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Research Article

The Contribution of Dynamic Exploration to Virtual Anatomical Learning

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Virtual Learning Environments are increasingly becoming part of the medical curriculum. In a previous study we (luursema et al., 2006) found that a combination of computer-implemented *stereopsis* (visual depth through seeing with both eyes) and *dynamic exploration* (being able to continuously change one's viewpoint relative to the studied objects in real time) is beneficial to anatomical learning, especially for subjects of low *visuo spatial ability* (the ability to form, retrieve, and manipulate mental representations of a visuo-spatial nature). A follow-up study (luursema et al., 2008) found the contribution of computer-implemented stereopsis to this effect to be small but significant. The present experiment investigated the contribution of dynamic exploration to anatomical learning by means of a virtual learning environment. Seventy participants were tested for visuo-spatial ability and were grouped in pairs matched for this ability. One individual of the pair actively manipulated a 3D reconstruction of the human abdomen; the other individual passively watched the interactions of the first individual on a separate screen. Learning was assessed by two anatomical learning tests. Dynamic exploration provided a small but significant benefit to anatomical learning.

1. Introduction

Increasingly, Virtual Learning Environments (VLEs) are becoming a staple of the medical curriculum. Surgical simulators help young surgeons train laparoscopic skills (e.g., [1]), and electronically enhanced manikins add physiological parameters to procedures traditionally trained on nonaugmented manikins. In anatomical learning too, VLEs are increasingly used to complement traditional media such as anatomical atlases, anatomical manikins, and dissection [2]. Acquiring a mental model of human anatomy, including its visuospatial aspects, provides the medical student with an essential framework for any further study in the medical field. In searching to optimize the effectiveness of VLEs for anatomical learning, earlier research assessed the effect of a combination of computer implemented stereopsis and dynamic exploration, and the effectiveness of computer-implemented stereopsis alone on this learning [3, 4]. The research reported here continues this series by investigating the contribution of computer implemented dynamic exploration to anatomical learning. We will mostly ignore the vast literature on surgical training simulators here, as this literature is concerned with training motor skills, with little relevance to our focus on spatial cognition.

Anatomical learning is largely learning of a visuospatial nature. Two factors present in anatomical learning by dissection are stereopsis and dynamic exploration, both of which are lost in anatomical atlases. *Stereopsis* is the visual sense of depth that is based on differences in patterns of light projected on both retinae. Stereopsis is one of the most important visual depth cues in one's *personal space*, which can be defined as "the zone immediately surrounding the observer's head, generally within arm's reach and slightly beyond" [5]. *Dynamic exploration* refers to the possibility to actively and continuously change one's view towards objects under study. Stereopsis and dynamic exploration are thought to be functionally coupled for goal-directed motor behavior in personal space [6], which is corroborated by recent research in endoscopic skills training [7].

The importance of the combination of these factors in visuospatial *learning* (as contrasted to training) is less clear. Although Luursema et al. [3] recently showed that a combination of VLE implemented stereopsis and dynamic exploration during an anatomical study phase led to better results on subsequent anatomical tests, stereopsis alone only had a slight positive impact on anatomical learning in a similar experiment [4]. It is not clear whether a large effect for dynamic exploration, or the effect of the functional coupling of stereopsis and dynamic exploration are responsible for the effect found in the former experiment.

Another factor influencing anatomical learning is *visuo-spatial ability*, which refers to the ability to form, retrieve, and manipulate visuo-spatial mental representations [8]. The relevance of visuo-spatial ability for medical practitioners was demonstrated in several studies that found visuo-spatial ability to correlate highly with success as an endoscopic surgeon (e.g., [9, 10]). Additionally, [11] found a significant positive correlation between spatial learning disabilities and underachievement in an anatomy course for second-year medical students at Cape Town University. A comprehensive review of the important role of spatial cognition in medicine, with special attention to its practical implications, can be found in [12]. In addition, Luursema et al. [3] found that participants of low visuo-spatial ability benefited more from the condition that included both stereopsis and dynamic exploration than participants of high visuo-spatial ability.

