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The role of stereopsis in virtual anatomical learning

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ABSTRACT

The use of virtual learning environments in the medical field is on the rise. An earlier experiment [Luursema, J.-M., Verwey, W.B., Kommers, P.A.M., Geelkerken, R.H., Vos, H.J., 2006. Optimizing conditions for computer-assisted anatomical learning. Interacting with Computers, 18, 1123–1138.] 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 with respect to the objects studied 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). The present experiment investigated the contribution of computer-implemented stereopsis alone to anatomical learning. Two groups with a similar distribution of visuo-spatial ability were formed; one group studied a 3D computer model of the human abdominal anatomy in a stereoptic condition, the other group studied the same anatomy in a *biocular* condition (both eyes exposed to the same image). Although visuo-spatial ability was the most important variable predicting anatomical learning, computer implemented stereopsis provided a significant benefit for one of the post-tasks assessing this learning.

1. Introduction

1.1. Background

The use of Virtual Learning Environments (VLEs) in the medical curriculum is on the rise. Over the last decade, many dedicated medical VLEs have been developed. High end, stand-alone examples include laparoscopic simulators (e.g., Immersion's LapSim, or the Xitact series) and electronically enhanced manikins (e.g., Laerdal's product series). E-learning examples include electronic patient simulations (see Le Beux and Fieschi, 2007 for a recent survey) and anatomical learning environments (Jastrow and Vollrath, 2003 give an overview of such learning environments based on *the visible human project*, a high profile project that included the creation of computerized 3D models of human anatomy based on anatomical cross-sections). Acquiring accurate mental representations of human anatomy is a sine-qua-non for the medical practitioner, the human body being the frame of reference for all other medical knowledge and skills. In earlier research, we reported on the beneficial effects of a combination of computer-implemented stereopsis and dynamic exploration on virtual anatomical learning, especially for participants of low visuo-spatial ability (Luursema et al., 2006). The experiment reported here continues this line of research by taking a closer look at the effects of computer-implemented stereopsis on anatomical learning, without dynamic exploration.

1.2. Media for anatomical learning

Traditionally, human anatomy is taught by means of dissection, complemented by anatomical atlases and manikins. Three self-evident features of dissection will be made explicit here, as they bear on the discussion of anatomical VLEs below. A first important feature of dissection is the availability of *haptic information*: even though a living body provides a very different haptic experience compared to a dead body that has been chemically treated to prevent decay, haptic cues still provide relevant information as to qualities such as weight, flexibility, surface structure, size, and shape. Since the technical implementation of haptic feedback in other media, including VLEs, is still far from satisfactory, haptic information can be considered a unique and irreplaceable feature of dissection.

Second, a number of visual depth cues that are available in dissection usually lack in other media. Prime amongst those is *stereopsis* which 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" (Cutting and Vishton, 1995). The perception of stereop-

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tic depth is available in dissection, as well as in studying manikins.

The third feature of dissection is *dynamic exploration* (the possibility to actively and continuously change one's view towards objects of study). This is a given in dissection and manikins, and can be implemented in VLEs too.

In contrast to these advantages of dissection, anatomical atlases and VLEs provide the possibility to contextualize the presented anatomy within a medical knowledge frame. In this sense, both anatomical atlases and VLEs make a great companion to dissection, helping students to create a mental representation of the studied anatomy where topological knowledge of this anatomy is integrated with medical concepts not provided by dissection.

Another advantage of anatomical atlases, manikins and VLEs over dissection is the convenience of use of the former: a dissection room is arduous and expensive to maintain, and not as flexible in its deployment as atlases, manikins, and VLEs are.

Obviously, it is necessary to indicate that, in contrast to dissection, *mediated* anatomical learning (e.g., through atlases, manikins, VLEs) filters out much of the richness of the original anatomy, presenting students a representation that merely retains the conceptual model of its makers instead. This can lead to a situation where students discover only what they are supposed to discover, preventing them to enrich their knowledge beyond the provided model. The training of medical skills is likely to be facilitated if in an earlier (anatomical learning) stage students had the opportunity to test provided conceptual models against the reality of first hand dissection experience. Additionally, keenness to incidental anatomical exceptions and the uniqueness of patients' morphologies as provided by dissection is likely to be crucial to medical competence.

