as it was identical to one of the study objects. The right object was the “target” object: it was either the same or a mirrored version of original object. All target objects were 180° rotated over the x-axis, y-axis, or z-axis, compared to the original objects.

General procedure and design

Before the experiment started, participants were tested on their VSA, using Vandenberg and Kuse’s Mental Rotations Test (MRT-A) (Vandenberg & Kuse, 1978; Peters et al., 1995). This test was used to determine to what degree participants were able to mentally rotate

Shepard and Metzler's objects (1971). Participants compared an original object to four rotated alternatives and identified the two identical objects from them. In three minutes, participants completed as many trials as possible from a total of 24 trials. The number of correct trials determined the participant's test score and subsequent VSA group (low, middle, or high ability) allocation.

After the participants had received explicit instructions to study the 3D objects as thoroughly as possible, the experiment started with 2 blocks of practice trials followed by 12 blocks of experimental trials. The three exploration conditions, each covering four blocks, were counterbalanced across participants. A block of trials consisted of a study phase and a test phase. Each block comprised two simple and two complex objects randomly drawn, with the order of object complexity counterbalanced.

Study phase procedure

Each block started with a study phase in which participants studied four objects in one of three exploration conditions. In the passive exploration condition, participants observed 3D objects, while these objects rotated 360° over the x-axis, y-axis, and z-axis, with no interaction possible (Figure 1, middle frame). In the active exploration condition, participants were able to explore objects interactively by rotating the object in any direction with a computer mouse (Figure 1, right frame). Each object was presented for 30 seconds, with a 5 second interval between objects. In a third condition, participants conducted a simple math task and studied no objects (Figure 1, left frame). The math task was used to keep the participants occupied during the same period in which four objects were studied (i.e., 140 seconds) and provided the participant's baseline condition for the test phase. Performance in the baseline condition reflected the participant's general ability to rotate unknown objects.

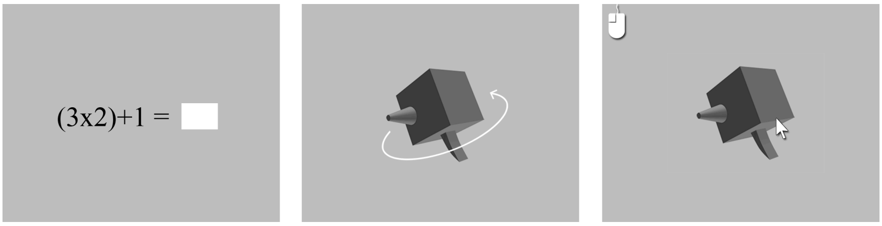

Figure 1. Schematic overview of the different exploration conditions. The baseline (left), in which participants conducted a simple math task, the passive (middle), and the active (right) conditions.

Test phase procedure

Each test trial started with a 750 ms presentation of a black fixation cross in the centre of the screen followed by an original and a target object, presented simultaneously on the screen (Figure 2). Target objects were presented with either a 180° rotation over the x-, y-, or z-axis, and identical or mirrored compared to the original object. When these two objects appeared, the participants were required to determine as quickly and accurately as possible whether or not these objects were identical. These test objects remained visible until a key-response was given: m for same object, z for mirrored object. Response latency and accuracy were recorded automatically. No feedback was given until the end of the test block. This procedure continued until response was given on the four previously studied objects, with six different test trials per object; rotated once over each axis and identical as well as mirrored. So, each test block contained 24 test trials. A total of 288 responses were given in the 12 blocks of the complete experiment.

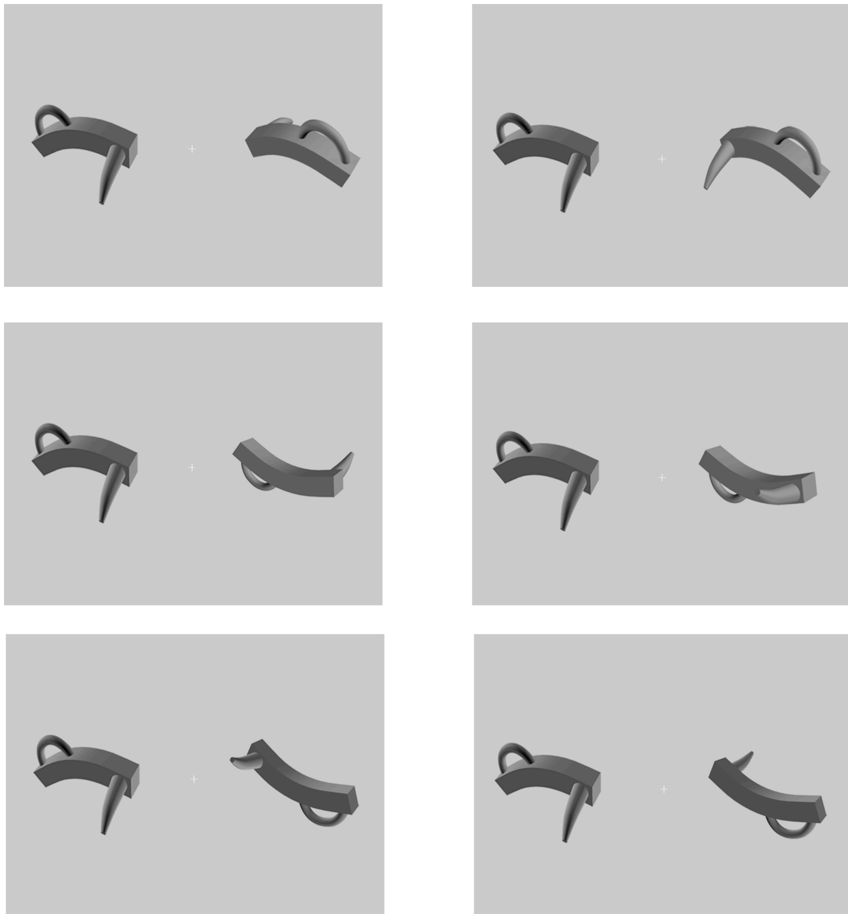

Figure 2. Screenshots of the displays as shown in the test phase. The left displays depict identical objects, the right displays mirrored objects. Target objects (right on the display) were always rotated over one of its axes compared to the original objects (left). Each object was displayed six times in total; rotated over each of its axes, identical and mirrored.

RESULTS

Per block, trials in which reaction times exceeded three times the standard deviation from the mean were discarded. In total, three percent of the data set was excluded from our analyses. Reaction times and accuracy data were analyzed using two separate repeated-measures 3 x 2 x 3 ANOVAs, with Exploration Condition (baseline, passive, and active) and Object Complexity (simple and complex) as within-subjects variables and VSA Group (low, middle, and high) as between-subjects variable. Planned comparisons were performed to test whether the participants improved their performance differently after active compared to passive exploration of objects, in the low, middle, and high VSA Groups. Two additional repeated-measures 3 x 2 x 2 ANOVAs were run on the reaction times and accuracy data to investigate a possible effect of gender difference, with Exploration Condition (baseline, passive, and active) and Object Complexity (simple and complex) as within-subjects variables and Gender (male, female) as between-subjects variable.

Pre-test

The between-subjects variable VSA Group consisted of a low, middle, and high VSA group, each group comprising 12 participants. The participants were divided into the three groups according to their scores on the MRT-A pre-test; for an overview, see Table 1.

Table 1. Overview of the VSA groups with their MRT-A scores (ranging from 0 to 100 % correct answers).

VSA Group	n	Mean	SD	Min	Max
Low	12	33.3	8.0	16.7	45.8
Middle	12	54.8	3.5	50.0	58.3
High	12	71.2	8.2	58.3	88.0
Total	36	55.8	15.1	16.7	88.0

Accuracy

Participants were more accurate in their decisions after the active exploration (*M* = 79.7%) than after the passive exploration (*M* = 78.8%) and after the baseline condition (*M* = 74.9%), $F(2, 66) = 9.61$, $p < .001$. A difference between the baseline condition and both the passive and active exploration conditions was revealed ($F(1, 33) = 13.14$, $p = .001$), but not between passive and active exploration specifically ($F(1, 33) = 1.27$, $p = .260$). A main effect of Object Complexity was present, $F(1, 33) = 15.58$, $p < .001$. Regardless of exploration condition, participants were more accurate mentally rotating simple (*M* = 79.7%) than complex objects (*M* = 75.9%). Furthermore, an effect of VSA Group was revealed, $F(1, 33) = 8.68$, $p = .006$ (for an overview see Figure 3). The high VSA group was more accurate (*M* = 78.9%) than the middle VSA group (*M* = 76.2%) and the low VSA group (*M* = 71.9%).

Moreover, with the baseline condition discarded, the repeated measures ANOVA revealed a significant interaction between VSA Group and Exploration Condition, $F(2, 33) = 5.45$, $p = .009$. Participants in the low VSA group improved their performance after active exploration (*M* = 75.5%) compared to passive exploration (*M* = 71.1%), $F(1, 11) = 5.51$, $p = .009$. However, participants in the middle and high VSA groups did not, with respectively $F(1, 11) = 1.57$, $p = .24$ and $F(1, 11) = 0.03$, $p = .87$. The results did not show an interaction effect between Object Complexity and VSA Group, $F(2, 33) = 2.15$, $p = .13$. In addition, no significant interaction was found between Object Complexity and Exploration Condition, $F(2, 66) = 0.61$, $p = .54$.

The repeated measures ANOVA with Gender as between-subjects variable did not reveal a significant main effect of Gender, $F(1, 33) = 1.11$, $p = .30$. Male participants (*M* = 79.9%) were as accurate as the female participants (*M* = 76.6) in the experiment. Furthermore, no significant interaction effects with Object Complexity and Exploration Condition were observed.

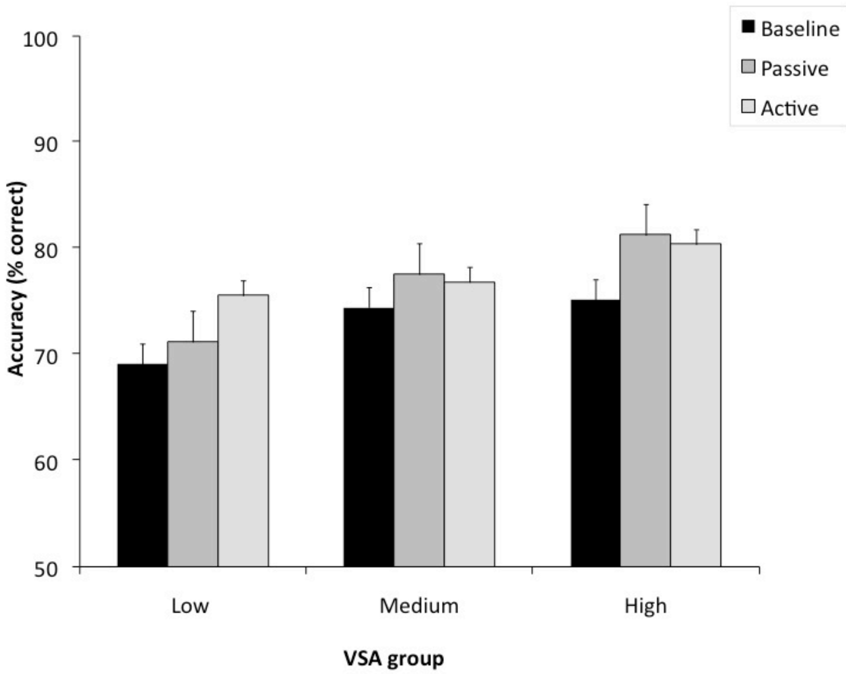

Figure 3. The percentage of correctly identified target objects during the test phase for each VSA group, with their mean standard error indicated. Each bar represents the mean accuracy of both the simple and complex objects together.

Reaction Times

A main effect of Object Complexity was revealed on reaction times, $F(1, 33) = 273.33$, $p < .001$. In general, participants were faster ($M = 3915$ msec) reacting to simple objects than to complex objects ($M = 4857$ msec). No significant main effect was observed between the male participants ($M = 4284$ msec) and the female participants ($M = 4425$ msec), $F(1, 33) = 0.79$, $p = .38$. Further, the data did not reveal any significant effects; hence, a possible speed accuracy trade-off was ruled out (for an overview see Table 2).

Table 2. Overview of the mean RT in msec with their standard error of mean (SEM) for each VSA group on complex and simple objects in the three exploration conditions.

M (SEM)	Baseline		Passive		Active	
VSA Group	*Complex*	*Simple*	*Complex*	*Simple*	*Complex*	*Simple*
Low	4720 (231)	4008 (183)	5332 (347)	4348 (282)	5145 (231)	4260 (239)
Middle	4869 (348)	3863 (259)	4522 (337)	3777 (248)	4812 (206)	3742 (222)
High	4834 (315)	3685 (260)	4809 (365)	3700 (236)	4671 (269)	3852 (231)

DISCUSSION

The current study investigated the effect of interactive exploration of 3D objects and the differences between individuals. Previous studies showed that participants improve their performance on a spatial task after interactive exploration of objects, compared with passive observation (Harman et al., 1999; James et al., 2001). Luursema et al. (2006) suggested that only participants with a low VSA benefit from interactive exploration when studying anatomical information. In line with this observation, we expected that interactive exploration of 3D objects improves constructing mental representations and that the effect depends on the participant's VSA. For the purpose of our study, we divided participants into three VSA groups (i.e., low, middle, and high) and assessed their mental rotation ability after interactive, passive, or no exploration of objects.

The low VSA group improved their performance on a mental rotation task after interactive exploration compared with passive observation of objects. However, the middle and high VSA groups did not improve their performance. Furthermore, the low VSA group did not increase their performance in the passive exploration condition compared to the baseline condition, whereas in the other two groups did. These findings suggest that after either passive or active exploration of objects mental representations are stored in memory, which are later used when performing a mental rotation task. However, the differences between the VSA groups suggest that the low VSA group only used these representations after active exploration, whereas the middle and high VSA groups used these after passive exploration as well. So, in contrast to the earlier studies of Harman et al. (1999) and James et al. (2001), no evidence was found for a general effect of interactive exploration across all three VSA groups.

There are two possible explanations for the absence of a general effect. Either the participants' VSA or the use of a mental rotation task in the test phase resulted in the differing results from these previous studies. Which of these manipulations caused the different results as compared to previous studies is not clear. In the first case, it is possible that in the present study the mean VSA of the participants was higher than in the earlier studies of Harman et al. and James et al., which could have influenced the main effect of interactive learning. However, the differences in the mean VSA between the studies is unknown. A second possible explanation for the absence of a general effect is that the participants were not required to refer to the object representations in order to conduct the mental rotation task. This could have flawed the main effect. However, the fact that the participants did use the representations in most conditions except for the passive condition in the low VSA group is an interesting finding.