Having established a learning benefit for the combination of stereopsis and dynamic exploration, and having found a small benefit for stereopsis alone, we were interested to assess the learning benefit of dynamic exploration. Similar to our earlier study, we expected participants of low visuo-spatial ability to benefit more from dynamic exploration than participants of high visuo-spatial ability because they are probably less able to construct a 3D mental representation through passive viewing alone.

"Dynamic exploration" as an experimental condition was implemented by coupling participants of similar visuo-spatial ability, allowing one participant to actively manipulate the stimulus material, and making the other participant passively watch the explorations of the first participant.

2. Method

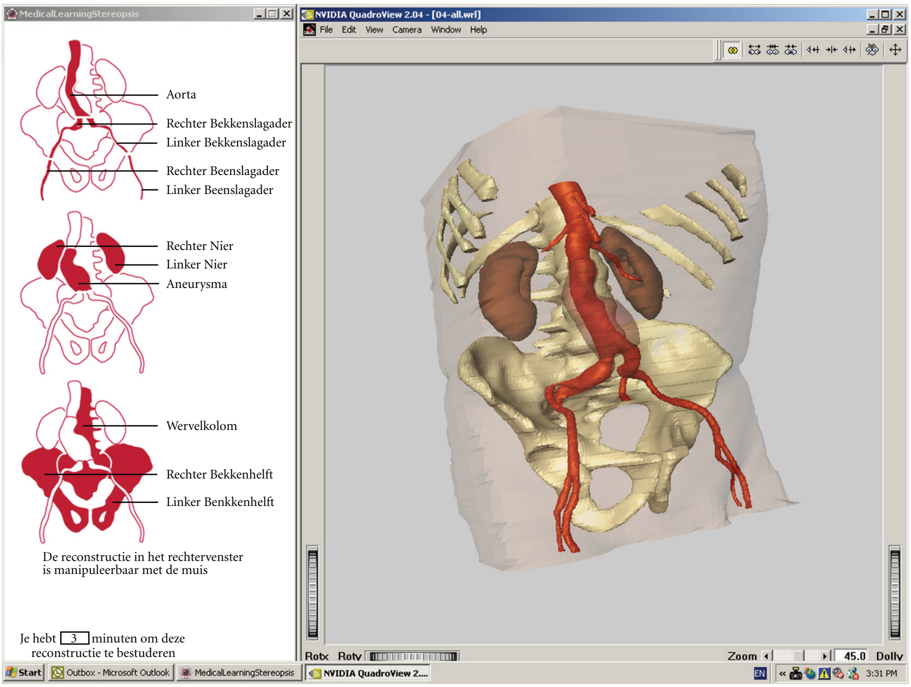
2.1. Participants. Participants were university students from the Faculty of Behavioral Sciences, University of Twente. All participants were naïve to the used experimental setup. They received either course credit or six Euros for their participation. All participants were native Dutch speakers. All had limited knowledge of human abdominal anatomy (not exceeding high school level, this was verbally indicated by the participants in response to a question to that effect by the experimenter). Participants were between 18 and 53 years of age. A total of 70 participants took part (20 women and 50 men). All reported normal or corrected to normal vision.

2.2. Procedure. Before the actual experiment, all participants were tested for visuo-spatial ability, using the Vandenberg and Kuse mental rotation test [13, 14]. Based on the outcome of this test, participants were ranked according to visuo-spatial ability, and pairs were formed by alternately assigning participants to either the active or the passive condition of the experiment. A yoked design [15] was used for the study phase of the experiment. This means that the two participants of each pair were simultaneously tested, with one participant actively manipulating the 3D reconstructions of the human abdominal anatomy that were displayed (active condition). The other participant passively watched the explorations of the active participant on a separate screen (passive condition). Participants were kept unaware of this design during the experiment. A screen divided the experiment space, making it impossible for the participants to see each other's actions. During the study phase participants were asked to wear headphones that exposed them to white noise, to cancel out the sound of mouse clicks that might otherwise have cued the participants to the experimental design.