Summing up, traditional anatomical learning methods involved direct and mediated methods, each having their unique qualities. Direct methods (i.e., dissection) offer haptic information, 3D visual information, and dynamic exploration, while mediated methods (i.e., anatomical atlases and manikins), provide conceptual knowledge, and convenience of use. For the development of detailed anatomical knowledge, these methods should be seen as supplementary rather than supernumerary. Nowadays, VLEs offer the possibility to implement two features traditionally associated with dissection and not with mediated medical learning, namely stereopsis and dynamic exploration. However, little is currently known as to the effectiveness of these two features for anatomical learning.

1.3. Human factors

Stereopsis is one of the most important visual depth cues in personal space, especially for prehension (Servos et al., 1992; Bradshaw et al., 2004). One could say that stereopsis and prehension are functionally coupled with respect to goal-directed motor behavior in personal space (dynamic exploration being the goal-directed motor behavior under study here). Endoscopic surgery, where practitioners generally get visual feedback on their actions by means of a two-dimensional video display, has over the years provided an important applied field to test the ecological validity of this coupling.

Initially, inconclusive results were reported, mostly due to technical limitations; e.g., a combination of shutter glasses and a relatively low monitor refresh rate will lead to noticeable flicker (as in Wentink et al., 2002), which is very likely to influence test results. Other studies implemented stereoptic feedback and biocular feedback on different systems, without controlling for image resolution and other relevant system differences. The reader is referred to Huber et al. (2003) for a more detailed discussion of this older work. A recent, better controlled study has confirmed the expected superiority of endoscopic performance under three-dimensional (stereoptic) imaging, compared to two-dimensional (biocular) imaging (Byrn et al., 2007).

In contrast, we do not know whether the coupling of stereopsis and dynamic exploration contributes also to visuo-spatial learning (of which anatomical learning is but one example). However, Luursema et al. (2006) recently showed that a virtual anatomical study phase that combines stereopsis and dynamic exploration, led to better learning than a study phase that involved only exploration of standard anatomical views (top, side, and front). Whether this can be ascribed to stereopsis, dynamic exploration, or its combination is as yet unclear.

Successful learning depends on the formation of mental representations of the information to be learned. For anatomical learning, where the information to be learned is visual and spatial in nature, *visuo-spatial ability* is a cognitive ability that needs to be taken into account. Visuo-spatial ability refers to the ability to form, retrieve and manipulate visuo-spatial mental representations (Carroll, 1993; Hegarty and Waller, 2005). 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., Risucci, 2002; Wanzel et al., 2002). Additionally, Rochford (1985) 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 Hegarty et al. (2007). Luursema et al. (2006) 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. This finding could potentially impact anatomical instruction by suggesting a way to support students of low visuo-spatial ability.

To assess the contribution of stereopsis to the benefit of combined stereopsis and dynamic exploration for anatomical learning, we compared two groups of participants, which were subjected to different anatomical study phases after which they were tested for their amount of anatomical learning. For both groups, the study phase showed an auto rotating 3D model of human abdominal anatomy. Participants in the stereoptic study phase wore shutter glasses by means of which they experienced the presented models stereoptically. Participants in the biocular study phase did not wear any specific headgear, and consequently experienced the model *biocularly* (both eyes were exposed to identical images). Anatomical learning was assessed by two tests, an identification task and a localization task. Visuospatial ability was measured by the Vandenberg and Kuse mental rotation test (Vandenberg and Kuse, 1978; Peters et al., 1995).

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

Also, although stereopsis can be easily implemented across the whole range of virtual learning environments, its potential for learning has been largely unexplored. If computer-implemented stereopsis proves to be beneficial to visuo-spatial learning, this would be of consequence to the implementation of educational practices in virtual environments where this type of learning is critical.

2. Method

2.1. Participants

Participants were university students and employees from the faculty of Behavioral Sciences, University of Twente. All participants were native Dutch speakers. All reported limited knowledge of human abdominal anatomy (not exceeding high school biology level). Participants were between 19 and 34 years of age. A total of 46 participants took part (30 women and 16 men). All reported normal or corrected to normal vision. All participants were naïve to the tasks they were to perform in this experiment.

