The Applicability and Benefits of Virtual Reality for the Cognitive Sciences: The Case of Context-Dependent Memory

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Abstract

Immersive virtual reality (VR) offers important benefits over non-immersive displays, such as increased ecological validity and high experimental control. Studies in cognitive science using immersive VR are however still rather limited in number. The current paper illustrates the opportunities to apply VR in the cognitive sciences by using an immersive adaptation of a classic study by Godden and Baddeley (1975) on environmental context-dependent memory (ECDM). In this memory study, retrieval was facilitated when the context between learning and testing matched. In line with the literature showing small effects for context-dependent recall, the current study indicated a marginally significant ECDM effect for one virtual context, but when deep processing was controlled, a significant ECDM effect was obtained. In demonstrating the applicability and benefits of immersive VR, this study at last opens a doorway to the large-scale implementation of immersive VR for the cognitive sciences.

Keywords: virtual reality; immersive; learning strategies

Introduction

Due to a combination of improved fidelity and affordability in recent years, virtual reality (VR) and related immersive technologies have gained popularity. In academia, prominent reasons for the use of VR include its possibilities to investigate human emotion and behavior (Diemer, Alpers, Peperkorn, Shiban, & Mühlberger, 2015), and for enabling immersive training (Bowman & McMahan, 2007).

In part, these possibilities stem from VR's ability for high immersion, which is the fidelity produced by a VR system. Immersion is suggested to be positively related to arousal (Diemer et al., 2015) and learning (Meehan, Insko, Whitton, & Frederick P. Brooks, 2002). Factors affecting immersion include field of view, and the extent to which a VR display physically surrounds the user (Bowman & McMahan, 2007).

A key benefit of immersive VR displays is increased ecological validity, as opposed to the screens of small-size and thereby less ecologically valid desktop monitors (Loomis, Blascovich, & Beall, 1999; Parsons, 2015). VR may therefore be of special benefit in cases where there is a need for more ecologically valid paradigms. VR additionally allows for fine-grained control over virtual environments, which can be tailored to fit specific research needs (Mühlberger, Bülthoff, Wiedemann, & Pauli, 2007).

Importantly, the combination of VR's benefits of increased ecological validity and high experimental control may enable a happy medium between true-to-life but less controlled real situations and highly controlled but less realistic test site settings (Loomis et al., 1999; Parsons, 2015).

In spite of its advantages as compared to more traditional techniques, the number of studies in the cognitive sciences which employ immersive VR is still rather limited. A number of possible roadblocks may have impeded a more wide adoption of immersive VR. This may include an unsatisfactory level of fidelity and the considerable time and skills required for creating virtual environments. Due to technological advancements in recent years, these barriers have been reduced.

In light of these developments, the current study aims to exemplify how the unique affordances of state-of-the-art immersive VR could benefit the cognitive sciences. For this purpose, a classic study by Godden and Baddeley (1975) on environmental context-dependent memory (ECDM) was adapted to VR using a highly immersive 360-degree Cave Automatic Virtual Environment (CAVE), as an example of how traditional designs may be converted to immersive settings.

ECDM refers to the way environmental surroundings affect memory performance: Information retrieval is facilitated when the environmental context during retrieval and encoding match compared to mismatches. Due to its reliance on contextual information, ECDM is a fitting example for demonstrating the increased ecological validity of immersive VR.

In the original study by Godden and Baddeley (1975), groups of divers learned lists of words in two different contexts, namely either on land (D: Dry) or underwater (W: Wet). The groups were then tested for their memory of the words either in the same context as the learning context (DD, WW), or in a different context (DW, WD). The number of correct, freely recalled words was found to be higher when the learning and testing contexts matched, indicating an ECDM effect (Godden & Baddeley, 1975).