After the study phase, learning was measured with an identification test and a localization test. Test order was randomized over the pairs, but the tests themselves were identical for all participants. The study phase was administered from a computer that allowed for stereoptic vision being implemented by shutter glasses. Two monitors were attached to this computer. The introduction to the study phase, as well as the tests following the study phase, were administered from a separate computer setup, allowing both participants of each pair to work individually in those phases of the experiment. A researcher always was present during the experiment. The room was equipped with all the hardware and software necessary, and was shut off from possible disturbances during the experiment. All explanations were provided on screen, in Dutch.

2.2.1. Study Phase. Example items of the identification test and localization test were presented to participants prior to the experiment. They were told to use the study phase to prepare for these two tests (Figure 1 shows a screenshot of the study phase). During the study phase, labeled reference figures for the eleven anatomical parts of the abdomen relevant to the tests were visible (left side of Figure 1). The active participant of a pair manipulated a 3D model of the referenced abdominal anatomy, by using the mouse to change the viewpoint towards the 3D model. Viewpoint manipulation was restricted to rotation over any of the reconstruction's Cartesian axes. Passive participants could not interfere with or influence this reconstruction, and witnessed the active participant's explorations. Stereopsis was implemented for all participants by shutter glasses. All participants were given three minutes to learn the shape, name, and spatial relations of these eleven anatomical parts of the abdomen.

2.2.2. Identification Test. One test to assess anatomical knowledge was the identification test (see upper frame of Figure 2). This test consisted of four familiarization trials



De reconstructie in het rechtervenster is manipuleerbaar met de muis

Je hebt 3 minuten om deze reconstructie te bestuderen

Figure 1: Screenshot of the study phase. Participants either actively manipulated the 3D anatomy on the right or passively watched the manipulations of the active participant.

and twenty test trials. Participants were told to start a trial by pushing the “5” key on the numeric keypad at the right side of the keyboard. As a result of this action, a CT cross-section with one highlighted anatomical structure appeared, joined by a list with names of the eleven anatomical structures. At the release of this key the picture of the cross-section disappeared. The CT cross-sections used for this test were the same ones that had been used to construct the various visual materials used during the study phase.