2.2. Procedure

Before the actual experiment, 91 potential participants were tested for the ability to see stereoptically, and for visuo-spatial ability. Stereopsis was tested with the TNO-test for stereoscopic vision. It demands participants to distinguish figures from a background in random dot figures within thirty seconds (Okuda and Wanters, 1977). Six participants of insufficient stereoptic ability were excluded from further participation. The remaining 85 participants were tested for visuo-spatial ability using Vandenberg and Kuse's mental rotation test (Vandenberg and Kuse, 1978; Peters et al., 1995). From this group, 46 subjects were randomly selected for participating in the study reported here. The selected participants were ranked according to visuo-spatial ability, and alternately matched in pairs over the two conditions of the experiment. This provided an equal distribution of visuo-spatial ability over both conditions.

The selected participants then learned about human anatomy in a study phase that differed for the two groups. Afterwards their knowledge was assessed with an identification task and a localization task. The order of these two tasks was counterbalanced across the participants in each group. The study phase and both tasks were carried out on an individual basis in a specially prepared experimental room. It contained the hardware and software necessary for the experiment and was shut off from possible disturbances during the experiment. All task-instruction and error feedback was provided on screen in Dutch.

2.2.1. Study phase

At the beginning of the experiment, example items of the two tests (see below) were presented to participants. They were informed to use the study phase to prepare for these two tasks. The study phases of each group contained labeled reference figures for the eleven anatomical parts of the abdomen relevant to the tasks (Fig. 1 shows a screenshot of the study phase). During this study phase, the *biocular group* watched a 3D model of the referenced abdominal anatomy, which rotated around its vertical axis. Participants could not interfere with, or influence, this animation. The *stereoptic group* explored the same auto-rotating 3D-reconstructions of the abdominal anatomy, but here stereopsis was implemented by means of shutter glasses. All participants were given three minutes to study the shape and mutual relations of these eleven anatomical parts of the abdomen. Only participants in the stereoptic group wore shutter-glasses, reasoning that asking participants in the biocular group to wear special headgear that turns out to be non-functional would distract them, and thus bias test results.

2.2.2. Identification task

One test used to assess anatomical knowledge was the identification task (see upper frame of Fig. 2). It consisted of four familiarization trials and twenty test trials. Participants were instructed to start a trial by pushing the '5' button on the numeric keypad at the right side of the keyboard. This action made an anatomical CT cross-section appear with one highlighted anatomical structure, joined by a list with eleven names of anatomical structures. With the release of the button the picture of the cross-section disappeared. The anatomical cross-sections used for this task were the ones that had also been used for constructing the 3D visual materials of the study phase.

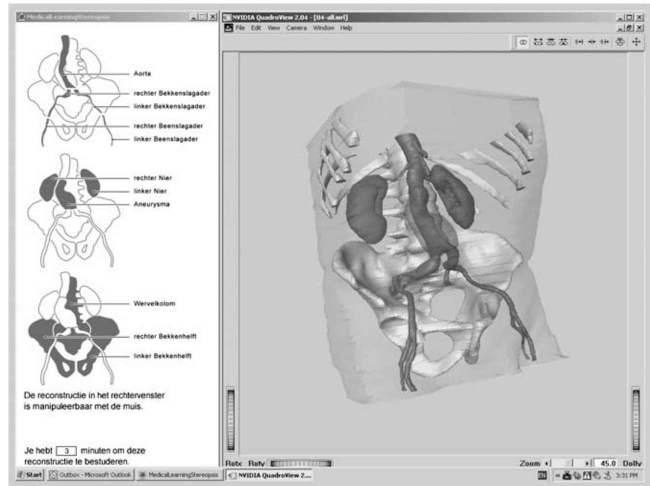

Fig. 1. Screenshot of the study phase. Participants studied either the autorotating 3D anatomy stereoptically (with shutter glasses) or biocularly (without shutter glasses).

Participants were instructed to release the button only when they had identified the highlighted structure by selecting one of the given anatomical names. They then mouse-clicked the corresponding name in the list at their own pace. Reaction times were defined as the time the button was held down during each trial. If after 10 s 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 task.

2.2.3. Localization task

The other test of anatomical knowledge was the localization task which consisted of three familiarization trials and twenty test trials. Participants were instructed to indicate on a frontal-view screenshot of the studied anatomy (lower left frame of Fig. 2), the correct horizontal level of a CT-based anatomical cross-section (lower right frame of Fig. 2). These cross-sections were taken also from the scans used to develop the material for the study phase. Each trial involved presentation of another cross-section. The order in which the cross-sections appeared was randomized across participants.