Alternatively, the effect of interactive exploration as found in the low VSA group can also be an effect of attention. It is possible that participants with low VSA did not focus in the passive condition on the objects but did in the active condition, whereas the other two groups focused on the objects in both conditions. When participants do not view the objects during the learning phase, they do not build up accurate mental representations from them (Christou & Bülhoff, 1999). However, in the instructions to the participants prior to the experiment we emphasized that the objects should be studied as thoroughly as possible, because these objects would be tested afterwards. These instructions cannot fully rule out an effect of attention, but prevented it as much as possible. Nevertheless, future research should control for the effect of attention experimentally.

Furthermore, participants were slower and less accurate with objects build up from five compared to three components. This suggests that participants compared objects by their components in the test phase rather than as a whole. James et al. (2001) suggested that interactive exploration provokes participants to use a more successful holistic strategy when processing objects. Our experiment took the possibility into account that especially the low VSA groups changed their strategy to a more successful one after interactive exploration. Gauthier and Tarr (1997) already showed that strongly familiar objects are processed more holistically, whereas unfamiliar objects are processed analytically. In line with this finding, we expected the same principle for simple and complex objects, since simple objects are easier familiarized than complex objects. Thus, when participants use a holistic strategy with simple object and an analytical strategy with complex objects, one would expect a large difference in the test phase between the two types of objects. When both types of objects are processed more holistically, one would expect smaller differences in the performance in the test phase. Furthermore, when the low VSA group changed their strategy, whereas the high VSA group did not need to, we expected to find an interaction effect between Object Complexity, Exploration Condition, and VSA Group. However, only a general effect of Object Complexity was found in the reaction times. So, no evidence was found that indicates that interactive exploration provoked holistic processing of objects or a strategy change in either VSA group.

In conclusion, the studies of Christou and Bülthoff (1999), Harman et al. (1999) and James et al. (2001, 2002) did not take the possibility into account that the effect of active exploration is dependent on individual differences in VSA. The present results suggest, however, that populations with varying VSA are differently affected by active exploration of objects. Cornoldi and Vecchi (2003) pointed out the relevance of individual differences in visuo-spatial memory. They showed the limitations of visuo-spatial working memory and found that populations varying on certain characteristics (e.g., in age or gender) are differently affected by these limitations. They argued that visuo-spatial working memory is a multi-componential cognitive function, which involves different types of visuo-spatial mechanisms (ranging from passive to active storage). We propose that active storage is stimulated by interactive learning and that populations varying in their VSA are differently dependent on this incentive. This does not implicate previous findings that motoric activity affects perception and mental representations. However, it does refine any conclusion suggesting that the effect is general for different populations. Therefore, our current research underlines the importance to consider individual differences, especially in VSA, when investigating the visuo-spatial system.

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Chapter 3

Active exploration improves the quality of the representation of virtual 3D objects in visual memory

ABSTRACT

The effect of active exploration on constructing objects representations in memory was investigated. In four experiments, participants studied twelve objects by active exploration and twelve other objects by passive observation. Subsequently, participants were tested on their ability to mentally rotate or recognize these studied objects. Results revealed that active exploration: 1) does not affect mental rotation, 2) affects object recognition, 3) compensates for the recognition of visually degraded objects, and 4) is not due to general differences in attention. These findings underline the benefit of active exploration for object recognition and suggest that the benefit is a result of the action itself.

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INTRODUCTION

To familiarize themselves with a new object, people have a strong tendency to manipulate this object with their hands and examine it from different perspectives. It may be proposed that this active exploration actually improves the consolidation of information regarding the identity and functionality of these objects in memory. In line with this, the research literature on visual perception treats the role of performing actions as an important subject and assumes that action and perception are strongly interrelated. Gibson (1950, 1979) argued that visual perception and action should be considered as two complementary aspects of human behavior, with one being reliant on the other, and vice versa. According to Gibson, actions are mainly coordinated by visual perception, and also the main purpose of visual perception is to perform actions within an environment (see also e.g., Held, 1965; Neisser, 1976). This supposed mutual relation between action and perception may indeed be taken as an argument why people have a strong tendency to actively explore objects: active exploration will affect the (visual) processing of these objects, and thereby it will also improve multiple aspects of the representations of these objects in memory. Nevertheless, what cognitive processes actually benefit from this active exploration of objects is a matter of debate.

As Gibson stated, perceptual information is usually gathered by performing actions within an environment, and visual perception mostly concurs with eye, head, or body movements. A large body of evidence supports the assertion that this dynamic nature of visual perception plays an important role in the storage of spatial information in memory (e.g., Appleyard, 1970; Christou & Bülthoff, 1999; Chance, Gaunet, Beall, & Loomis, 1998; Luursema et al., 2006; Péruch, Vercher, & Gauthier, 1995; Sun, Chan, & Campos, 2004; Wang & Simons, 1999). For example, Christou and Bülthoff (1999) provided evidence that active exploration of environments improves subsequent scene recognition. In this study, a simulated environment was studied actively by controlling one's own movements with a SpaceBall computer mouse or passively by observing another person's actions. To motivate active explorers to move around the environment as much as possible, they had to search for markers placed at different locations. In both active and passive conditions these markers had to be memorized. On a subsequent recognition task, the ability to discriminate between views of locations taken from the studied environment and views of locations from a novel environment was tested. The results revealed no significant differences in the recognition of actively and passively locations when these locations contained the to-be-memorized markers. However, if these locations did not contain the markers, actively studied locations were more easily identified than passively studied locations. This suggests that in the passive condition locations were only memorized with the instruction to do so, whereas in the active condition locations were also memorized without this instruction. Therefore, the researchers proposed that active exploration results in more complete spatial encoding in memory.

In a similar manner, a number of studies investigated the role of active exploration on constructing object representations in memory. A study of Harman, Humphrey and Goodale (1999) revealed an effect of active exploration on subsequent object recognition. In this study, 3D objects were first studied actively through manual rotation, or passively through observation of a recorded rotation. Afterwards, the ability to discriminate studied objects from novel objects was tested in a recognition task. The results showed that actively explored objects were better recognized than passively observed objects. James, Humphrey and Goodale (2001) revealed a similar effect on subsequent mental object rotation. In this study, a mental rotation task was used in which two objects, presented from different viewpoints, were compared to determine whether or not the objects were the same. Results showed that the comparison of actively explored objects was more accurate than the comparison of passively explored objects. This was further refined by a study of Meijer and Van den Broek (2010), in which it was shown that an effect of active exploration on mental rotation was found, but now only for people who had relatively low visuospatial abilities. These results suggest that active exploration triggers certain visuo-spatial processes that aid the efficiency with which objects are represented in memory, but only for individuals with low visual spatial ability.

Various hypotheses have been proposed to explain the effect of active exploration. James et al. (2001) observed that during active exploration specific viewpoints of objects were preferred. These researchers showed that plane views of the objects, such as frontal or side views, were selected more often and for a longer duration in the study phase as compared to intermediate views. It is possible that these views are important to construct accurate mental representations of these objects, because here the greatest amount of change in the visibility of the object features occurs with the smallest object rotations (Perret & Harries, 1988; Perret, Harries, & Looker, 1992). This may be taken to suggest that active exploration of objects facilitates free control over the selection of plane views, which in turn improves constructing object representations in memory. In the following, this hypothesis will be denoted as the free control hypothesis. Another possibility mentioned by James et al. is that active exploration may create stronger associations between the different views of the objects stored in memory. This might improve object recognition, because familiar object views are more easily accessed due to these stronger associations, and novel views are more easily derived from the existing object representations. It would also explain improved mental rotation performance, because the same associations would be reactivated as when the object was physically rotated. This hypothesis may be denoted as the association hypothesis.

Both aforementioned hypotheses support the notion that active exploration affects visual processing of an object and, thereby improves the quality of the visual representation of this object. From the literature emerges, however, another possible influence of active exploration on constructing object representations: the possibility that active exploration incorporates a motoric component as well. This hypothesis will be denoted as the motoric hypothesis. The involvement of a motoric component is supported by a number of studies, which provided evidence for an interaction between visual and motoric processing of studied objects (e.g., Creem & Proffitt, 2001; Wexler, Kosslyn, & Berthoz, 1997; Wiedenbauer, Schmid, & Jansen-Osmann, 2007; Wohlschläger & Wohlschläger, 1998). For example, these researchers suggested that mental rotation not only involves visual processes, but also covert motor processes. In this case, active exploration leads to a qualitatively different storage of objects in memory. Not only visual characteristics of an object are stored, but also the actions that can be performed on this object. This hypothesis provides some support by a study of Pecher, Zeelenberg, and Barsalou (2003) who argued on the ground of their data that conceptual processing is grounded in the sensorimotor system and shares many mechanisms with perception and action. This can also account for storing concepts, or representations, of objects. Thus, after active exploration one might rely on non-perceptual information as well which may facilitate the ability to recognize and especially to mentally rotate explored objects.

Another explanation that was not fully acknowledged in previous studies is the idea that the effect of active exploration may simply reflect differences in the allocation of visual attention, being enlarged in the case of active exploration. It has been argued that the relation between action and perception is realized through attention and that attention is in fact a selection of cognitive resources to conduct an action (e.g., Allport, 1987; Neumann, 1987; Van der Heijden, 1992; Van der Heijden, 2004). This may explain the results of Christou and Bülthoff (1999), which showed an effect of active exploration on recognition of unmarked but not of marked locations. Attention is likely to be increased on marked as well as unmarked locations when the environment was actively explored. However, when the environment was passively observed, attention was increased only on the marked locations due to the requirement to memorize these locations. Therefore, differences in the allocation of attention may be proposed as an alternative to explain the effect of active exploration of objects. This hypothesis will be denoted as the attention hypothesis. When an object is actively explored, attention is automatically allocated on this object, whereas in the case of passive observation, the amount of attention will probably be much smaller. Increased attention during active exploration of an object may improve the visual processing of this object and thereby result in improved quality of an object representation in memory. Previous studies merely instructed the participants to attend the objects in all conditions as carefully as possible. However, this instruction does not guarantee that participants actually did so.

The current study first aimed to test the motoric hypothesis. Because previous studies revealed an involvement of covert motor processes in mental rotation (e.g., Wexler et al., 1998), we expected that differences in rotation performance would at least partially reflect changes in the motor-related object representations. Therefore, in our first experiment, participants first actively and passively studied objects, and subsequently, they were tested on a mental rotation task. This experiment is similar to an earlier study of Meijer and Van den Broek (2010), which did not provide evidence for a main effect of active exploration on subsequent mental rotation. However, there were two methodological issues that could have caused an absence of an effect. First, participants did not receive the same sequence of viewpoints of the objects in the passive and active study conditions. In the passive condition, objects rotated continuously 360° over each of the objects' axes, whereas in the active condition only a limited number of object viewpoints were selected by manual control. This could have resulted in a difference in visual processing between the passively and actively studied objects, which could have diminished the effect of active exploration on a subsequent mental rotation task. Second, the fact that objects were presented more than once in the test phase was not taken into account. The earlier presentation of an object may affect the mental rotation performance on later presentations of this object (so-called pro-active interference). Possibly an effect of active exploration was only revealed on the first presentations of the objects in the study phase, when pro-active interference could not have occurred. This could have decreased the sensitivity of the mental rotation task in finding a possible effect of active exploration. Therefore, in Experiment 1 some further refinements were carried through to control for a possible influence of these issues. We decided to implement a so-called yoked design in the study phase. In this design, one participant actively explores a number of objects while another passively observes the actions of the other, which ensures that the same sequence of viewpoints is presented for the active and the passive observer. In our experiment, after presenting 50 % of the objects the roles of the active and passive observer were exchanged, which is the common procedure in a yoked design. Moreover, the presentation order of objects in the test phase of the experiment was taken into account as a within-subjects variable.

EXPERIMENT 1

Methods

Participants

Twenty-two persons (6 males and 16 females) participated either in exchange for course credits or they participated voluntarily. Participants' age ranged from 19 to 41 years with a mean age of 22.5 years. All participants were right handed and reported normal or corrected-to-normal visual acuity. Furthermore, they were naïve with regard to the displayed objects and the purpose of the experiment. The study was approved by the ethics committee of the Faculty of Behavioral Sciences, and all participants signed a written informed consent.

Stimuli and apparatus

For the experiment, 48 new virtual 3D objects were created using the 3D modeling program Art of Illusion (Free Software Foundation, Inc.). These objects were composed of three or five "geon-like" components (Biederman, 1987) and were colored gray. Each object consisted of a big centre component with smaller components directly attached to it. These 3D objects were used as study and test objects.

The study objects were presented in the centre of the screen with a mean diameter of 20 cm. The test objects were presented pairwise, left and right on the screen, with a mean diameter of 10 cm each (see Figure 1). The left object was termed the "original object" and the right object was termed the "target object". A target object was either the same as or a mirrored version of the original object and was always rotated 180° over the x-, y-, or z-axis. In both the study phase and the test phase, objects were presented on a light gray background. The participants viewed the objects from a distance of approximately 60 cm.

Experimental design and apparatus

A so-called yoked design was used to ensure that participants had identical views in the active and passive study conditions. Therefore, two Pentium IV computers connected to two 17-inch CRT computer monitors were used in the experiment. The software program Authorware (Macromedia inc.) with the Cortona VRML Client 5.1 (Parallel Graphics, Inc.) plug-in presented the study objects. E-Prime 1.1 (Psychology Software Tools, Inc.) presented the test objects and acquired the necessary data through standard computer keyboard. Each computer monitor was connected to two computers through a switchbox. This made it possible to switch the computer monitors from one computer to the other. At the start of the study phase, both monitors were connected to computer 1. This enabled one participant (at monitor 1) to manipulate the study objects actively with a standard computer mouse while another participant (at monitor 2) observed these manipulations passively. Thus, to perform the experiment it was necessary that participants were tested in pairs simultaneously. Halfway the study phase, the monitors were switched to computer 2 and the participants' roles were exchanged. Participants were not informed about the presence of the other participant. In the test phase, the computer monitors were "uncoupled": monitor 1 was switched back to computer 1 and monitor 2 remained switched to computer 2.

Task and procedure

The experiment was divided in a study phase and a test phase. First, participants studied a set of 24 objects in a study phase of which 12 objects were studied in the active condition and another 12 in the passive condition. The objects were studied 30 seconds each, with a 5 second interval between them. The order of objects in the study phase was randomly selected. However, the participant pairs always received the same order, because of the yoked design. Before the experiment started, participants were instructed to memorize these objects as accurately as possible. The experiment started with two practice objects to familiarize the participants with the study phase procedure.