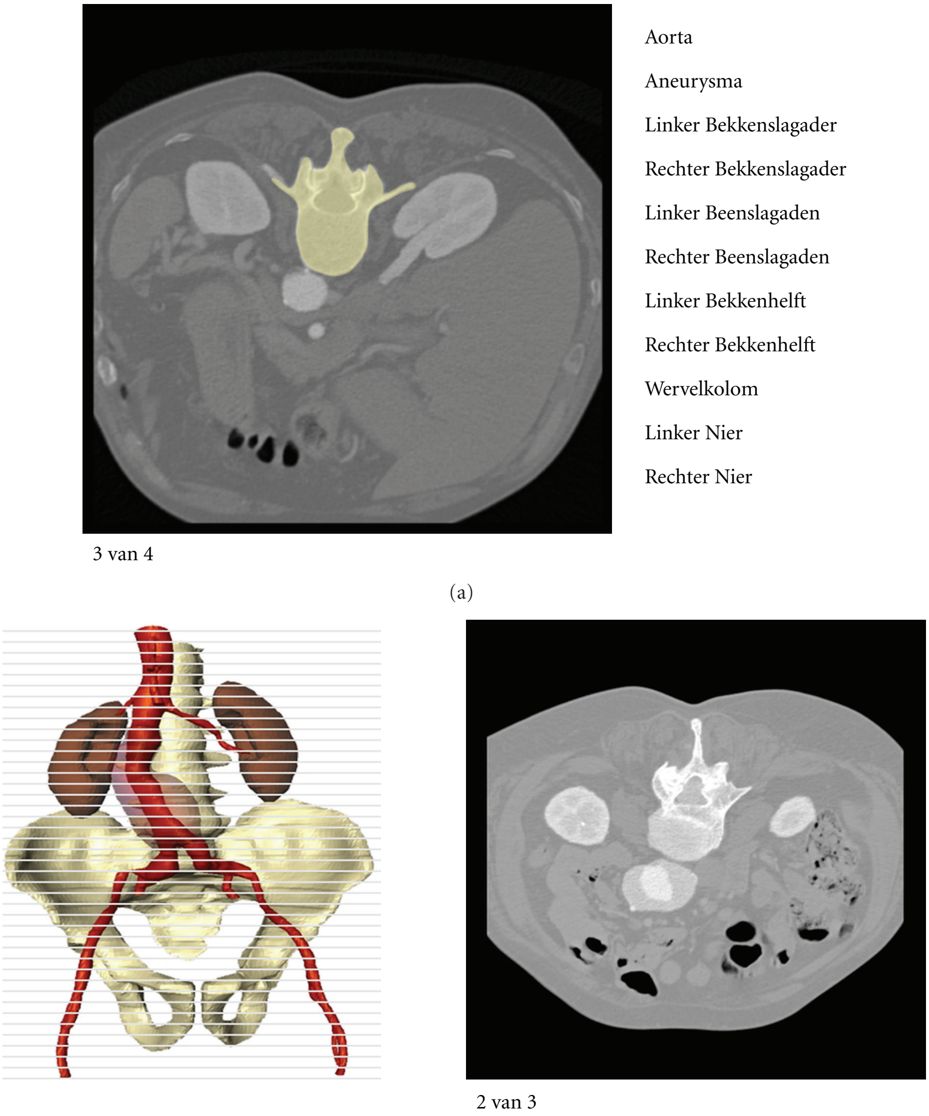
Participants were instructed to release the key only when they had identified the highlighted structure as one of the listed anatomical structures and then to mouse-click the corresponding name in the list at their own pace. Reaction times were defined as the time the key was pressed during each trial. If after 10 seconds the button had not been released, the picture with the cross-section disappeared anyway. Errors were defined as clicking an incorrect name or no name at all. After each trial error feedback was given. No shutter glasses were worn during this test.

2.2.3. Localization Test. The other anatomical knowledge test was the localization test, consisting of three familiarization trials and twenty test trials. Participants were asked to indicate on a frontal-view screenshot of the studied anatomy, the correct horizontal level of a CT cross-section (lower frame of Figure 2). Again, the cross-sections were taken from the same scans that had been used to develop the material for the study phase of the experiment. In each trial a different cross-section was shown. The order in which the cross-sections appeared was randomized between participants.

Participants were instructed to start a trial by pushing the “5” key on the numeric keypad to make a cross-section appear. At the release of this key the picture of the cross-section disappeared. They were further instructed to release the key as soon as they had identified the level from which this cross-section was taken, and then to click at their own pace the corresponding line out of a series of lines overlaying the frontal-view screenshot. If after 15 s the key was not released, the cross-section disappeared and an error was scored. Reaction time was defined as the time the key was held during each trial. A correct answer was defined as clicking the line corresponding exactly with the cross-section, or the line directly above or below it. After each trial error feedback was given. As in the identification test, this test did not involve the use of shutter glasses.

2.3. Apparatus. Stereopsis was implemented by a setup including two pairs of Stereographics’s CrystalEyes CE-3 active shutter glasses, an E-2 emitter and Stereo Enabler, a Pentium 4 computer running Windows XP, two 1900 CRT-monitors (Ilyama Vision Master Pro 454), and a PNY-Quadro 4 580XGL videocard. This setup allowed for a monitor refresh rate of 140 Hz, and thus for an effective refresh rate of 70 Hz for each eye, preventing noticeable flicker.