Participants were instructed to start a trial by pushing the '5' button on the numeric keypad to make a cross-section appear. With the release of the button the cross-section disappeared. They were further instructed to release the button as soon as they had identified the level from which this cross-section was taken, and then to click at their own pace with the mouse the corresponding line out of a series of lines overlaying the frontal-view screenshot. If after 15 s the button had not been released, the cross-section disappeared and an error was scored. Reaction time was defined as the time the button 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. This task did not involve the use of shutter-glasses either.

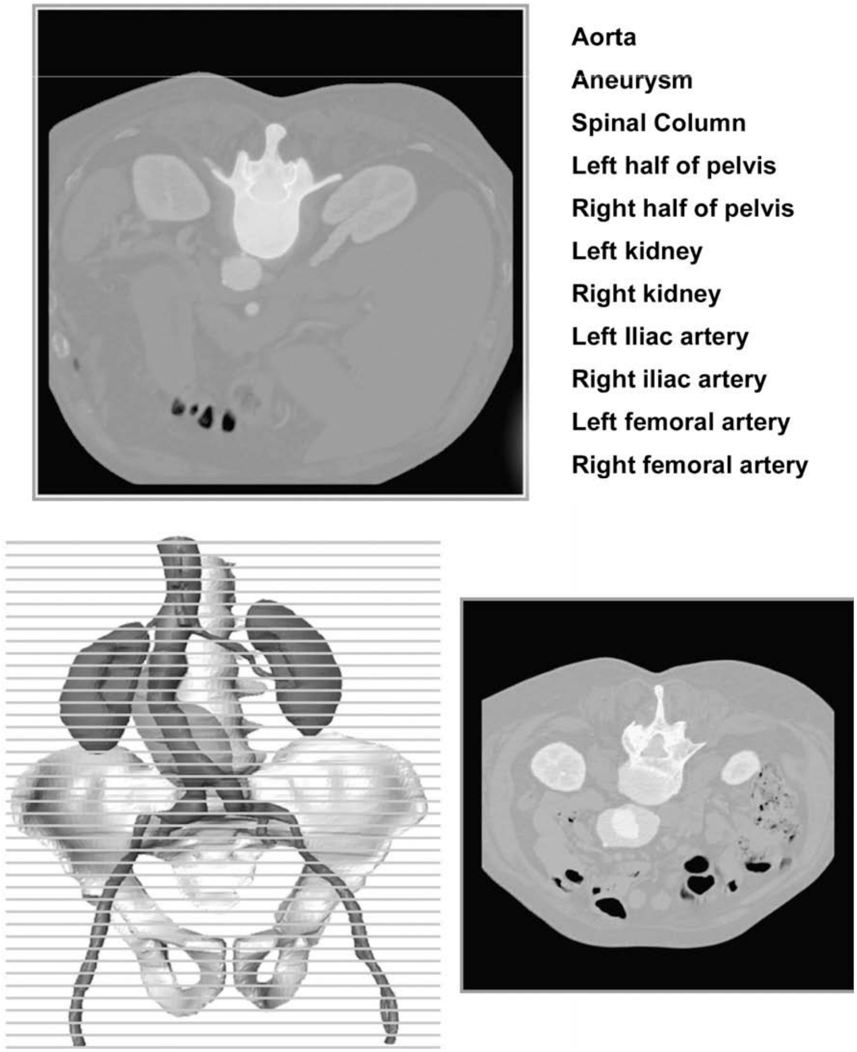

Fig. 2. Screenshots of an item of each of the two tasks. On top the identification task with the eleven possible names of the highlighted structure, at the bottom the localization task that involved selecting the level in the left image from which the right image was taken. Names were in Dutch, but are given in English here for purposes of illustration.

2.3. Apparatus

In the stereoptic condition, stereopsis was implemented by a setup including Stereographics's CrystalEyes CE-3 active shutter-glasses, an E-2 emitter and Stereo Enabler, a Pentium 4 computer running Windows XP, a 1900 CRT-monitor (Ilyama Vision Master Pro 454) and a PNY-Quadro 4 580XGL videocard. This set-up allowed for a monitor refresh rate of 140 Hz, and thus for an effective refresh rate of 70 Hz for each eye, which is sufficient to prevent 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 models were post-processed in 3D Max and Cosmoworlds, after which the resulting VRML models were 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. Adobe's Authorware software was used to create the software part of this experiment, including study phases, experimental tasks, and logfiles for each participant necessary for data-analysis.