In the test phase, the participants were required to perform a mental rotation task. The participants were instructed to determine as accurately as possible whether target objects were the same as or a mirrored version of the original objects. Feedback about participants' performance was given at the end of each block (mean reaction time and accuracy). When mean reaction time was too slow (above 6500 msec) or accuracy too low (below 75 %), participants were encouraged to improve their performance. Responses were acquired with a standard keyboard. Participants indicated “same objects” with the “m” button, and “mirrored objects” with the “z” button. Participants judged in total 48 objects in six separate blocks. Each block contained eight objects of which two were passively observed objects, two actively explored objects, and four were novel objects. Participants received four test trials per object: target objects were rotated over two of its axes and the same as well as mirrored compared to the original objects. Thus, each block consisted of 32 trials. In total, participants received 192 experimental trials.

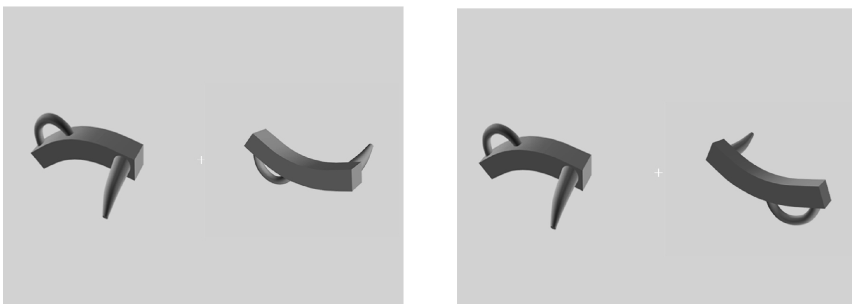

Figure 1. Examples of the stimuli employed in the mental rotation task as presented in the test phase. On the left, the objects are 180^{o} rotated and the same; on the right, the objects are mirrored versions of each other.

Data analysis

Performance in the test phase was measured in terms of accuracy (% correct answers) and RT (msec). Because objects were presented more than once within the test phase, the first presentation may affect the performance on later presentations (i.e., so-called pro-active interference). Therefore, the order of object presentation was accounted for in the analyses. Reaction times and accuracy data were analyzed using two separate repeated-measures 3 x 4 ANOVAs, with Study

Condition (no-study, passive, and active) and Presentation Order (1 to 4) as within-subjects variables. Additional comparisons were made to specifically test differences between the active and passive study condition, and between the passive and no-study condition. Moreover, accuracy performance in each condition was compared to a 50 % baseline performance, at which participants would have randomly guessed, to determine whether participants had conducted the task appropriately.

Results

Figure 2 shows the mean accuracy in the mental rotation task. The analysis of the accuracy data did not reveal a significant main effect of the Study Condition in the mental rotation task, $F(2, 42) = 0.02$, $p = .981$, $\eta^2 = .001$. The participants achieved a comparable level of accuracy for the passively studied, actively explored, and the novel objects, with respectively 72.9, 73.5, and 73.7% correct responses. Likewise, no significant differences between novel and passively studied objects, $F(1, 21) = 0.41$, $p = .527$, $\eta^2 = .019$, and between passively and actively studied objects were found, $F(1, 21) = 0.73$, $p = .401$, $\eta^2 = .034$. However, for all objects, accuracy was better than the 50 % baseline performance; for novel objects, $F(1, 21) = 88.15$, $p < .001$, $\eta^2 = .808$; for passively studied objects, $F(1, 21) = 47.88$, $p < .001$, $\eta^2 = .695$, and for active explored objects, $F(1, 21) = 89.50$, $p < .001$, $\eta^2 = .810$. No significant main effect of Presentation Order of objects was found, $F(3, 63) = 0.99$, $p = .403$, $\eta^2 = .045$. Participants were equally accurate on the first presentation of an object in the test phase as on the following three presentations. Analysis of the RTs did not reveal an effect of Study Condition, $F(2, 42) < 1.00$, $p > .50$.

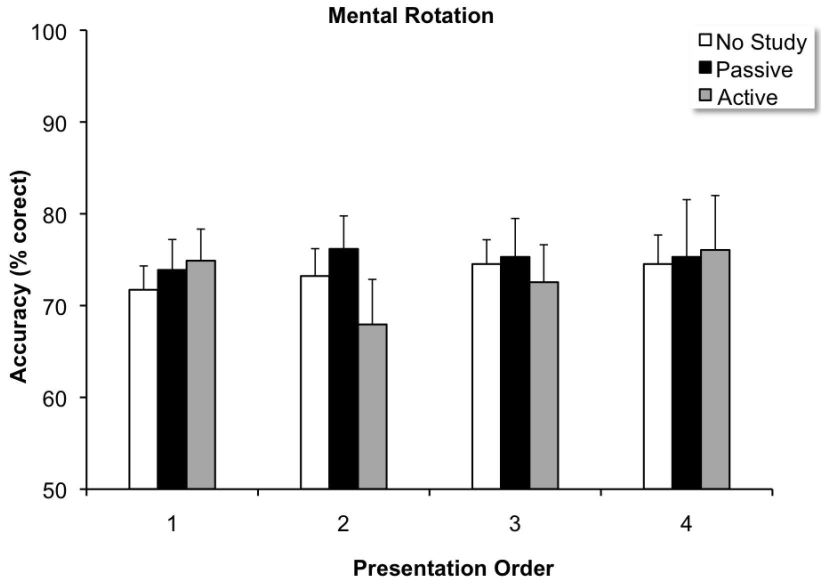

Figure 2. The participants' performance in the mental rotation task as a function of presentation order. Error bars represent the standard errors of the mean. Note that a score of 50% is at chance level.

Discussion

Our first experiment aimed to test the motoric hypothesis by investigating the effect of active exploration of objects on a subsequent mental rotation task. The prediction was made that if active exploration would induce motor-related object representations, then a difference in mental rotation performance should be observed. However, our results did not confirm this prediction. Although participants conducted the mental rotation task appropriately (i.e., above chance level), they did not benefit from either passively or actively studying the objects. The absence of an effect in the presentation order of objects in the test-phase excluded the possibility that pro-active interference could explain the absence of an effect of active exploration. Thus, these results are in contrast with earlier studies that showed an influence of study condition in a mental rotation task (e.g., James et al., 2001; Wiedenbauer et al., 2007). Given the fact that the effect of active exploration on a mental rotation task was not consistent across studies, one might argue that motor-related representations are not strongly activated due to earlier active exploration. This raises the idea that active exploration affects visual rather than motor-related object representations. Therefore, a second experiment was run to test the effect on the visual representations, with an identical study phase as in our first experiment.

A task that is commonly used to assess visual object representations in memory is a recognition task (for an overview, see Peissig & Tarr, 2007). Therefore, in Experiment 2, the mental rotation task in the test phase was replaced by an object recognition task. Similar to a study of Harman et al. (1999), participants first studied objects actively or passively and subsequently, they were tested on their ability to discriminate between studied and novel objects. In contrast to this study, possible pro-active interference was taken into account. Since each object was presented more than once in the test phase, earlier presentations of the objects could influence later presentations. If pro-active interference occurred, this would be an extra indication that visual memory was involved. Thus, we expected that the use of a recognition task might tap on different memory representations that may be affected by prior active exploration, although this test may be less sensitive for motor-related representations. In the object recognition task, a single object was presented on the computer screen and participants had to indicate whether or not they had studied the object before. We asked participants to respond as accurately as possible. We expected that performance improved in the active as compared to the passive condition.

EXPERIMENT 2

Methods

Participants

Twenty-two persons (7 males and 15 females) participated in exchange for course credits. The participants ranged from 18 to 25 years in age with a mean age of 20.7 years. All participants were right handed and reported normal or corrected-to-normal visual acuity. Further, they were naïve with regard to the displayed objects and the purpose of the experiment. The study was approved by the ethics committee of the Faculty of Behavioral Sciences, and all participants signed a written informed consent.

Stimuli and apparatus

The same stimuli were used as in Experiment 1 in the practice phase, but in the test phase only one object was presented in the centre of the screen with a diameter of 10 cm.

Experimental design and apparatus

The same design and apparatus was used as in Experiment 1.

Task and procedure

The study phase of the experiment was the same as in Experiment 1. The test phase, however, contained an object recognition task instead of a mental rotation task. In total 48 objects were presented in the test phase, of which 12 were actively explored, 12 were passively observed, and of which 24 new objects were presented. Participants were instructed to determine as accurately as possible with a time limit whether or not they had studied the object before in the study phase. The test phase was divided into six blocks each containing eight objects, half of which were studied and half of which were not. On the keyboard the “z” button had to be pressed for “old objects”, and the “m” button had to be pressed for “new objects”. Participants received feedback after each block about their performance. When mean reaction time was too slow (above 1500 msec) or accuracy too low (below 75 %), participants were encouraged to increase their performance. The time limit was lower than in Experiment 1, since object recognition is generally performed faster than mental rotation. Within each block, an object was presented four times from different perspectives. Thus, each block consisted of 32 trials and the order of trials was random. In total, the test phase contained of 192 test trials.

Data analysis

Analyses primarily focused on the “old objects” by comparing the active exploration and passive observation conditions. Because objects were presented more than once within the test phase, the first presentation might interfere with the performance on later presentations. Therefore, the order of object presentation was included as a factor in the analyses. Accuracy and RT data were analyzed using two separate repeated-measures 2 x 4 ANOVAs, with Study Condition (passive and active) and Presentation Order (1 to 4) as within-subjects variables.

Results

Figure 3 shows the mean accuracy in the object recognition task. In contrast to Experiment 1, analysis of the accuracy data revealed an effect of the study condition, $F(1, 21) = 4.33$, $p = .049$, $\eta^2 = .171$. Actively studied objects were recognized more accurately (M = 55.6 %) than passively studied objects (M = 46.3 %). Furthermore, no significant main effect of Presentation Order of objects was found, $F(3, 63) = 1.87$, $p = .143$, $\eta^2 = .08$. Thus, no influence of pro-active interference was found for the studied objects. Furthermore, analysis of the RTs showed no significant differences between the active and passive conditions, $F(1, 21) < 1.00$, $p > .40$.

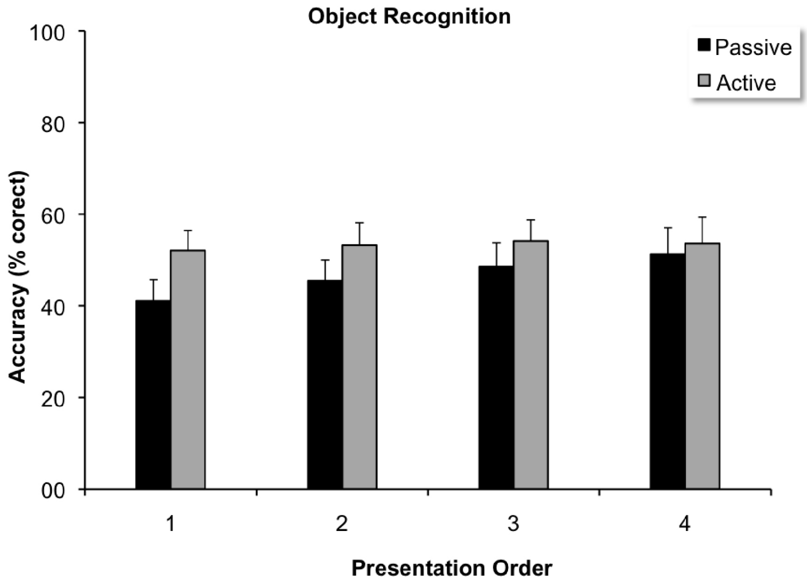

Figure 3. The participants' performance in the object recognition task as a function of presentation order.

Discussion

The aim of Experiment 2 was to investigate the effect of active exploration on the quality of visual object representations by using an object recognition task in the test phase. It was expected that if active exploration affects visual representations, then an improved recognition of actively studied objects should be observed. The results confirmed this prediction, which was consistent with the idea that active exploration affects visual rather than motor-related representations of the objects.

To investigate to what extent active exploration improves object representations, a follow-up experiment was conducted. In this experiment we examined whether active exploration may compensate for the recognition of visually degraded objects. For this purpose, the quality of the object images in the test phase was varied. In general, participants decrease their recognition of objects when these are visually degraded (Biederman, 1987). Therefore, in our third experiment, a condition was added in which half of the objects in the test phase were covered with a mask. Based on the results in Experiment 2, we expected to find a difference between the active and passive condition for the unmasked objects. An improved recognition of actively studied masked objects as compared to passively studied unmasked objects would indicate that active exploration even compensates for the effect of stimulus degradation. This would further support the idea that active exploration affects visual object representations rather than motor-related representations.

EXPERIMENT 3

Methods

Participants

Thirty-six persons (14 males and 22 females) participated in the experiment in exchange for course credits, or they participated voluntarily. Ages ranged from 18 to 56 with a mean age of 24.4 years. All were right handed and reported normal or corrected-to-normal vision. The participants were naïve to the purpose of the experiment. The study was approved by the ethics committee of the Faculty of Behavioral Sciences, and all participants signed a written informed consent.

Stimuli

The same stimuli were used as in the prior experiments. However, in the test phase, half of the images of the 3D objects were masked (for an example, see Figure 4). Masks were randomly generated and covered approximately 45% of the object.

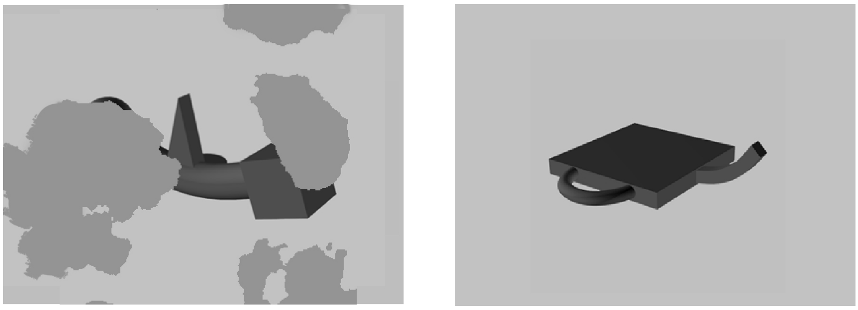

Figure 4. Examples of masked object (on the left) and a not masked object (on the right) as used in the test phase in Experiment 3.

Experimental design and apparatus

The design and apparatus used in this experiment was the same as the prior experiments.

Task and procedure

The same task and procedure were used as in the prior experiments. First, the participants studied 12 objects actively and 12 objects passively in a yoked design. After the study phase, the participants were tested in an object recognition task. Furthermore, half of the test trials contained masked object images. The participants were instructed to respond as accurately as possible whether or not the objects were studied before. The experiment consisted of 192 test trials.