Results of studies examining ECDM have been mixed. Memory performance was better when tested in the same compared to a different room (Unsworth, Spillers, & Brewer, 2012), with the same compared to a different background sound (Smith, 1985) and while wearing the same compared to different clothing (Finn, Patten, & McLachlan, 2010). Yet, other studies failed to find ECDM effects. Presenting different classrooms (Coveney, Switzer, Corrigan, & Redmond, 2013; Koens, Cate, & Custers, 2003; Saufley, Otaka, & Bavaresco, 1985) did not influence memory performance. In addition, Fernandez and Glenberg (1985) reported eight experiments in which ECDM effects could not be established by presenting different rooms.

The mixed results of these studies question the reliability of ECDM effects. Yet, a meta-analysis of 75 ECDM studies by Smith and Vela (2001) concluded that although environmental context effects on memory are small (d = .28), they are reliable, both for recognition and recall tasks. In addition, Smith and Vela (2001) found that the use of association during the time of learning played a role, as this diverts attention away from the environment, thereby reducing ECDM effects. In light of this, here we will examine whether the typically small effect of ECDM can be found when using immersive VR, and whether the effect is strengthened when association or other learning strategies which divert attention away from the environment at the time of learning are taken into account.

Virtually no studies investigating context dependency effects have employed immersive VR before. One exception is a study by Hockley, Bancroft, and Bryant (2012) which employed video glasses, with other studies instead focusing on the use of non-immersive desktop monitors for virtual stimulus presentation (e.g., Pacheco, Sánchez-Fibla, Duff, & Verschure, 2017; Pettijohn & Radvansky, 2016). The immersive properties of video glasses such as used in the study of Hockley et al. (2012) are however distinct from that of a more ecological 360-degree CAVE system as employed in the current study. Such a system is highly immersive by projecting virtual environments onto the walls of a room, which thereby fully surround the user. This is the difference of feeling to be present inside a virtual environment, as opposed to observing it via the window of a virtual display. The use of a CAVE system offers multiple additional advantages, such as the possibility for more naturalistic test taking, as participants have an unobstructed view of their own bodies and the physical test materials while being immersed in the virtual environments displayed by the CAVE.

For the outcome variables of the current study, the mean number of correctly recognized words was expected to decrease when there is a switch of environment between learning and testing (DW or WD), compared to when there is no switch (DD or WW). Similarly, mean retrieval times were expected to be longer for switching compared to not switching environments. The current study used a randomized between-subject design. In a meta-analysis by Smith and Vela (2001), no significant difference in memory performance was found between recognition and recall tests. In light of this result, the current study therefore employed a recognition task as this allowed the recording of retrieval times next to correct/incorrect responses, yielding an additional outcome measure for assessing ECDM effects. Lastly, the current study employed a multi-step process using latent semantic analysis (LSA) to determine the word stimuli, whereas the original study does not provide the specifics of the stimuli selection (Landauer & Dumais, 1997).

Method

Participants

A total of 66 persons (22 males and 44 females, age: M = 22.14, SD = 2.95, range = 18-30) participated in the study. Participants were all from Tilburg University and received partial course credit. Non-Dutch native speakers, persons younger than 18 years of age, persons with a history of epilepsy, migraine or dyslexia, and (expected) pregnant women were excluded from the study. This study was conducted with permission granted by the Research Ethics Committee at Tilburg University.

Apparatus

Virtual environments were displayed on four walls of a 5.2 x 5.2 WorldViz CAVE using Unity 3D version 5.3.5, providing a 360-degree view. Eight short-range 120 Hz projectors provided 5.12 x 2.75 meter projection of 2580 x 800 pixels per wall. Four cluster rendering workstations: Intel Xeon E5-1630 v3 3.70 GHz, 32 GB RAM, NVIDIA Quadro M6000, Windows 8.1 Pro 64-bit processed the synchronization of projections. Visual stimuli consisted of 2D panoramas of a mountainous landscape (D: Dry) and an underwater scene (W: Wet) (see Fig. 1). The resolution of both panoramas exceeded that of the total resolution of the four CAVE walls and were thus displayed at the highest possible level of visual quality.

Figure 1: Above: Crop of panorama D (Dry) condition (adjusted from Wikimedia Commons). Below: Crop of panorama W (Wet) condition (Google Earth, 2016).