3. Results

Scores for the mental rotation test and accuracy scores for the identification- and localization tasks were transformed to proportions correct for easier reading. Descriptive statistics for the accuracy scores on the identification- and localization tasks are shown in Fig. 3. For these knowledge tasks, latency was recorded as well, which was used to rule out an accuracy/ latency trade-off ($r = -.58$ and $r = -.24$ for the identification- and localization task, respectively). Three participants verbally indicated not to have comprehended the localization task, which was corroborated by their task scores (zero); their results were coded as missing data in the subsequent analyses. Trials clocked under .5 s were defined as missing values, and were left out in the analysis of the logfiles.

To assess differences in performance on the identification- and localization task as a function of visuo-spatial ability, experimental condition, and the interaction of these last two variables, two ANCOVAs were performed. One ANCOVA had identification task accuracy as its dependent variable, the other had localization task accuracy as its dependent variable. Both ANCOVAs had stereopsis (biocular versus stereoptic) as independent variable, visuo-spatial ability (as measured by the pretest) as a co-variable, and 'stereop-

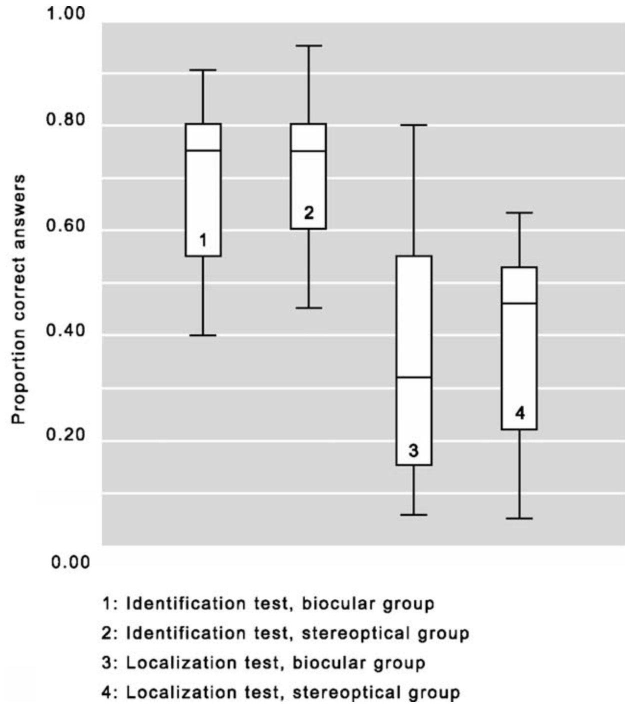

Fig. 3. Median, interquartile range and extreme values of the accuracy scores for each group and task.

sis' × 'visuo-spatial ability' as an interaction variable. This interaction variable was included both based on earlier similar research (Luursema et al., 2006), where this interaction proved significant, and on scatterplots that suggested such an effect for the current data (Fig. 4). Table 1 gives an overview of the results for these ANCOVAs (single tailed). Visuo-spatial ability proved to be significant for both post-task results, stereopsis only for the localization task.

Table 1
Analysis of variance for both dependent variables (single-tailed)

Source	*df*	*F*	*p*
Accuracy on the identification task ($n = 43$)			
Visuo-spatial ability (VSA)	1	15.4	.00
Stereopsis (ST)	1	1.9	.09
VSA × ST	1	1.9	.09
Accuracy on the localization task ($n = 43$)			
Visuo-spatial ability (VSA)	1	5.7	.01
Stereopsis (ST)	1	2.8	.05
VSA × ST	1	1.8	.09

The 'visuo-spatial ability' × 'stereopsis' interaction was not significant for either post-task.

4. Discussion

In Section 1, we argued that the use of Virtual Learning Environments (VLEs) in the medical curriculum makes it possible to implement both stereopsis and dynamic exploration, two features traditionally available only in dissection and anatomical manikins. Additionally, in VLEs conceptual knowledge can be provided, traditionally associated with anatomical atlases and medical textbooks. An earlier study (Luursema et al., 2006) showed that the combination of dynamic exploration and stereoptic presentation yielded better anatomical learning (especially for participants of low visuo-spatial ability). We now report an experiment that investigated the contribution of computer-implemented stereopsis on anatomical learning for participants of differing visuo-spatial ability.