Data analysis

Two repeated measures 2 x 2 x 4 ANOVAs were conducted, one for the accuracy data and one for the reaction times, with Study Condition (passive and active), Masking Condition (masked and unmasked) and Presentation Order (1 to 4) as within-subjects variables. Additional comparisons were made to compare the masked objects in the active study condition to the unmasked objects in the passive study condition.

Results

Figure 5 shows the mean accuracy on the object recognition task. The analysis of the accuracy data revealed a significant difference between the active and the passive study condition, $F(1, 35) = 29.34$, $p < .001$, $\eta^2 = .46$. Participants were more accurate in recognizing actively studied objects (M = 66.2 %) than passively studied objects (M = 46.2 %). There was also a significant difference between the masked and unmasked condition, $F(1, 35) = 7.58$, $p = .009$, $\eta^2 = .18$. Participants were more accurate in their recognition of intact objects (M = 60.2 %) than degraded objects (M = 56.7 %). The interaction between Study Condition and Masking Condition was not significant, $F(3, 105) = 2.90$, $p = .097$, $\eta^2 = .08$. The comparison between actively studied masked objects and passively studied unmasked objects was significant as well, $F(1, 35) = 14.92$, $p < .001$, $\eta^2 = .30$. Thus, the participants recognized actively studied objects more accurately even when they were visually degraded in the test phase (M = 62.9 %) than passively studied objects that were intact in the test phase (M = 46.8 %). Furthermore, there was a significant effect of Presentation Order of objects in the test phase, $F(3, 105) = 4.77$, $p = .004$, $\eta^2 = .12$. Participants showed improved performance on the later presentations as compared to the first presentation of objects. However, there was no interaction between the study condition and the order of presentation, $F(3, 105) = 1.68$, $p = .177$, $\eta^2 = .05$. In the RT data, no main significant differences were found of Study Condition, $F(1, 35) < 1.00$, $p > .40$, and Masking Condition, $F(1, 35) < 2.00$, $p > .10$.

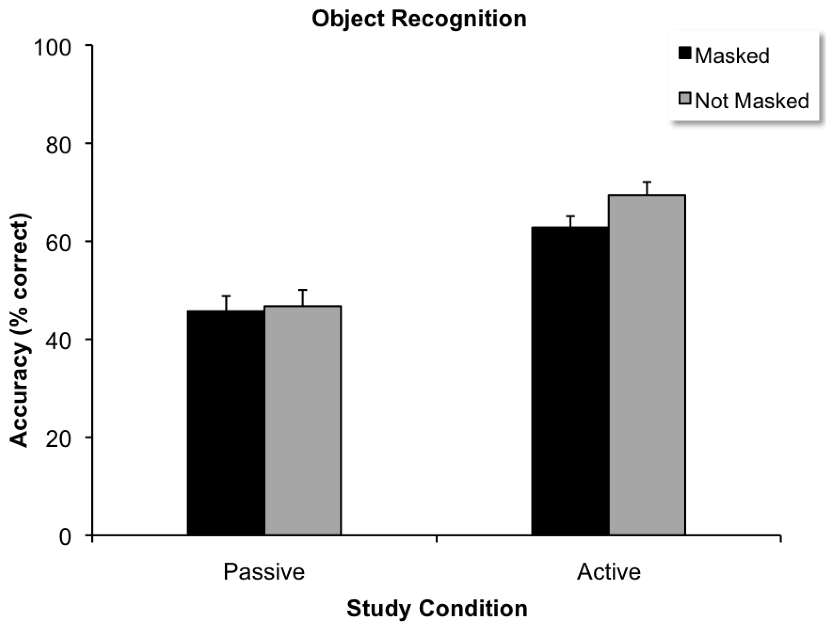

Figure 5. Recognition performance on masked and not-masked objects.

Discussion

The goal of Experiment 3 was to investigate to what extent participants are able to recognize intact and visually degraded objects after active exploration and passive observation. It was predicted that if active exploration would improve the visual object representations to a large extent, then participants might even more easily recognize the masked objects in the active condition than the unmasked objects in the passive condition. Our results confirmed this prediction, which further supports the idea that active exploration affects visual object representations rather than motor-related representations. Furthermore, presenting objects more than once in the recognition task provided an interesting result, as the order of earlier presentations affected the recognition of later presentations. This effect was also observed as a weak trend in Experiment 2. This may be considered as an additional indication for the involvement of visual memory in the test-phase: Presentation of a test object possibly activated the visual representation of this object and activation of this representation further improved recognition.

To further investigate the underlying cognitive processes that may explain the effect of active exploration on visual object representations, a final experiment was run. On the basis of the results of Christou and Bülthoff (1999) it may be argued that participants only devote attention to the marker locations in the passive study condition when these markers had to be memorized and not to the other unmarked locations. In the active study condition, however, participants always devote attention to the environment as they actively explore it. Therefore, the difference on a subsequent recognition task may be explained as a general difference in attention allocation in the passive and active study conditions. In our fourth experiment we further explored this attention hypothesis. This experiment extended our second experiment by adding a second group of participants who served as a control. In this attention group, a simple secondary task was employed to ensure that participants equally focused their attention on the objects during active exploration and passive observation. The study phase consisted of a random number of objects that were marked by a small spot hidden on the main body of the object. Participants had to detect the spots and count the number of marked objects in the test phase. The spots were difficult to detect, and only present on a random number of objects to ensure that participants attended to many viewpoints of the object. At the end of each condition in the study phase, they had to report the number of marked objects. The accuracy of the reported spots in the active and passive condition was compared to verify whether the secondary task had the same effect in both conditions. If attention was located on the objects in both study conditions, no differences in counting performance should be found. Furthermore, if attention in the attention group was increased on the passively studied objects improving further visual processing in memory, then subsequent recognition of these objects should also be improved. Finally, if a general difference in the allocation of attention on the objects fully explained the effect of active exploration, then recognition performance of passively studied should be improved to such extent that it was similar to that of actively studied objects.

EXPERIMENT 4

Methods

Participants

Twenty-four persons (11 males and 13 females) participated in exchange of course credits, or they participated voluntarily, without compensation. Ages ranged between 17 and 40 years with a mean age of 21.6 years. All participants were right handed and reported normal or corrected-to-normal visual acuity. Further, they were naïve with regard to the displayed objects and the purpose of the experiment. The study was approved by the ethics committee of the Faculty of Behavioral Sciences, and all participants signed a written informed consent.

Stimuli

The same stimuli were used as in the prior experiments. A second set of objects was created identical to those used in the prior experiments except that these were marked with a small gray spot (see Figure 6). The spot was slightly darker than the rest of the object to reduce the possibility of a pop-out effect.

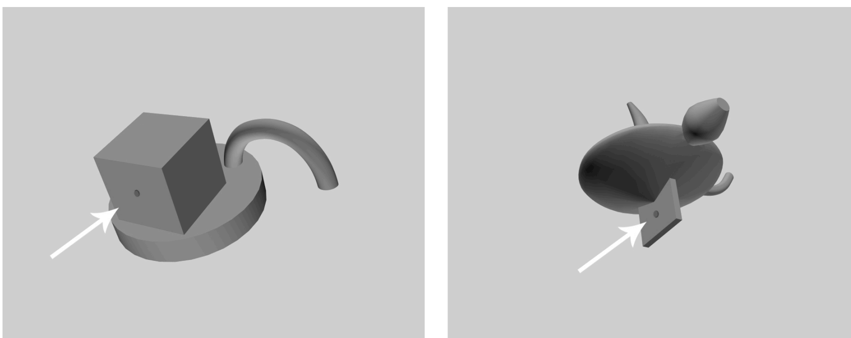

Figure 6. Examples the objects marked by spots as used in the study phase of the attention group in Experiment 4.

Experimental design and apparatus

The design and apparatus used were the same as in the prior experiments.

Task and procedure

Participants were divided into two groups receiving different study phases. One group of participants received the same task and procedure as in Experiment 2. A second group of participants received also the same task and procedure but with an additional task in the study phase. This group was instructed to detect small spots on the objects and count the total of marked objects. The total number of marked objects that appeared in the study phase was randomized to ensure that the participants inspected all object viewpoints as thoroughly as possible in both study conditions. At the end of each condition of the study phase participants were required to report the number of marked objects (min = 0, max = 24). The total number and presentation order of marked objects was randomized. Thus, some participants received more marked objects than others. The total number of correctly reported marked objects was recorded. After the study phase, the participants were assessed in an object recognition task as employed in Experiment 2. Both groups were instructed to decide whether or not they had studied the presented objects before. In total, each participant responded on 192 experimental trials.

Data analysis

Similar analyses were conducted as in Experiment 2 but now with the two attention groups as additional variable. Two 2 x 4 x 2 repeated measures ANOVAs were performed, one for the accuracy data and on for the reaction times with Study Condition (passive and active) and Presentation Order (1 to 4) as within-subjects variables, and Attention Group (attention and no-attention) as between-subjects variable. Furthermore, additional comparisons were made to investigate the differences between the conditions and the groups. Specifically, the no-attention group in the active condition was compared to the attention group in the passive condition to investigate whether attention fully accounted for the effect of active exploration. In the attention group, an additional comparison was made on the accuracy performance on the counting task between the active and passive condition. The accuracy rate in this task was determined by the number of reported marked objects divided by the number of presented marked objects.

Results

Figure 7 shows the mean accuracy on the object recognition task. The analysis of the accuracy data revealed a significant main effect of Study Condition, $F(1, 22) = 21.22$, $p < .001$, $\eta^2 = .49$. Participants more accurately recognized actively studied objects (M = 56.7 %) than passively studied objects (M = 38.5 %). Furthermore, no significant main effect of Attention Group was found, $F(1, 22) = 0.05$, $p = .824$, $\eta^2 < .01$. There was neither a significant difference between the attention and no-attention groups in the active condition ($F(1, 22) = 0.95$ $p = .340$, $\eta^2 = .04$) nor in the passive condition ($F(1, 22) = 0.20$, $p = .656$, $\eta^2 = .01$). Thus, the effect of active exploration was comparable in both attention groups. Finally, no significant main effect of Presentation Order was found, $F(3, 66) = 1.45$, $p = .236$, $\eta^2 = .06$. No main significant effects were found in the RT data for Study Condition, $F(1, 22) < 1.00$, $p > .50$, and Attention Group, $F(1, 22) < 1.00$, $p > .30$. In the study phase, no evidence was found that participants were more accurate in detecting and counting marked objects that were actively studied (M = 90.2 %) than marked objects that were passively studied (M = 88.9 %), $F(1, 22) = 0.75$, $p = .788$, $\eta^2 = .032$.

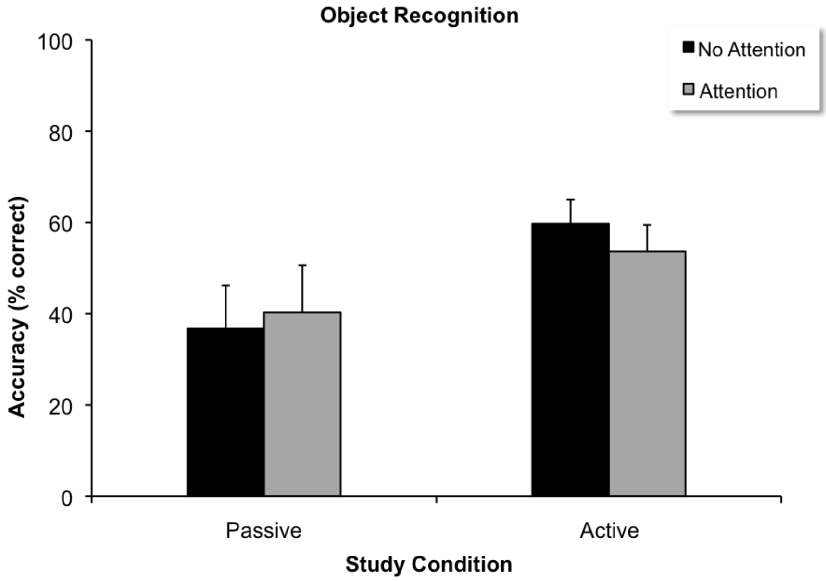

Figure 7. The participants' performance in the attention and no-attention group.

Discussion

In our fourth experiment, we tested the attention hypothesis, which holds that the effect of active exploration on object recognition is caused by a general difference in the allocation of attention on the objects in the study phase. It was predicted that if a general difference in attention played a significant role, then the effect of active exploration should disappear when the participants were forced to focus their attention on the objects in both study conditions. However, in both the attention and no-attention group similar differences were found between the passively and actively studied objects. Thus, the results of Experiment 4 are not in accordance with this prediction and, therefore, do not support the attention hypothesis. However, there is another explanation for the effect of active exploration, which involves focused attention. In the active condition object views were intentionally selected and participants specifically attended these views. In the passive condition object views were not intentionally selected and attention may have been divided over the presented views. This view may be considered as an extension of the idea of James et al. (2001), who proposed that active exploration improved object representations in memory because it facilitates a free selection of relevant viewpoints. The selection of object views may have concurred with an increased attention on these views, eventually improving the visual object representations in memory.

GENERAL DISCUSSION

The aim of the current study was to further investigate the cognitive processes that underlie the effect of active exploration on constructing object representations in memory. Four hypotheses were taken into consideration that might explain the effect of active exploration: the free control, association, motoric, and the attention hypotheses. In four experiments, participants first studied objects passively or actively, and subsequently they were tested similar to the studies of Harman et al. (1999), James et al. (2001), and Meijer and Van den Broek (2010).

First, the motoric hypothesis was examined in more detail in our first and second experiments. Our results showed that active exploration affected subsequent object recognition (Exp.2), but not mental rotation (Exp.1). These results suggest that active exploration induces visual rather than motor-related object representations. These results are consistent with the findings of Meijer and Van den Broek (2010), which also did not show a general effect of active exploration on mental rotation. However, the results were not in line with the findings of James et al. (2001), which did reveal an effect on a mental rotation task. The fact that James et al. were able to find an effect of active exploration may be explained by the type of test task they used in their experiments. First, objects were always rotated in the horizontal plane, which would have made mental rotation considerably easier. Furthermore, these researchers employed a perceptual match task in which studied objects were compared to target objects that were either the same or novel. Therefore, in this matching task participants could have relied on their recognition of the target objects to make their decisions. Thus, although James et al. used a mental rotation task, participants could rely on their ability to recognize the objects. In our test task, however, participants were able to compare the objects, without knowing whether or not they had studied these before.

However, there is an alternative explanation for the absence of an effect on mental rotation in our experiment. In contrast with James et al., participants in our study compared test objects, which were always rotated 180º over one of their axes compared to each other. Possibly, this allowed the participants to alter their mental rotation strategy. Murray (1997) showed that participants are able to mentally "flip" objects with an 180º rotation rather than mentally rotate these objects, which could enhance same-mirror decisions in the test phase in all conditions. Thus, the participants' performance may not have been determined by the quality of the stored object representations, but rather by the ability to apply a "flipping" strategy. In this case, motor-related representations may have been activated, but could not be revealed in the test phase. The fact that test objects were shown more than once with a rotation over different axes in the test phase of the experiment reduced this possibility of applying "flipping" strategies. Nevertheless, future research should take this possibility into account.