Materials

Godden and Baddeley (1975) do not provide examples of the stimuli used in their study. Constraints applied onto the stimuli are mentioned, however no specifics are stated.

To illustrate, it is mentioned that the stimuli consisted of unrelated words, however no specifics are provided regarding the method used to determine word relatedness.

The current study therefore employed new word stimuli, which were semantically unrelated. An initial English word list was generated using the MRC Psycholinguistic Database (Wilson, 1988) (applied filters: syllables: 2-3; concreteness: 450-700; imageability: 450-700), and was thereafter translated into Dutch. LSA was applied onto these words, using a LSA space consisting of 65 million words of the Dutch version of Wikipedia. Words were excluded that were (1) semantically related (e.g., *commander* and *lieutenant*), or (2) semantically related to names of visual or auditory elements contained in the land and underwater scenes (e.g., *island*). Two 36-item word lists were compiled from the words which remained after applying all selection criteria. Two additional 36-item word lists were created by separately randomizing the words of the first two. Examples of Dutch words included in the current study and their English equivalents are presented in Table 1. Sixteen different audio playlists were made for each combination of condition and word list, which were randomized between participant groups.

Questionnaires, including a short demographic survey and an open question about word learning strategies, as well as a word recognition test were presented using Qualtrics survey software (Qualtrics, Provo, UT).

Procedure

A maximum of four persons participated simultaneously. Upon entering the lab, participants first received an information letter and signed an informed consent form. Next, the purpose of the task was explained verbally to the participants, and were handed a pair of wireless headphones, used for providing pre-recorded instructions and auditory stimuli presentation. Then, participants were seated on chairs near the center of the CAVE, each facing one of the four walls, and followed pre-recorded audio instructions presented via wireless headphones. In the learning phase participants were immersed in either the dry (D) or the wet (W) virtual environment while twice listening to a playlist of 36 to be memorized words.

Table 1: Examples of Dutch word stimuli included in the study and their English translations.

Dutch	English
bondgenoot	ally
commandant	commander
flannel	flannel
mandarijn	tangerine
minister	minister
motor	motor
muziek	music
noedel	noodle
onderarm	forearm
paragraaf	paragraph
rabbijn	rabbi
tijdschrift	magazine
zilver	silver

In order to minimize the possibility that learned words remained in short-term memory, participants subsequently copied 15 auditorily presented numbers onto paper, and completed a list of questions. During this time, all four CAVE walls were white, irrespective of condition.

Next, in the testing phase, participants were either presented with the same virtual environment (DD or WW) or a different virtual environment (DW or WD) from the one in the learning phase. While immersed in the virtual environment, participants used a laptop to complete a forced-choice word recognition test. The test contained 72 words, half of which had been presented during the learning phase. There were two word orders in the test, which were equally divided between the participants of each group. After all participants finished the test, they were guided back to the adjacent room by the experimenter. There, they completed a post-questionnaire which contained a question about word learning strategies. Finally, they received a debriefing document with additional details about the purpose of the study, concluding the session. The total session duration was approximately 30 minutes. An overview of the experimental procedure is provided in Figure 2.

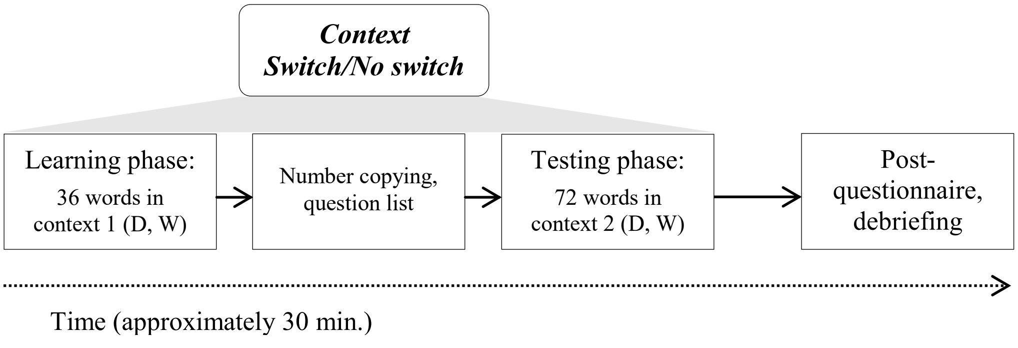

Figure 2: Overview of experimental procedure.