The 3D anatomical objects were constructed on the basis of CT data from a patient suffering from an abdominal aortic aneurysm. The Surfdriver software package was used to trace the relevant anatomy in every slice, after which Surfdriver automatically generated 3D DXF-models. These



Aorta
Aneurysma
Linker Bekkenslagader
Rechter Bekkenslagader
Linker Beenslagaden
Rechter Beenslagaden
Linker Bekkenhelft
Rechter Bekkenhelft
Wervelkolom
Linker Nier
Rechter Nier

3 van 4

(a)

2 van 3

(b)

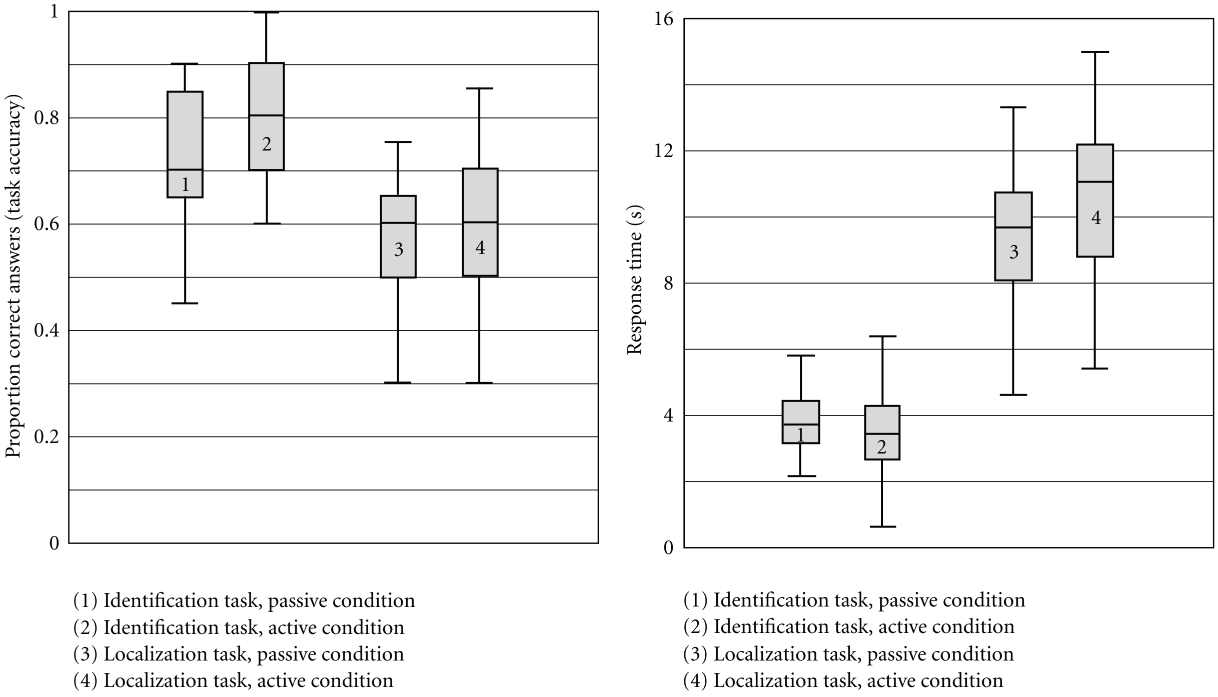
FIGURE 2: Screenshots of an item of each of the two tests. (a) the identification test with the eleven possible names of the highlighted structure, and (b) the localization test that involved selecting the level in the left image from which the right image was taken.

models were postprocessed in 3D Max and Cosmoworlds, resulting in VRML models ready for use in both conditions of the study phase. During the study phase, these models could be explored by means of the Nvidia QuadroView 2.04 application. The introduction to the study phase, as well as the tests following the study phase, were run from two Pentium 4 computers with 17″ monitors. Adobe's Authorware software was used to create the software part of this experiment, including study phases, experimental tests, and logfiles for each participant necessary for data analysis.