The idea that active exploration induced visual rather than motor-related object representations was further supported in Experiment 3. The finding that visually degraded objects were recognized more easily after active exploration than intact objects after passive observation suggests that active exploration can even compensate for the effect of stimulus degradation. In other words, the high quality of the memory representation built up during active exploration compensates for the low visual stimulus quality during the recognition phase.

In our fourth experiment, we further examined the attention hypothesis. The results of this experiment revealed that an effect of active exploration did not diminish when participants were forced to allocate their attention on the objects in both the active and the passive condition. Therefore, it can be concluded that the effect of active exploration does not simply reflect a general difference in the allocation of attention on objects in passive and active study conditions. The fact that there was no difference in the detection of marked objects in both study conditions confirms the idea that the allocation of attention in the passive and active study conditions was rather comparable.

Nevertheless, the possibility may be considered that there is still a difference between passive and active study conditions in focused attention. During active exploration specific object views were intentionally selected and therefore, more attention may have been devoted to these views as compared to passive exploration. As indicated in our introduction, the results of Christou and Bülthoff (1999) revealed an effect of study condition in the recognition of unmarked but not of marked locations, suggesting that focused attention indeed plays an important role in the effect of active exploration.

To summarize, the present study underlines the relevance of motoric activity on visual processing in human memory. This relevance has important implications for a number of professional situations, such as designing complex products. Active exploration improves learning in virtual environments, particularly when complex structures or objects are involved. The current study provides evidence that it is the action itself that improves learning rather than a general increase in attention. Therefore, the interactive characteristic has an important additional value in a virtual environment for individuals who have to work in this environment: interaction with this environment is much better than simply presenting an animation of the same professional situation. Gibson (1950, 1979) already stressed the significance of a relation between action and perception decades ago. Now, with increasing technological possibilities, virtual active exploration of complex structures and objects has become an everyday reality. The current study confirms the usefulness of this approach.

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PART II Case Studies

Chapter 4

Navigating through Virtual Environments: Visual realism improves spatial cognition

ABSTRACT

Recent advances in computer technology have significantly facilitated the use of Virtual Environments (VEs) for Small and Medium Enterprises (SMEs). However, achieving visual realism in such VEs requires high investments in terms of time and effort while its usefulness has not yet become apparent from research. Other qualities of VEs, such as the use of large displays, proved its effectiveness in enhancing the individual user's spatial cognition. The current study assessed whether the same benefits apply for visual realism in VEs. Thirty-two participants were divided into two groups, who explored either 1) a photo-realistic or 2) a non-realistic supermarket presented on a large screen. The participants were asked to navigate through the supermarket on a predetermined route. Subsequently, spatial learning was tested in four pen and paper tests that assessed how accurate they had memorized the route and the environment's spatial lay-out. The study revealed increased spatial learning from the photo-realistic compared to the non-realistic supermarket. Specifically, participants performed better on tests that involved egocentric spatial knowledge. The results suggest visual realism is useful for VEs because it increases the individual user's spatial knowledge in VEs. Therefore, the current study provides evidence that it is worthwhile to invest in the implementation of visual realism in VEs.

Meijer, F., Geudeke, B. L., & Broek, E. L. van den (2009). *CyberPsychology and Behavior, 12(5)*, 517-521.

INTRODUCTION

In the past decades, the use of Virtual Environments (VEs) has become more and more widespread. In numerous of professions new techniques are introduced to simulate virtual situations to increase insight, train skills, or test usability. For example, in product design VEs can provide scenarios in which prototypes are tested early in development (Tideman, Van der Voort, & Van Houten, 2008). This provides a number of advantages to the developers: Not only are expensive, time-consuming mockups avoided, future use problems are uncovered and easily anticipated as well. However, VEs are generally used only by large companies because of the complexity and costs.

Only recently, with the technique becoming more accessible, VEs has become available for companies with a smaller budget, such as Small and Medium Enterprises (SMEs). Whether it is feasible to use VEs depends on a range of constraints among which 1) the experienced immersion of users, 2) the resources and knowledge required, and 3) the development time of VEs. In this paper, we will focus on the first constraint. This issue is investigated within the development of a new supermarket. In particular, we address the relation between immersion and human visual spatial cognition.

Slater et al. (1996) stated that the immersive character of VEs is determined by: i) the amount of sensory systems (i.e., vision, sound, touch), ii) the extent that information is provided from any direction, iii) the extent that external noise is excluded, the correspondence between the user's behavior and the system's feedback, and iv) the degree of sensory richness - or realism.

Without any dispute, multisensory VEs will increase immersion. However, for SMEs such a setup is far from realistic, considering the constraints they have. For example, with multisensory VEs, the synchronization of the sensory modalities is both crucial and challenging and, consequently, not feasible. A similar argument can be provided for Slater et al.'s second requirement. A VE providing information from any direction (e.g., a CAVE) is still far too expensive for SMEs, in terms of both purchasing and maintenance. The third requirement, external noise, can be well controlled with the choice of a suitable (noise free) room for applying the VE. This leaves, Slater et al.'s fourth requirement: realism. A certain level of realism can be achieved for all sensory modalities; for example, odor, temperature, tactile, sound, vision. In general, the more realistic a modality needs to be; the more expensive it will become to achieve this. Although the benefit of realistically mediated environments is evident (e.g., gaming), for other applications it is less so. This also holds for the use of visual realism, the modality that will be explored in the current research. In particular, we will address user's visual spatial cognition, as this is of interest for the case under investigation: the supermarket.

VEs enable an interactive, spatial exploration of environments, which is known to be beneficial. Pausch, Proffitt, and Williams (1997) found a better performance on a spatial search task in an immersive VEs compared to a desktop environment. Tan et al. (2006) showed an improved visual spatial performance on various tasks with large wall-sized displays compared to desktop displays. For an overview on the use of VEs with spatial learning from navigation, we refer to Darken, Allard, and Achille (1998).

In general, spatial learning from navigation is thought to occur in three successive stages (Siegel & White, 1975): 1) *Landmark knowledge*: the location of orientation points or landmarks; 2) *Route knowledge*: a set of paths, turns, and directions to reach a destination, which is spatially related to the person self (egocentric); and 3) *Survey knowledge*: a higher-order mental representation of the environment's lay-out, which is then no longer egocentric. Richardson, Montello, and Hegarty (1999) provided evidence that the acquisition of spatial knowledge of VEs follows the same stages as in real environments. Furthermore, Regian, Shebilske, and Monk (1992), Waller, Hunt, and Knapp (1998), Wilson, Foreman, and Tlauka, (1997), and others showed that learning VEs is highly predictive for learning similar real world environments. This suggests that similar cognitive processes are involved in the two environments. Therefore, the stage model of Siegel and White (1975) is relevant when determining the usefulness of visual realism in VEs. Consequently, the use of visual realism increases *route* and *survey knowledge* of the users. Additional evidence for this hypothesis is provided by Christou and Bülthoff (1999), who indicated the importance of the quantity of the presented information during navigation.

The current study extends these findings through exploring whether visual realism indeed enhances spatial learning in VEs by assessing the effect on the acquisition of *route* and *survey knowledge*. Two distinct groups of users were placed in front of a large screen and guided through 1) a photo-realistic VE and 2) a non-realistic VE. Afterwards, spatial learning was tested in four tests that assessed how accurate they had memorized the route and the environment's spatial lay-out.

MATERIALS AND METHODS

Participants

Thirty-two students of the University of Twente participated in the experiment in exchange of course credits. The participants were randomly assigned to the photo-realistic VE (10 women, 6 men; mean age 21.6 years) and the non-realistic VE (10 women, 6 men; mean age 22.4 years). One participant was discarded from the analyses after receiving the incorrect test environment. All participants were right handed, reported no known visual or neurological disorders, and were naive concerning the purposes of the experiment.

Figure 1. Left: overview of the supermarket. Right: viewpoints of the various sections.

Materials and apparatus

The VE was a supermarket (T-Xchange) (see Figure 1, left frame) that consisted of several sections with groceries; for example, fruit, vegetables, meat, and milk (see Figure 1, right frames). The basic objects of the VE were modeled with 3D Studio Max (Autodesk, Inc.) and, subsequently, created using Quest3D (Act-3D, B.V.). Two versions of the supermarket were modeled: photo-realistic and non-realistic VE; see Figure 2. Note that the absence of semantic information in the non-realistic VE made the supermarket unrecognizable as such. A desktop computer running Windows XP (SP2) with a 42" Panasonic TH-42PY70 plasma screen (resolution of 1920 x 1080 pixels and frame rate of 60 Hz) was used to present the supermarket. Participants were seated in front of the screen at 150 cm distance, in a darkened room. They used a standard keyboard and mouse to navigate through VE: the up-, down-, right-, and left arrows to walk; the mouse movements to look in any direction.

Figure 2. Left: The non-realistic VE. Right: The photo-realistic VE.

Procedure

Pretests

Before the actual experiment started, the participants filled in pen and paper tests. First, participants provided demographic data. Next, they filled in an adapted version of the Game Experience Questionnaire

(GEQ) (IJselsteijn, de Kort, & Poels, in prep.), which distinguished three levels of experience with playing games. Subsequently, participants completed the Hegarty's Perspective Taking/Spatial Orientation Test (2004) to assess their ability to imagine different perspectives or orientations in space. The deviation in participant's drawing direction determined their score.

Learning phase.

In the learning phase, the participants initially familiarized themselves with moving around in the VE outside the supermarket. Afterwards, they were guided verbally to the entrance of the supermarket and, subsequently, through it on a fixed learning route, see Figure 3. The learning route started and ended at the entrance of the supermarket. Each path was visited once except for four that were not visited and two that were visited partly twice. There was no time constrain as there was only one route and pace possible. Nevertheless, time to complete the learning phase was recorded accounting for the possibility that participants could stop to look around in the VE. Since the participants were already cognitively loaded in the visual domain, verbal instructions were used as guidance; for example, go left here, at the end go right, or turn around. To motivate participants to actively learn the layout of the supermarket, they were instructed beforehand to pay as much attention to the VE as possible. Also, they were informed that their spatial knowledge of the VE would be assessed later on.

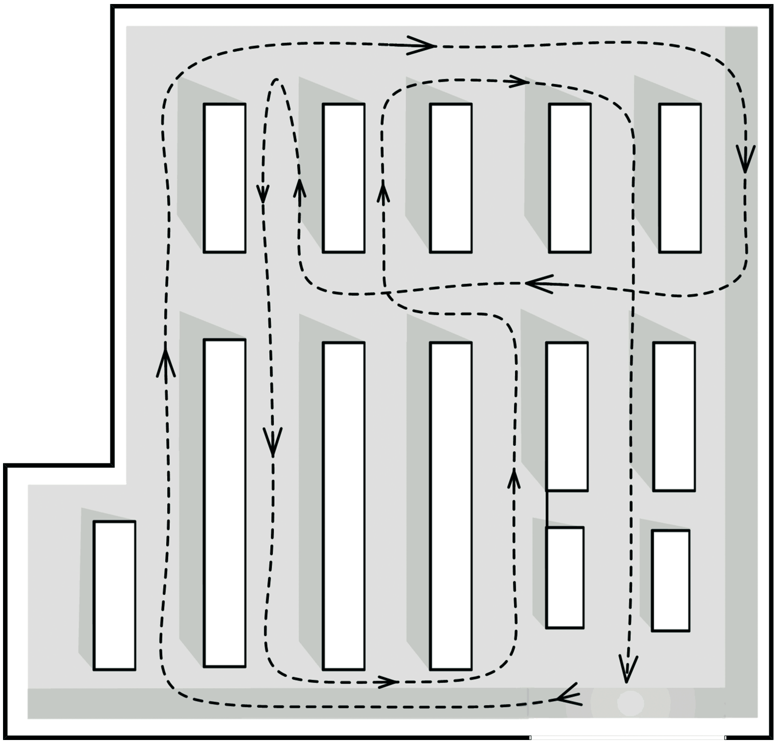

Figure 3. The learning route through the virtual supermarket.

Test phase.

After the participants completed the learning phase, they were tested on their knowledge of the supermarket. Four tests were used: two tests (the first and third) to assess their route knowledge and two tests (the second and fourth) to assess their survey knowledge. Participants conducted the tests individually.

Route reversal task: Participants conducted a reversed route navigation task to assess their acquired spatial knowledge during the learning phase. Participants were instructed to walk the learned route in the opposite direction in the supermarket; see also Figure 3. Their route and completion time were recorded as precisely as possible with a stopwatch. Their accuracy was determined with a scoring method based on Asselen, Fritschy, and Postma (2006). Along the route, there were 28 decision locations in sequential order; each intersection of paths represented a decision location. When participants included such a location in their route, one point was given, and another point when they walked in the right direction onward. In addition, participants were given two points for a correct starting location and another two for a correct finishing location. Consequently, participants could obtain a maximum score of 60. After participants completed the route reversal task, they left the supermarket and proceeded with the remaining of the test phase on paper.

Map identification task: The participants were given ten supermarket lay-outs. Each map was offered on paper separately. Participants were able to rotate it, to fit their mental reference view. They were asked to identify the correct map of the supermarket between nine distracter maps. The distracter maps differed from the correct map in that these contained an incorrect amount of isles, an incorrect orientation of isles, an incorrect outline, a mirrored outline, or a combination of these deviations. Participants were able to try twice to select the correct map. After the second attempt, it was recorded whether or not the correct map was identified. There was no time-constraint.

Route drawing task: Participants were instructed to draw the learned route on the correct map of the supermarket with a pen on plain paper. Accuracy and completion time was recorded. The same scoring method as in the route reversal task was used.

Viewpoint recognition task: The participants were given 15 pictures of the supermarket, from distinctive viewpoints; for example, see Figure 1, right frame. Participants were assessed whether or not they recognized viewpoints and how they related these viewpoints to the map. They observed the picture and indicated the location and the direction of this viewpoint on a map. Completion time and accuracy were recorded. Correct locations and directions exceeding less than 90 degrees from the actual direction were scored as one point.

RESULTS

Two multivariate analyses of variance (MANOVAs) were conducted to investigate our hypotheses: one for the accuracy and one for the completion time data, with as within-subjects variable Task (route reversal, map identification, route drawing, and viewpoint recognition), as between-subjects variable VE (photo-realistic, non-realistic), and with as covariable the score on Hegarty's test. The self reported game experience did not show any influence and, hence, was ignored in the analyses.