Results and Discussion

All statistical tests were conducted using analysis of variance (ANOVA) F-tests, unless stated otherwise. Normality and homogeneity of variance were respectively tested with the Kolmogorov–Smirnov test and Levene's test. Statistical significance is reported two-tailed ($\alpha = .05$). For retrieval times, only those of correct answers on the word recognition test were used in the analyses. There were no retrieval times < 200 ms. Individual retrieval times of 3 standard deviations above the individual retrieval time means were removed. Technical problems occurred for two participants during the testing phase. Data for these participants were therefore excluded from further analyses. The remaining participants (Total n = 64; DD: n = 16; DW: n = 15; WD: n = 17; WW: n = 16) were included in the analyses.

Results confirmed that there was no statistically significant difference in performance, neither due to the environment of learning, $F(1, 62) = .03$, $p = .861$, $\eta_p^2 < .001$, nor due to the environment of testing, $F(1, 62) = 1.90$, $p = .174$, $\eta_p^2 = .030$. No effect of environment switch was found between the learning and testing phases, $F(1, 62) = 1.74$, $p = .192$, $\eta_p^2 = .027$.

However, for DD-DW an effect of environment switch approaching statistical significance was found with a lower mean score in the switch condition, consistent with the pattern of ECDM in the literature of decreased performance in the presence of a switch, *Welch's* $F(1, 19.77) = 3.69$, $p = .069$, but not for WW-WD, $F(1, 31) < .01$, $p = .974$, $\eta_p^2 < .001$ (DD: $M = 63.5$, $SD = 3.06$; DW: $M = 60.0$, $SD = 6.40$; WW: $M = 62.0$, $SD = 5.34$; WD: $M = 62.06$, $SD = 4.79$).

In everyday life, one may be exposed more to environments bearing resemblance to mountainous landscapes as compared to underwater scenes. The absence of an effect of switch for WW-WD may therefore have been caused by the perception of the mountainous environment D to be less out of the ordinary as compared to the underwater environment W. Following this reasoning, the transition from environment D to W induces a stronger disturbance to the retrieval process compared to the reverse W to D order, thereby resulting in a stronger ECDM effect.

Retrieval times for correct responses on the word recognition test yielded no effect of environment switch, $F(1, 62) = .30$, $p = .586$, $\eta_p^2 = .005$. Effects of environment switch when comparing DD-DW and WW-WD separately were not statistically significant either, DD-DW: $F(1, 29) = 1.21$, $p = .280$, $\eta_p^2 = .040$, WW-WD: $F(1, 31) = .57$, $p = .456$, $\eta_p^2 = .018$. Thus, effects of environment switch when comparing condition DD with DW approached significance only for the number of correct responses, and not for retrieval times. ECDM effects for the number of correctly recalled items without any effects on the8 speed at which these items were recalled have been reported previously (Unsworth et al., 2012). Unsworth and colleagues (2012) interpret these findings by suggesting that a context switch influences the associative strength of items and therefore the probability that an item is remembered without influencing the time it takes to remember those items. Therefore, ECDM effects might be found on the number of correct responses without finding any effects on retrieval times.