3. Results

Accuracy for the mental rotation test (used as a proxy for visuo-spatial ability) and accuracy for both anatomical learning tests were transformed to proportions correct for easier interpretation. Boxplots for accuracy and latency on both anatomical learning tests, an identification test and a localization test, are given in Figure 3. To rule out a latency/accuracy tradeoff, correlations were calculated between latency and accuracy for both tests. A latency/accuracy trade-off could not be ruled out for the localization test ($r = .41, P < .001$), consequently latency was taken on board as a covariate in the ANCOVA bearing on that test.

All dependent variables were subjected to a Kolmogorov-Smirnov 1 test, no significant deviations from the normal distribution were found. Consequently, parametric tests were used for the statistical analysis. Two ANCOVAs were done with, respectively, identification test accuracy and localization test accuracy as dependent variables. For the identification test ANCOVA, between-subject factor was



(a)

(b)

FIGURE 3: Boxplots show median, interquartile range, and extreme values of both the accuracy and latency scores, for each group and test.

TABLE 1: Analysis of covariance results for post test accuracy (single tailed).

Source	*df*	*F*	*P*
Accuracy on the identification test ($n = 70$)			
Visuo-spatial ability (VSA)	1	4.81	.02
Dynamic exploration (DE)	1	3.01	.04
VSA × DE	1	1.05	.16
Accuracy on the localization test ($n = 70$)			
Visuo-spatial ability (VSA)	1	5.74	.01
Dynamic exploration (DE)	1	.04	.42
VSA × DE	1	.00	.47
Localization test latency	1	15.85	.00

dynamic exploration (i.e., passive or active). Visuo-spatial ability (as measured by pretest accuracy) was used as a covariate. Visuo-spatial ability × dynamic exploration was calculated as well. For the localization test ANCOVA, dynamic exploration was again used as a between subjects factor. Latency and visuo-spatial ability were used as covariates. Visuo-spatial ability × dynamic exploration was used as an interaction variable. Results for these analyses are given in Table 1.

4. Discussion

An experiment was reported that investigated the contribution of dynamic exploration during a study phase to anatomical learning, as measured by two anatomical tests. It was hypothesized that dynamic exploration would be beneficial to anatomical learning, especially for participants of low visuo-spatial ability. Dynamic exploration only affected the identification test, active participants performed significantly better on this test than passive participants. Localization test latency significantly affected localization test accuracy, which may have masked positive effects for dynamic exploration on this test. In earlier variations of this experiment, no such effect for latency was found. In future experiments latency will need to be controlled more strictly. The positive contribution of dynamic exploration to visuo-spatial learning represents an extension of earlier findings of James et al. [15], who found a benefit for dynamic exploration to virtual learning on a recognition task, in a similar experimental paradigm.

Visuo-spatial ability significantly affected anatomical learning for all participants, on both posttests. No interaction effects were found for dynamic exploration and visuo-spatial ability, suggesting that the added value of dynamic exploration is similar for both people of high- and low-visuo-spatial ability. This finding is in contrast with our earlier finding that a combination of stereopsis and dynamic exploration is more beneficial to learners of low-visuo-spatial ability than to learners of high-visuo-spatial ability [3]. Effect magnitude of experimental treatment was largest for the combined stereopsis/dynamic exploration study, mainly due to benefits of this combination for participants of low-visuo-spatial ability. Apparently, learners of low-visuo-spatial ability benefit most from an implementation of virtual anatomical learning that approaches natural exploratory behavior, extending the known benefits of combined stereopsis and dynamic exploration for task execution [6] to visuo-spatial learning.

To bridge the gap between this "proof-of-principle" study and the medical learning field, additional studies will have to be conducted with anatomical learning material more suitable to medical practice, and medical students or medical professionals as participants. We have however no reason to believe that basic learning mechanisms are different for medical professionals and our current participants.

In conclusion, dynamic exploration positively affects anatomical learning. Educational designers are well advised to allow their students to dynamically explore virtual anatomical objects in learning environments that are meant to teach visuo-spatially complex material.

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