In the accuracy data, an overall effect for VE was found, indicating that participants in the photo-realistic VE performed better than those in the non-realistic VE, $F(4, 26) = 3.26$, $p < 0.03$, $\eta^2 = 0.33$. Between subject effects are shown in Table 1. Furthermore, an overall effect for VE in the completion times data was found, which showed that participants in the photo-realistic VE were faster than those the non-realistic VE, $F(3, 27) = 3.65$, $p < 0.03$, $\eta^2 = 0.29$. The within-subjects variable map identification was left out in this analysis, because completion time was not recorded during this task.

A separate t-test was conducted for the route completion times in learning phase. A significant difference was found between the completion times of the photo-realistic and non-realistic VE ($t(30) = 3.00$, $p < 0.01$) , $r^2 = 0.23$. In the photo-realistic VE, participants took more time (M = 291 sec, SD = 138 sec) than in the non-realistic VE (M = 199 sec, SD = 50 sec) to complete the learning route.

Table 1. Mean scores of the accuracy data and completion times in the photo-realistic and non-realistic virtual environment (VE) on the four tasks. * $p < 0.05$, ** $p < 0.01$

	Photo-realistic VE	Non-realistic VE	MANOVA
Accuracy (% correct)			$F(1, 29)$ =
Route Reversal	67.2	58.0	2.70**
Map Identification	50.0	37.0	1.84
Route Drawing	58.0	62.7	1.75
Viewpoint Recognition	65.0	52.5	2.90**
Completion Times (sec)			
Route Reversal	176.8	231.1	2.78*
Route Drawing	152.3	145.9	0.12
Viewpoint Recognition	444.3	505.7	2.10

DISCUSSION

The current study investigated the usefulness of visual realism for VEs, within the context of the redesign of a supermarket. In an experiment, the effect of visual realism was tested on the acquisition of spatial knowledge of VEs. Participants were guided through a photo-realistic or a non-realistic supermarket and tested on their knowledge afterwards. The results show that participants in the photo-realistic VE were more accurate on the route reversal and the viewpoint recognition tasks than participants in the non-realistic VE. In contrast, no significant differences were found between the two supermarkets in the route drawing and the map identification tasks. Since average accuracy percentages were considerably lower than the maximum scores, this could not be a result of a ceiling effect.

The current study showed that participants during the learning phase in the photo-realistic VE spent more time in the supermarket than those in the non-realistic VE. This suggests that the participants attend longer to VEs with visual realism. This is in line with the findings of Christou and Bülthoff (1999), who proposed that the degree of spatial learning in VEs depends on the amount of information viewed. Probably, participants use visual realism to give the environment semantic value, which helps them to navigate through environments. Then, visual realism has the same role in the acquisition of spatial representations as landmarks, although less evident. We suggest that visual realism contributes to the content of VEs and, with that, its uniqueness. Following the landmark, route, and survey knowledge theory of Siegel and White (1975), users form knowledge about the content of VEs, enhanced by visual realism, and next (egocentric) route knowledge. The last step, however, forming (non-egocentric) survey knowledge, is less certain to occur.

For SMEs, it is relatively easy to implement visual realism in VEs in contrast to other modalities. Therefore, we have focused mainly on vision. However, the effects of using smell, touch, and sound in VEs on spatial cognition remains an interesting subject. Furthermore, the current study did not account for the minimum level of visual realism required to enhance spatial knowledge, or a maximum level when spatial cognition is no longer affected. The exact relation between visual realism and spatial knowledge is not yet quantified. Future research has to further explore this issue. Nonetheless, this research can be of great interest for SME in that it shows where to invest when developing VEs without spending too many resources. Often, when developing VEs, the use of innovative hardware is stressed. We suggest that it is not merely hardware that defines a VE. Our study provides evidence that investing time and effort in the development of visual realism in VEa is important. The individual users increase their spatial knowledge from it. Most of all, it provides a definite answer to the application fields other than the entertainment industry: Yes, realistic VEs do work better.

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Chapter 5

Synthetic Environments as a visualization method for product design

ABSTRACT

In this paper, we explored the use of low fidelity Synthetic Environments (SE; i.e., a combination of simulation techniques) for product design. We explored the usefulness of a low fidelity SE to make design problems explicit. In particular, we were interested in the influence of interactivity on user experience. For this purpose, an industrial design case was taken: the innovation of an airplane galley. A virtual airplane was created, including an interactive model of the galley. First, three groups of participants explored the SE in different conditions: Participants explored the SE interactively (Interactive condition), watched a recording (Passive Dynamic condition), or watched static images (Passive Static condition). Afterwards, participants were tested in a questionnaire on how accurately they had memorized the spatial layout of the SE. The results revealed that interactive SE does not necessarily provoke participants to memorize spatial layouts more accurately. However, the effect of interactive learning is dependent on the participants' Visual Spatial Ability (VSA). Consequently, this finding supports use of interactive exploration of prototypes through low fidelity SE for the product design cycle when taking the individual's characteristics into account.

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INTRODUCTION

Engineers and product designers learned by (bitter) experience that differences in backgrounds, interests, and paradigms can cause stakeholders to have different ideas, or so called mental models (Johnson-Laird, 1980; Pylyshyn, 1973), of the product. This can cause huge problems in, for example, communication and cooperation and, consequently, might result in a disappointing product design. For the creative process of product design, designers traditionally use a drawing board and CAD software. However, recent technological developments enabled designers to employ new tools to support their creative process. In this paper, we explore the use of low fidelity Synthetic Environments (SE) to make specific design problems explicit.

The term “Synthetic Environments” refers to the use of a combination of simulation techniques, such as Virtual Reality (VR), Augmented Reality (AR), and Gaming technology to facilitate an artificial experience of certain situations (Wang et al., 2008). These technologies intend to maximize the user’s experience by realistically simulating a complex visual environment, possibly including sound, touch, or smell. The use of VR was originally mostly confined to military applications, for example to train soldiers for combat situations, because of the high costs involved with this type of technology. However, the rapid development of computers in recent decennia has made it feasible for other application fields to use this type of technology as well. Henceforth, SE has become within reach for academic, commercial, industrial and educational domains (Burdea & Coiffet, 2003). We will focus on one of these domains specifically: industrial product design.

Due to the increased technological possibilities and decreased costs the use of SE has gained much interest of industrial companies to innovate their product design process. An SE provides several possibilities that traditional methods in product design do not facilitate. First, it visualizes a virtual context for the future use of a certain product. A (virtual) prototype can be tested in the earliest stages in its development on its effectiveness and usability (Smulders, Van den Broek, & Van der Voort, 2007; Van den Broek et al., 2008). Therefore, possible problems with the product are uncovered when adaptations are still easily made. Second, SE facilitates the involvement of end-users in the beginning of the design process, their opinions serving as an additional source of information for the designers (Tideman, Van der Voort, & Van Houten, 2008). Third, SE stimulates the communication between the different stakeholders in the design process (Landman, Van den Broek, & Gieskes, 2009). Various stakeholders, such as designers, managers, or clients, who often use a different terminology, understand each other better with SE, not longer depending on the interpretation of separate images but on their experience with the (virtual) prototype.

For an effective application of low fidelity SE in the design process, there are two important constraints:

1) Financial: As for each new technique, SE have to show that they aid real-world design processes and, hence, save both time and money. To enable this, a SE should provide as much as possible the context that is relevant for the stakeholders; i.e., the amount of (visual) realism. Visual realism has shown to be an important factor for user experience (Slater et al., 2009). Furthermore, visual realism increases visual spatial knowledge about the navigational space Meijer, Geudeke, & Van den Broek, 2009).

2) Interactivity: This characteristic is known to improve both user experience and spatial knowledge (Farell et al., 2003; Larsson, Västfjäll, & Kleiner, 2007). The current paper will investigate to what extent this characteristic is important for SE.

There is a large body of research that investigated why interactivity improves spatial knowledge of virtual environments. Christou and Bülthoff (1999) for example, showed that recognition of scenes in virtual environments is improved after interactive exploration as opposed to passive observation of an identical exploration. These researchers proposed that the user’s possibility to control their viewpoints in the virtual environment contributes to more accurate mental representations in human visual spatial memory. James, Humphrey and Goodale (2001) reported a similar effect of interactivity for the exploration of unfamiliar 3D objects. These researchers showed that people who explored 3D objects interactively chose specific viewpoints that seemed most useful to them. They concluded that these viewpoints are essential to build up more complete mental representations. However, we found in prior experiments that the effect of interactivity on visual spatial memory is dependent on the user's Visual Spatial Ability (VSA) (Meijer, Van den Broek, & Schouten, 2008; Meijer & Van den Broek, 2010). Users with a low VSA benefit from interactivity, whereas those with a high VSA do not. This finding indicates that users with a low VSA are not able to build up mental representations of 3D objects by passive observation, but are able to do so by interactive exploration. Users with a high VSA are able to build up object representations in both conditions. In summary, there is much evidence that interactivity enhances spatial knowledge, especially for users with a low VSA, because it enables them free control of their viewing direction in the virtual environment. We suggest that an improved spatial knowledge of virtual objects (i.e., prototypes) and environments (i.e., contexts) is the first important step to increase communication between the stakeholders and to reach consensus between them.

In the present study, we investigated the effect of interactivity and the influence of VSA on user experience and spatial knowledge of a low fidelity SE. We were interested whether the findings of previous research could be applied to an actual design case. For this purpose an SE was developed in which the specifications of the design case were used as input. The study was divided into three parts. 1) In a pre-test, the user's VSA was assessed. We expected that an effect of interactivity would be dependent of VSA. 2) In a learning phase, participants learned the spatial layout of the SE. In this part of the study, the possibility to interactively explore the SE was varied. Either the participants interactively explored the SE, observed a recording of another participant's interactive exploration, or viewed static images of the SE. The last condition was used as baseline condition. We expected that participants were better able to learn the spatial layout of the SE by interactive exploration, and were least able to learn it in the baseline condition. 3) In a test phase, participants received a questionnaire. The questionnaire assessed the participants' subjective experience of the spatial layout and the accuracy of the participants' mental representation of the SE. We expected that participants would show the highest scores in the interactive learning condition and the lowest scores in the baseline condition.

Figure 1. Images taken from the SE of the airplane cabin with the galley.

METHODS

Participants

Twelve participants (5 men and 7 women), aged 20-32 years (mean = 28.1), were tested in the experiment. All had normal or corrected to normal vision and were naïve concerning the purposes of the experiment.

The Synthetic Environment

An industrial design case was used for the experiment: the innovation of an airplane galley. The design company Indes B.V. provided the case. An SE of an airplane cabin with the galley was developed with the 3D modeling software 3D Studio Max (Autodesk, Inc.) and Quest3D (Act-3D, B.V.). The SE was presented using a PC laptop (CPU: Intel Core2Duo 2.1GHz, Memory: 2GB) running Windows Vista (Microsoft, Inc.) connected to a 20-inch flat-screen monitor. A standard computer mouse and keyboard was used to walk through the SE. The arrow-keypad was used to walk from left to right and front to back. Holding the right mouse-button while moving the mouse enabled the participants to look around in the SE and to change the direction of the route. The left mouse-button was used to interact with the kitchen galley in the SE; a left button-click opened and closed the doors or moved the elevator up and down; see Figure 1 for an impression of the SE.

Pre-test

Before the experiment started, participants were assessed on their VSA; see also Figure 2. This was important, because in the test-phase of the experiment the participants were asked to recollect the spatial layout of the SE. Participants with a high VSA are more accurate on this task than those with a low VSA. Therefore, VSA was taken into account as a co-variable in our data analysis.

To test the participants' VSA, the Vandenberg and Kuse's Mental Rotations Test (MRT-A) was used (Peters et al., 1995; Van den Berg & Kuse, 1978). This test was used to determine to what degree participants were able to mentally rotate 3D objects. Participants compared an original object to four rotated alternatives and identified the two identical objects from them. In six minutes, participants completed as many of these comparisons as possible from a total of 24 comparisons. The percentage of correct comparisons determined the participant's test score and their VSA.

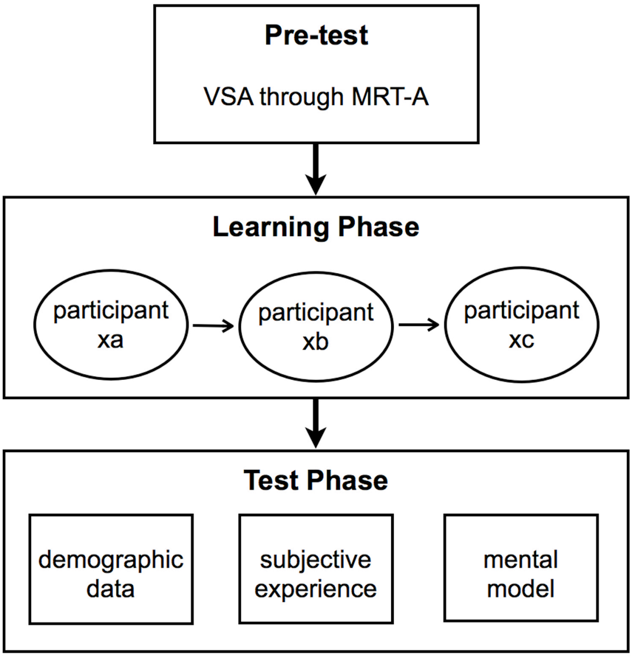

Figure 2. The three phases of the experiment, including its components. Moreover, the relation between the participants is depicted.

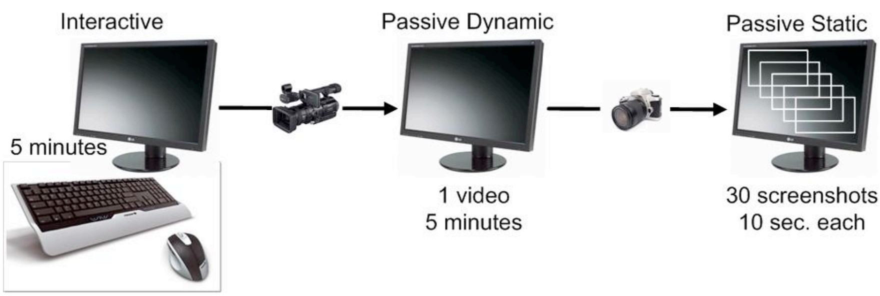

Figure 3. The three conditions of the learning phase, to which the participants were randomly assigned. Please note the relation between these conditions.

Learning phase

The learning phase consisted of three different learning conditions: an Interactive, a Passive Dynamic, and Passive Static learning condition; see also Figure 2 and 3. The participants were randomly assigned to one of these three conditions (i.e., four participants per condition). Prior to each of the conditions, participants were instructed to memorize the SE as accurately as possible, because they would subsequently be tested.