As stated in the introduction, ECDM effect sizes have been found to be reliable, but small (Smith & Vela, 2001). As such, it may be important to take factors into account which may attenuate already minor ECDM effects. Smith and Vela (2001) detail how deep processing of stimuli constitutes such a factor, as cognitive capacity is finite, and therefore happens at the expense of the encoding of environmental information, important for ECDM. Deep processing by way of associative learning of items is given special mention, as it does not use contextual information of the surroundings, which is thus encoded less (Smith & Vela, 2001). Consequently, the resultant item memory is more resilient to changes of scenery between learning and testing, as the memory trace contains little contextual information to begin with, reducing ECDM effects. McDaniel, Anderson, Einstein, and O'Halloran (1989) too have argued that

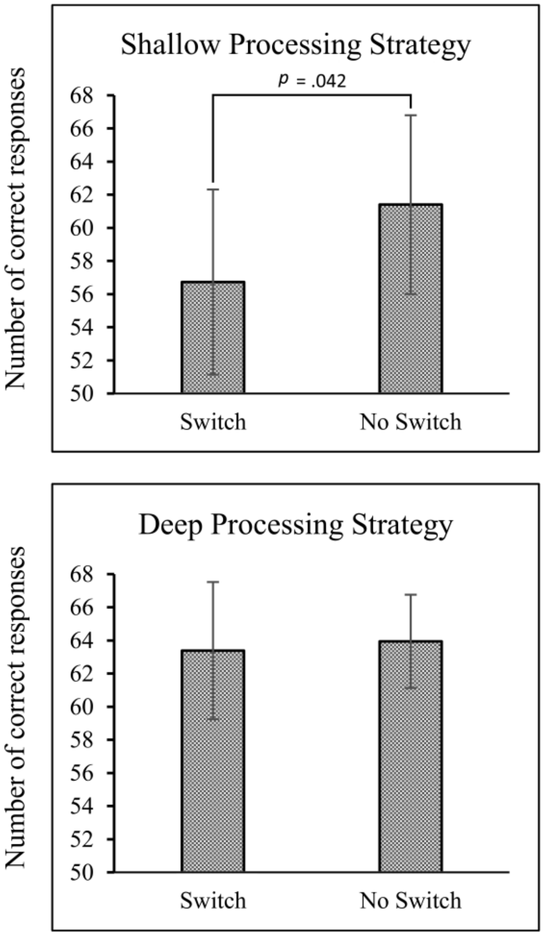

Figure 2: Mean number of correct responses in the word recognition test with environment switch and no switch between the learning and testing phases, for shallow processing (above) and deep processing (below) word learning strategy groups. Error bars show standard deviations of the mean.

ECDM effects may be reduced when items are associated, and additionally assert that this is also the case for relating information to one's own experience, or when mental imagery techniques are employed.

In light of these findings, in the current study self–reported participant word learning strategies were divided into shallow processing (silent word repetition, n = 26) and more resource intensive deep processing groups (e.g., associative learning, mental visualization, n = 38), as these strategies influence the attentional demand of the word learning task, thereby potentially modulating ECDM effects. In the context of the current study, controlling for learning strategies in this way is additionally warranted as word stimuli are especially susceptible to associative learning, one of the deep processing types of learning suggested to affect ECDM (Smith & Vela, 2001).

For the number of correct responses on the word recognition test, an effect of processing level was found, *Welch's* $F(1, 37.70) = 10.69$, $p = .002$. A statistically significant effect of environment switch was present for the shallow processing strategy group, $F(1, 24) = 4.62$, $p = .042$, $\eta_p^2 = .161$, however not for the deep processing group, $F(1, 36) = .23$, $p = .637$, $\eta_p^2 = .006$ (see Fig. 2), in line with the assertion of Smith and Vela (2001) that deep processing which averts attention from the environment may diminish ECDM effects. Thus, by classifying participants into shallow and deep processing groups, an ECDM effect was found for a word recognition test.

Regarding the retrieval times for correct responses on the word recognition test, a Mann-Whitney test and an ANOVA did not respectively show a statistically significant effect of environment switch for the shallow processing strategy group, $U = 81.00$, $z = -.078$, $p = .938$, $r = -.02$, nor for the deep processing strategy group, $F(1, 36) = .73$, $p = .398$, $\eta_p^2 = .020$. Therefore, no support was found for the hypothesis that environment switch increased word recognition retrieval times, irrespective of word learning strategy. This is in line with the findings of Unsworth and colleagues (2012) discussed above.