In the Interactive learning condition, the participants explored the SE freely with the mouse and keyboard; see also Figure 3. Participants were explicitly instructed to explore the kitchen galley by clicking on the galley doors and elevator. After 5 minutes the participants were instructed to stop. In this condition, the participants' actions were recorded and snapshots were taken each 10 seconds with the recording program FRAPS (Beepa, Inc.). This recording and these snapshots were used for the subsequent conditions. This was done to ensure that participants in the other two conditions observed identical viewpoints of the SE, and that only the type of learning was varied across participants.

In the Passive Dynamic learning condition, participants observed a recording taken from the prior participant in the Interactive condition, as is also shown in Figure 3. The procedure was identical to the Interactive condition, with the exception that participants were not able to interact with the SE in anyway. VLC media player software (VideoLAN, Org.) was used to present the recording.

In the Passive Static learning condition, participants viewed 30 snapshots taken from the video recorded of the participant in the prior Interactive condition, as is also shown in Figure 3. Each snapshot was presented for 10 seconds, which resulted in a total presentation time of five minutes. Again, participants were not able to interact with the SE in this condition. MS PowerPoint 2008 (Microsoft, Inc.) was used to present the snapshots.

Test phase

After the learning phase, participants were assessed in a questionnaire whether or not they had accurately memorized the spatial layout of the SE; see also Figure 2. The questionnaire was divided into three parts; for an overview of the questionnaire see Table 1.

In the first part of the questionnaire demographic data was collected, such as the participants' age, gender, education, but also their affinity with computer games and 3D modeling. The latter two questions were used to control for the possibility that participants who are experienced with computer games or 3D modeling software more easily memorized the SE than those who are not (Epstein, Higgins, & Thompson-Schill, 2005). Participants had to indicate whether they considered themselves as novice, advanced, or expert user. Furthermore, they indicated what type of games or 3D modeling software they used and how often.

The second part of the questionnaire assessed the participants' subjective experience of the SE. Five testing variables were distinguished: 1) To what extent participants had memorized the spatial layout of the SE in general, 2) the layout of the SE as a map, 3) the route through the SE, 4) to what extent they had identified themselves with the person walking through the SE, and 5) whether they were able to imagine to perform real actions with the airplane galley. Each variable comprised two questions. Thus, there were 10 questions in total this part. Answers were measured on a Likert scale from 1 to 5, indicating the range from "I do not agree at all" to "I fully agree".

The third part of the questionnaire tested the participants' ability to reproduce the spatial layout of the SE. First, participants were required to provide size estimations of the airplane cabin in general, such as the cabin length, cabin width, cabin height, and path width. Second, participants estimated the size (height and width) of the two galleys. Third, they estimated the number of doors in the left and right galley. Fourth, they indicated the orientation of the galley and whether the doors faced the front or back of the airplane. This part of the questionnaire consisted of 10 questions in total.

Table 1. Overview of the research variables with example questions used in the questionnaire.

Part	Research Variable	Example Question	Type of Measurement
1	Demographics	*What kind of education did you attain?*	Open questions
	Gaming Experience	*Do or did you play computer games?*	Multiple choice
	3D Modeling Experience	*Do you have experience with 3D graphic software?*	Multiple choice
2	Spatial Memory	*I can remember the spatial layout of the SE.*	Likert Scale
	Survey Knowledge	*I can remember the SE as a map.*	Likert Scale
	Route Knowledge	*I can remember the route that was walked through the SE.*	Likert Scale
	Egocentric Representations	*I had the feeling to move through the SE myself.*	Likert Scale
	Ability to Imagine Actions	*I know how to operate the airplane galley.*	Likert Scale
3	Size of the Cabin	*What was the height of the cabin (in meters)?*	Open question
	Size of the Galley	*What was the width of the left galley?*	Open question
	Layout of the Galley	*How many doors did the right galley have?*	Open question
	Orientation	*Did the doors face to the back or to the front of the airplane?*	Open question

RESULTS

Before the analyses were conducted, VSA, subjective experience, and estimation error scores were averaged per participant and per condition. Subsequently, the relative estimation errors (ε) in % were calculated by dividing the absolute estimation error (δ) through the absolute estimated size ($\hat{s}$) in meters. Formally, this can be denoted as follows:

$$\varepsilon = \frac{\delta}{\hat{s}} \cdot 100,$$

where $\delta = | \hat{s} - s |$ with s being the absolute size in meters (i.e., the size as envisioned for the SE) and $| \cdot |$ denotes the absolute value of $\cdot$. Please note that the participants' estimation was taken as our ground truth and not the absolute size, as this is more or less arbitrary. This is easily shown when the equation above is rewritten as $\varepsilon = | 1 - s/\hat{s} | \cdot 100$. However, as this starting point can be judged as being rather unconventional, we have verified its possible influence on the results. Additional analyses revealed that similar results would have been obtained, when using the absolute size as ground truth.

After the relative estimation errors ε were determined, various analyses were run to evaluate the data of the questionnaire. First, VSA was compared to the average scores of the subjective experience and the average relative estimation error ε. The results revealed that VSA in the Passive Dynamic condition was highest, followed by the Interactive condition, and was lowest in the Passive Static condition. Since we expected that VSA would have an impact on the effect of interactivity, we took these differences into account in our further analyses. The number of Gaming and/or 3D modeling experts was constant across conditions and did, therefore, not influence the effect of interactivity. As expected, participants showed the highest subjective experience scores in the Interactive condition, followed by the Passive Dynamic and Passive Static conditions. In contrast to our expectations, however, participants were least accurate estimating sizes in the Interactive condition; for a complete overview, see Table 2.

From the Subjective Experience - VSA plot it becomes evident that participants in the Interactive condition showed higher Likert scores than the other two conditions irrespective of VSA; see Figure 4 (top). Participants in the Passive Static condition all showed the lowest scores. Thus, the effect of interactivity seems to be robust for subjective experience even for a small group of participants. Furthermore, VSA did not seem to affect the subjective experience.

From the Estimation Error – VSA plot it becomes clear that the participants in the Passive Dynamic condition showed the lowest relative estimation errors ε, but also scored high on the VSA test; see Figure 4 (top). Participants in the Interactive condition showed the highest relative estimation errors ε. However, one clear exception to this is present in the interactive condition, with a relative estimation error ε of 9.2% and a VSA score of 29, as is shown in Figure 4 (bottom). Two participants of the Interactive condition showed respectively exceptional low and high relative estimation errors (i.e., respectively ε = 9.2% and ε = 37.6%), when taking into account their VSA scores (i.e., respectively 29 and 50); see also Figure 4 (bottom). Thus, from this plot it becomes clear that the participants varied significantly in their relative estimation errors in the Interactive condition, an effect for which no simple (e.g., linear) relation was found with VSA.

To test the effect of interactivity on relative estimation error ε and the influence of VSA, a linear best fit trend analysis was conducted with VSA (range: 0-100) and learning condition (Interactive, Passive Dynamic, Passive Static) as independent variables and the average relative estimation error ε as dependent variable. The results of the linear best fit analysis of [$\varepsilon = a \cdot (100 - \text{VSA}) + b \cdot \text{condition} + c$] showed that a = 0.16, b = -2.74 en c = 16.8, with a root mean square error (*rms*) of 8.5. When the two participants were discarded who showed a large deviation on the scores, it showed a = 0.30, b = -8.00, and c = 21.3 with a *rms* of 6.0. This indicates that the relative estimation error ε decreases with higher VSA scores and increases with interactivity.

Table 2. Overview of the average scores, as recorded for each of the learning conditions. Note that all values are percentages, except for the subjective experience scores.

Learning Condition	VSA score	3D/Gaming Experts	Subjective Experience	Estimation Error (ε)
1. Interactive	46	25	4.35	24.39
2. Passive Dynamic	66	25	4.00	13.52
3. Passive Static	34	25	3.35	20.69

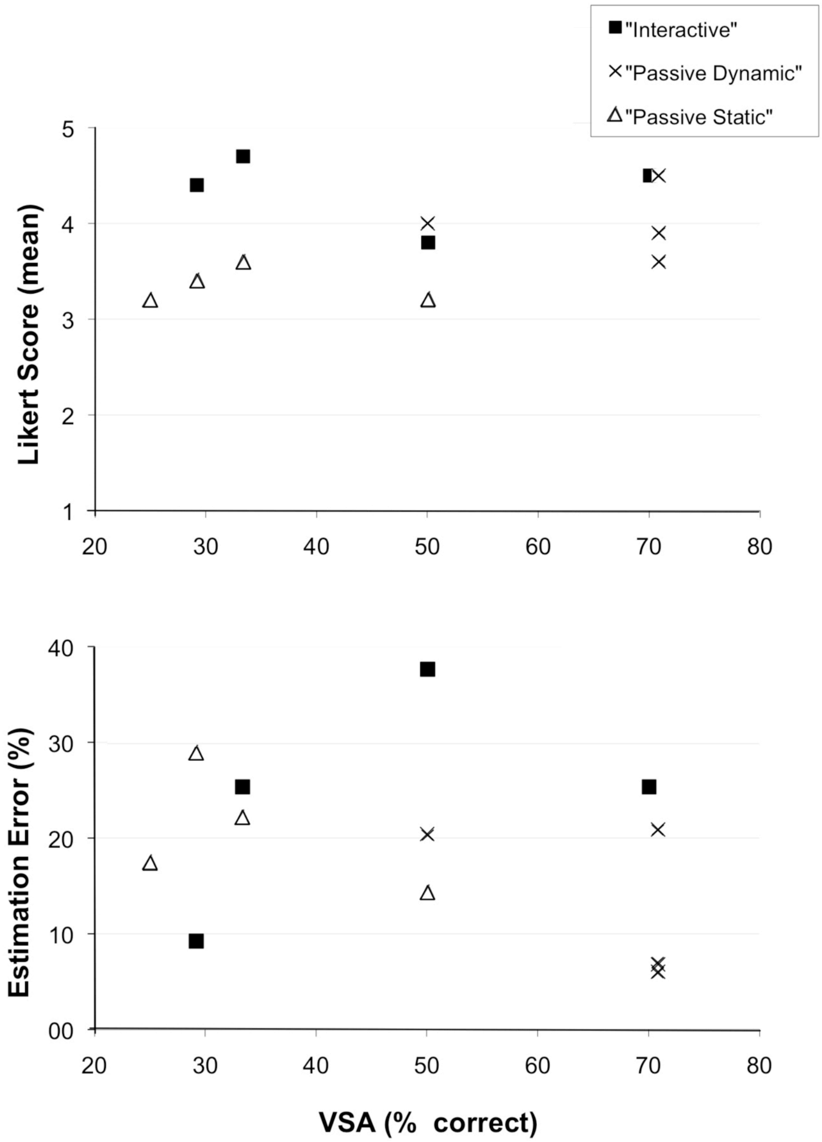

Figure 4. Plot of the average Likert scores (top) and relative estimation errors ε (bottom) compared to VSA. Each condition is indicated separately and each data-point represents one participant.

Next, a more thorough comparison was made between the participants' subjective experience of the spatial layout of the SE in the three learning conditions. Overall, the results revealed the highest average scores in the Interactive condition, followed by the Passive Dynamic condition. The lowest scores were revealed in the Passive Static condition. These differences were most evident on three of the five research variables: the ability to remember the route walked through the SE, to form egocentric representations, and to imagine real actions with galley. Participants in the Passive Static condition scored lower those in the Passive Dynamic condition. Those in the Interactive condition scored highest. See Table 3 for an overview of the mean scores per research variable.

Finally, the participants' ability to reproduce the spatial layout of the SE by estimating the size of the airplane cabin, the airplane galley, the layout of the galley, and the orientation of the galley was analyzed. A repeated measures ANOVA on the accuracy data was run with estimation, 10× measured, as within subjects variable and learning condition (Interactive, Passive Dynamic, and Passive Static), gender (male, female), and VSA (scores: 25, 29(2x), 33(2x), 50(3x), 70, 71(3x)) as between subjects variables. The results revealed a main effect of Learning condition, Learning condition $F(2, 1) = 334.0$, $p < .04$. The participants were more accurate in the Passive Dynamic condition as compared to the Passive Static condition. Against our expectations, participants in the Interactive condition were least accurate estimating the spatial layout of the SE. Furthermore, a main effect of VSA score was found, $F(4, 1) = 172.1$, $p = .06$ (one-tailed). Participants with high VSA were more accurate estimating than those with a low VSA. The interaction between learning condition and VSA was also significant, $F(3, 1) = 375.8$, $p = .04$. Also, a significant main effect was found of gender, $F(1, 1) = 553.5$, $p = .03$. Male participants performed better than the female participants, which is in line with other research (Hirnstein, Bayer, & Hausmann, 2009). See Table 4 for an overview of the mean accuracy of estimating the spatial layout of the SE.

Table 3. Overview of the participants' subjective experience of the spatial layout of the SE; i.e., part 2 of the questionnaire.

Learning Condition	Spatial Memory	Survey Knowl.	Route Knowl.	Egocent. Repres.	Imagining Actions
1. Interactive	4.63	4.63	4.50	3.63	4.38
2. Passive Dynamic	4.75	4.38	4.00	3.13	3.75
3. Passive Static	3.75	4.13	3.75	2.50	2.63

Table 4. Overview of the participants' error in estimating the spatial layout of the SE; i.e., part 3 of the questionnaire. Table cells represent the mean error from the values used in the SE in percentages.

Learning Condition	Cabin Size	Galley Size	Galley Layout	Orientation
1. Interactive	29.0	28.7	16.2	0.00
2. Passive Dynamic	19.9	17.7	4.30	0.00
3. Passive Static	18.0	21.1	31.0	0.00

DISCUSSION

In the present experiment, we investigated the effect of interactivity on user experience and spatial knowledge of a low fidelity SE. An SE was developed of an actual design case: the innovation of an airplane galley. Participants learned the SE either in an Interactive, Passive Dynamic, or Passive Static learning condition. In the Interactive condition, they were able to explore the SE freely with a computer mouse and keyboard. In the Passive Dynamic condition, the participants observed a recording and in the Passive Static snapshots of another participants' exploration of the SE. Afterwards they were tested on their subjective experience and the accuracy of their mental representation of the spatial layout of the airplane cabin and galley. We also investigated the influence of VSA. We expected that participants would improve their subjective experience and the accuracy of their mental representations in the Interactive condition compared to the Passive Dynamic and the Passive Static condition. We expected poorest scores and accuracy in the Passive Static condition. Furthermore, we expected that the effect of interactivity would be dependent of participants' VSA.