In cases where the ANOVA assumption of homogeneity of variance was violated, the results of equivalent non-parametric tests were presented. This did not affect statistical significance. For reasons of completeness, here we provide the ANOVA F-tests results of these cases: Effect of environment switch on DD-DW: ANOVA: $F(1, 29) = 3.85$, $p = .059$, $\eta_p^2 = .117$. Effect of processing level on performance: ANOVA: $F(1, 62) = 12.74$, $p = .001$, $\eta_p^2 = .170$. No effect of shallow processing on retrieval times: ANOVA: $F(1, 24) < .01$, $p = .995$, $\eta_p^2 < .001$.

General Discussion

The current study demonstrated the applicability and benefits of VR for conducting studies in the field of cognitive science, where immersive VR has yet to be widely adopted. For this purpose, an immersive adaptation was created of a classic ECDM study by Godden and Baddeley (1975) which leveraged the increased ecological validity of immersive VR. We showed that word recognition performance differences were marginally significant between DD and DW groups, with improved scores in the DD group, for which there was no switch of context between learning and testing. This is consistent with the findings in the literature, in which ECDM effects are reliable but small on average (Smith & Vela, 2001), and which stresses the importance of controlling for factors potentially affecting already small ECDM effects. Deep processing of items may be one such factor, as this may happen at the expense of the encoding of environmental information (Smith & Vela, 2001). After classifying participants into shallow and deep processing groups, ECDM effects were found to be stronger, as word recognition performance was significantly improved in the absence of a context switch. This supports the notion that the effect of learning strategies should be taken into account, which may otherwise mask ECDM effects.

For further validation of the use of immersive virtual environments for ECDM studies, the design of the current study may be expanded to incorporate both real, immersive VR and desktop monitor ECDM conditions, so as to determine how the effects thus obtained may compare.

By using the example of ECDM, the current study shed light on the applicability and benefits of the use of immersive VR for research topics in the field of the cognitive sciences. As a next logical step, it would be valuable to leverage the inherent ability of immersive VR for increased ecological validity coupled with high experimental control, in order to take investigations into ECDM and other research topics in the field of the cognitive sciences to the next level. To illustrate using the example of ECDM, as indicated by Godden and Baddeley (1975), in conditions in which learning and testing contexts are required to be identical, there might still be discrepancies when using real settings, for instance due to changes in weather conditions, light intensity, background noise and other factors. That such factors indeed affect ECDM has for instance been shown for clothing (Finn et al., 2010), noise levels (Bell et al., 1984) and background sounds (Smith, 1985). Using VR, the potentially debilitating effects of these and other confounding variables can be effectively removed from the study design.

As there is complete control over which type of stimuli to use and which to exclude, VR can additionally be utilized to investigate the degree to which individual contextual components may contribute to ECDM effects, with a fine-grained level of control unattainable when using real environments. Similarly, a modulating effect of learning strategies on ECDM can now be examined in detail through direct experimental manipulation, following the example of McDaniel et al. (1989). Importantly, using VR, this can be done while keeping the contextual elements of the virtual environment constant.

The benefits of immersive VR, here presented for the particular case of ECDM, are equally applicable to a wide range of research topics in the field of cognitive science, which stand to benefit from increased ecological validity coupled with high experimental control. In recent years, the benefits of immersive VR have been enhanced further through rapid technological advancements, which have made it more realistic, immersive and intuitive to use, and have simultaneously reduced the time- and cost associated with the development of virtual stimuli. As a result, immersive technologies have become more accessible, and can be applied to an even wider range of research areas.

The current study was but one example of the way in which conventional cognitive science study designs may be effectively adapted to immersive settings, thereby benefitting from the unique affordances of immersive VR. The ECDM example of the current study thereby paves the way to a wide adoption of immersive VR in the cognitive sciences, opening up exciting opportunities for new avenues of ecologically valid research.

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