The results partly confirmed these expectations. As expected, participants in the Interactive condition showed the highest average scores on the subjective experience compared to the other two conditions. Those in the Passive Static showed the lowest. Differences between the conditions were largest on three of the five research variables of this part of the questionnaire: acquisition of route knowledge, acquisition of egocentric representations, and imagining actions. In the Interactive condition, participants indicated more strongly that they remembered the route through the airplane cabin, sensed to have explored the SE themselves, and were able to imagine real actions with the airplane galley.

In contrast to our expectations, participants in the Interactive condition were not more accurate when they had to reproduce the spatial layout of the SE. When participants had to estimate sizes of the airplane cabin and galley, they were in fact least accurate in the Interactive and most accurate in the Passive Dynamic condition. One possible explanation for this unexpected effect is the average VSA score in the conditions: Average VSA scores were highest in the Passive Dynamic conditions. However, a linear best fit analysis of Learning condition and VSA showed that not only estimation accuracy improved with higher VSA scores, but also with less dynamic conditions (respectively: Interactive, Passive Dynamic, and Passive Static). Thus, the impaired performance of participants in the Interactive condition cannot merely be explained by VSA. This is in contrast with prior research (Christou & Bülthoff, 1999; Farell et al., 2003; James, Humphrey, & Goodale, 2001; Meijer, Van Broek, & Schouten, 2008; Meijer & Van den Broek, 2010).

Another possible explanation for this result is that the camera position in the Interactive and Passive conditions is continually changed, which can make it difficult for participants to get a precise idea about the size of the SE. In the Passive Static condition the participants observed still images of the SE each for 10 seconds. This period can be used to fully focus on the size of the SE. Christou and Bülthof (1999) provided evidence that the viewpoints taken in a virtual environment determine the accuracy of the mental representations built from them. Future research should take into account that the time these viewpoints last also is of influence. Furthermore, the difference between the Interactive and Passive Dynamic conditions is possibly explained by the fact that participants in the Interactive condition concentrate more on performing actions than on the spatial layout of the SE. In fact, the participants were explicitly instructed to interactively explore the airplane galley. In the Passive Dynamic condition participants did not receive this instruction so they were able to fully focus on the spatial layout of the SE. This possibility is supported by the finding that participants in the Interactive condition indicated to be better able to imagine actions with the product than in the Passive Dynamic condition.

In sum, we did not find that interactivity improved visual spatial memory directly. In contrast to prior research we found the opposite effect: Participants performed poorly estimating the spatial layout of the SE. We suggested that there are a number of unknown factors that may have modulated the effect of interactivity. Future research should further investigate these factors. The present study did confirm, however, that interactivity affected the participants' responses on questions addressing their subjective experience of the SE. In particular, participants who interactively explored the SE indicated to be better able imagining actions with the virtual prototype. Therefore, we conclude that interactive exploration of prototypes through SE improves the stakeholders' mental models of product design especially about its practical functionality.

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Chapter 6 Conclusions

To design products, companies operate in an increasingly complex environment. Currently, there is a large demand for innovation and the average life cycle of products is short. Products have also become complex, which requires a large number of people to develop them. Therefore, companies are urged to use new methods and technologies to make their product design processes more effective and efficient. A promising method to innovate a design process is the use of a Synthetic Environment (SE). In an SE, virtual products can be tested in their possible future environments. Furthermore, designers can involve different kinds of stakeholders of the design process, such as managers and product end-users, to acquire feedback about a product's design. To improve the effectiveness of SEs in design processes, it is crucial that designers take the people who use the SE into account. Various cognitive processes, such as perception, attention, and memory impose important implications for the implementation of SEs. The present dissertation investigated the influence of two typical characteristics of SEs, interactivity and visual realism, on visual processing of spatial information.

An important characteristic of SEs is that users are able to interact with virtual products in their future environments. It was hypothesized that interactivity improves the users' mental representations of virtual products in visual spatial memory. These mental representations increase the users' understanding of the potential design problems and stimulate discussions about the product's design with other users (Landman, Van den Broek, & Gieskens, 2009). As a result, this improves the quality of the users' feedback to the designers, which leads to more effective design solutions. The effects of interactivity were investigated in Chapters 2, 3, and 5. In Chapter 2, the possibility was examined that interactive SEs are more useful for some stakeholders than for others. Since different kinds of stakeholders take part in the SE, there may be a variation in the effectiveness of interactivity between them. In a basic study, the effect of interactivity on constructing mental representations for different groups of users varying in their visual spatial ability (VSA) was investigated. In Chapter 3, the benefits of interactivity for the users were more thoroughly studied. The effect of interactivity on constructing visual related and action related mental representations was investigated. In Chapter 5, in a case study, the influence of interaction in SEs on users experience was investigated.

Another important characteristic of SEs is a realistic presentation of visual information. Generating visually realistic SEs is relatively easily implemented. In comparison with other characteristics, such as the presentation of multisensory information and immersion, visual realism requires fewer investments in terms of time and effort. Designers can implement visual realism to improve the users' sense of presence in an SE (Slater et al., 2009), which is considered important for the quality of their feedback about a product's design. In a case study, it was investigated whether or not visual realism improves on the users' ability to construct mental representations as well. Therefore, the effect of visual realism on cognitive processing of spatial information was investigated in Chapter 4.

From the research conducted in this dissertation, the following conclusions can be drawn with respect to the interactive characteristic of SEs. Interactivity is particularly effective for users who have a low VSA. The results of Chapter 2 revealed that participants with a low VSA were better able to mentally rotate interactively studied objects as compared to passively studied objects. However, participants with an average or high VSA were not. This suggests that interactivity is more important for stakeholders with low VSA than those with a high VSA. Product designers are likely to have high VSA, because they mainly rely on this ability to construct 3D product prototypes. Other stakeholders, such as product end-users, do not rely as much on this ability in their everyday's life and, therefore, are likely to have a low VSA. Consequently, the use of interactivity is more likely to have an effect when product end-users than when product designers take part in the SE.

Furthermore, interactivity significantly improves the users' ability to memorize the visual appearance of virtual products in SEs, rather than their ability to imagine actions with them. In Chapter 3, a study was conducted that further examined the cognitive processes affected by interactivity. This study provided more insight in the precise benefits of interactivity for the users. The results suggest that interactive exploration improves visual related and not action-related object representations. In addition, this study showed that the visual representations of interactively studied objects were more complete than passively studied objects. Also, the study revealed that the effect of interactive exploration on object recognition performance did not diminish when participants were forced to allocate their attention on the objects. Therefore, the possibility that the effect of interactivity is explained by an increased visual attention was ruled out. These results confirmed the usefulness of performing interactions with virtual products in SEs for the users.

Interactivity also improves the users' subjective experience of realism in SEs and their subjective ability to imagine actions with virtual products. This indicates that interactive SEs improve the quality of the users' feedback to the designers, in particular with respect to a virtual product's functionality. In Chapter 5, a study was conducted that investigated whether or not the findings of our laboratory experiments in Chapter 2 and 3 could be applied to a design case. In an experiment, participants explored a virtual airplane cabin interactively, watched an animation, or watched still images of the cabin. Afterwards, the participants were assessed to what degree they had memorized the spatial characteristics of the SE and to what extent they had experienced the SE as realistic. The results revealed that participants who had interactively explored the SE experienced it as more realistic than those who had watched either passively an animation or still images.

With respect to the usefulness of visual realism in SEs, the following conclusion can be drawn. Visual realism improves the users' ability to navigate through large scale SEs and to memorize the spatial layout of SEs. In Chapter 4, a study was conducted that investigated the influence of visual realism in an SE on spatial memory. In an experiment, participants were divided into two groups, who explored either a photo-realistic supermarket or a non-realistic supermarket. The participants firstly navigated through the supermarket following a predetermined route. Subsequently, they were assessed to what degree they had learned the spatial layout of the supermarket on different spatial tasks. The results showed that the participants in the photo-realistic SE were better able on the tasks associated with egocentric spatial knowledge (i.e., with respect to visual information that was directly viewed in the SE) than participants in the non-realistic SE. There was no difference in the participants' performance on tasks associated with allocentric spatial knowledge (i.e., with respect to visual information relating to higher-level cognitive maps). This suggests that an extra investment in visual realism is useful, but only when designers require feedback about the spatial characteristics of an SE that was directly viewed by the users.

In general, the findings of the current dissertation stress the importance of human cognition for SEs. Facilitating interactivity and implementing visual realism in SEs improves the users' ability to memorize spatial information, such as the lay-out of virtual objects and environments. This will increase the users' comprehension of the design problems and it will stimulate discussions with other users. Because there is a relationship between the users' ability to visualize situations in 3D and their creativity (Allen, 2010), it can be assumed that the number and quality of the suggested design solutions will also improve. Summarizing, designers have to focus on the users' characteristics to ensure an effective use of SEs. This implies that the use of SEs for product design can only be successful, if the designers realize that the most important aspect of SEs is the users, rather than the technology.

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SUMMARY

In recent years, Virtual Reality (VR) has become more and more feasible for design companies to improve their product design processes. VR enables designers to simulate product prototypes together with their future environments. Accordingly, scenarios can be created, in which designers can test their design solution. The use of VR in the earliest stages of the product design process with affordable technology is referred to as the use of Synthetic Environments (SEs).

The current dissertation is the result of a collaborative project with academic partners from industrial design and companies who were interested in the use of SEs for product design. The research of two basic and two case studies focused on investigating the effectiveness of SEs for the users. We expected that the users' insight in the possibilities and flaws in a product's design would increase if design situations were visualized and interactions were made with virtual prototypes. As a result, designers will receive more accurate feedback about a product's design, which leads to more effective design solutions.

Two basic studies were conducted to determine the effect of interactivity on learning performance of virtual 3D objects. The results of these studies showed that interactively studied objects were memorized more accurately than passively studied objects. Moreover, the results revealed that interactivity is more effective for users with a low visual spatial ability (VSA) than for those with high VSA. The results also showed that interactivity affected visual related object representations, rather than action related representations. This implies that users were better able to memorize the visual appearance of virtual objects than performing imaginary actions with them.

In addition, two case studies were conducted. The first case study investigated the relevance of visually realistic SEs for the users. The results confirmed the hypothesis that users were better able to memorize the spatial lay-out of visually realistic SEs than of a non-realistic SE. This suggests that extra investment in visual realism in SEs is useful and that this leads to an improved feedback about a product's design.

A second case study examined the influence of interactivity on the users' subjective experience of realism in SEs. The results revealed that the users experienced an interactive SE as more realistic than an

animation of the same environment. Users also stated that they were better able to imagine performing actions with a design. These results underlined the importance of interactive SEs from a users' perspective.

In conclusion, this dissertation showed that interactivity and visual realism are important characteristics of SEs, because it positively affects human memory. For the development of SEs it is therefore important to include these elements to ensure an effective application of SEs to product design. Furthermore, this dissertation emphasizes that designers should first define the users and their characteristics before they implement the technology of SEs.

NEDERLANDSTALIGE SAMENVATTING

Het gebruik van Virtual Reality (VR) is in de afgelopen jaren steeds toegankelijker geworden voor bedrijven om hun ontwerpprocessen te verbeteren. VR maakt het mogelijk dat producten in hun toekomstige omgevingen kunnen worden gesimuleerd. Met behulp van VR kunnen scenario's worden gecreëerd, waarin ontwerpers hun ontwerp kunnen toetsen. Het gebruik van betaalbare VR technologie vroeg in het ontwerpproces wordt gedefinieerd als een Synthetic Environment (SE).

Deze dissertatie is het resultaat van een gezamenlijk project waaraan academische partners en bedrijven hebben deelgenomen. Twee fundamentele en twee toegepaste studies werden uitgevoerd om de effectiviteit van SEs op de gebruikers aan te tonen. We verwachtten dat het inzicht in het ontwerp zou toenemen als ontwerpsituaties werden gevisualiseerd en de virtuele prototypes interactief bestudeerd zouden worden. Dit zou de kwaliteit van de feedback over een ontwerp verbeteren, wat bepalend is voor de doeltreffendheid van een ontwerp.

Om het effect van interactiviteit op het leren van virtuele objecten te onderzoeken, zijn er twee fundamentele studies uitgevoerd. De resultaten van deze studies onthulden dat gebruikers beter in staat zijn om interactief bestudeerde objecten te onthouden in vergelijking tot passief bestudeerde objecten. Bovendien toonden de resultaten aan dat interactiviteit hoofdzakelijk een effect had op gebruikers met een laag ruimtelijk inzicht. De resultaten onthulden ook dat interactiviteit de visueel-gerelateerde mentale representaties beïnvloedde en niet de actie-gerelateerde representaties. Dit impliceert dat de gebruikers in staat waren de visuele aspecten van de objecten te onthouden, maar niet de acties die ermee werden uitgevoerd.

Er werden ook twee toegepaste studies uitgevoerd. In de eerste toegepaste studie werd de relevantie van visueel realistische SEs voor de gebruikers onderzocht. De resultaten toonden aan dat gebruikers beter in staat waren de ruimtelijke indeling van een visueel realistische SE te onthouden dan van een onrealistische SE. Dit suggereert dat een extra investering in visueel realisme nut heeft en dat de feedback op het ontwerp zal verbeteren.

In de tweede toegepaste studie werd de invloed van interactieve SEs op de subjectieve ervaring van de gebruiker onderzocht. De resultaten toonden aan dat interactieve SEs als realistischer werden ervaren dan het zien van een animatie. De gebruikers gaven ook aan dat zij beter in staat waren denkbeeldige handelingen uit te voeren met het ontwerp. Deze resultaten onderstrepen het belang van het gebruik van interactieve SEs.

Samengevat toont deze dissertatie aan dat interactiviteit en visueel realisme belangrijke aspecten zijn van SEs, omdat zij het opslaan van informatie stimuleren en de subjectieve ervaring verbeteren. Voor de ontwikkeling van SEs is het daarom van belang deze aspecten toe te voegen, om zo een effectieve toepassing van SEs in het ontwerpproces te garanderen. Bovendien benadrukt deze dissertatie dat ontwerpers eerst de gebruikers en hun eigenschappen moeten definiëren, voordat zij beginnen met de implementatie van de technologie in SEs.

DANKWOORD

Dit proefschrift is het resultaat van 4 jaar onderzoek naar het gebruik van synthetische omgevingen in product ontwerp, uitgevoerd bij de afdeling Cognitieve Psychologie en Ergonomie aan de Universiteit Twente. Tijdens het onderzoek heb ik erg prettig samengewerkt met de afdelingen Ontwerp, Productie en Managent aan de Universiteit Twente en Design Engineering aan de Technische Universiteit Delft. Ook heb ik met plezier samengewerkt met SenterNovem en de bedrijven Indes, PANalytical en T-Xchange. Ik wil graag een aantal mensen in het bijzonder bedanken.

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JOURNAL PUBLICATIONS (PEER REVIEWED)

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