The results confirm earlier research that shows higher visuo-spatial ability significantly indicates better anatomical learning (Garg et al., 1999, 2001, 2002; Rochford, 1985). Additionally, having been exposed to a study phase with computer-implemented stereopsis implied significantly higher accuracy on an anatomical localization task. This confirms our hypothesis that computer-

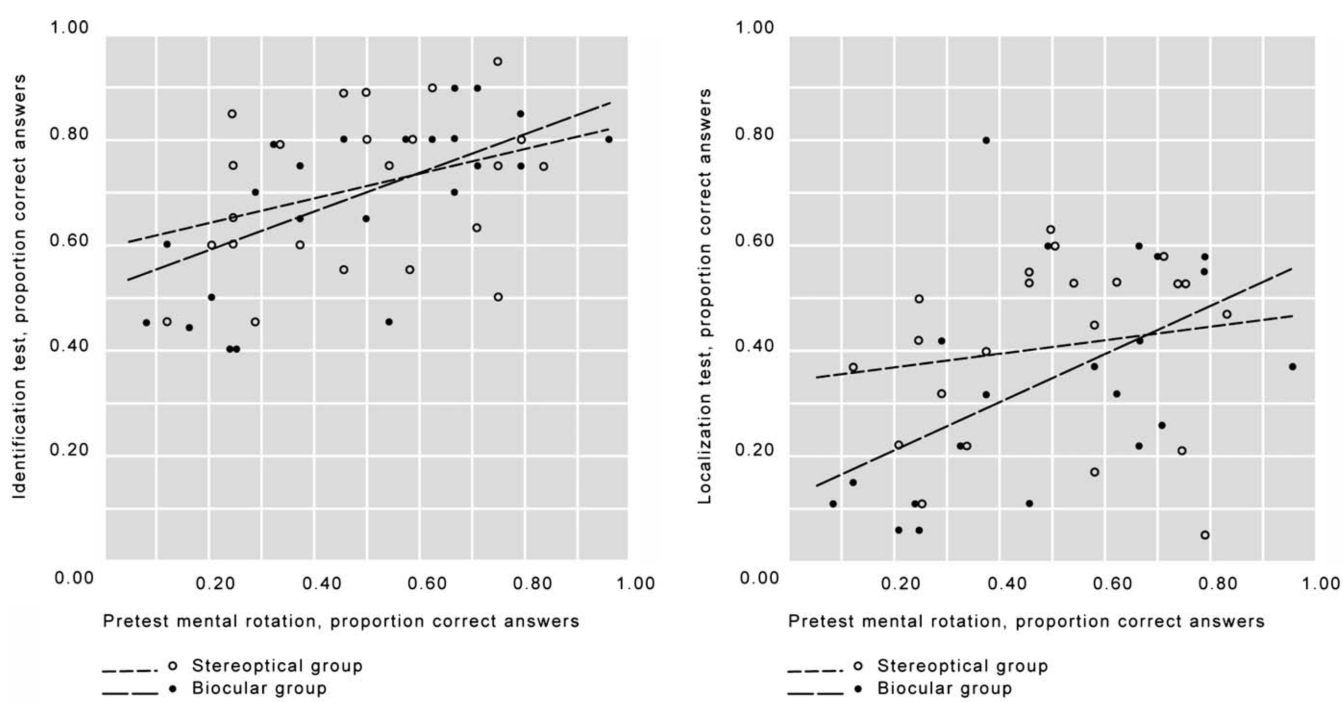

Fig. 4. Scatterplots for the biocular and stereoptic groups depicting the relationship between the results of the visuo-spatial ability test and the results of the identification task (left panel) and the localization task (right panel).

implemented stereopsis is partly responsible for the learning effect found from a combination of computer-implemented stereopsis and dynamic exploration on anatomical learning (Luursema et al., 2006).

An effect found in the latter study was that participants of low visuo-spatial ability benefited more from a combination of stereopsis and dynamic exploration than participants of high visuo-spatial ability, who did not benefit significantly from this combination. This interaction effect was not found for visuo-spatial ability and stereopsis (without dynamic exploration) in the current study. As can be gleaned from Fig. 4 and Table 1, there is a tendency towards such an interaction, but this failed to reach significance ($p = .09$). The difference in magnitude of experimental effect between the two studies cannot yet be wholly attributed to dynamic exploration; in contrast to the experiment reported here, our previous study featured a control condition with static stimuli, causing the visual depth cue of motion parallax to be absent. This also reduced the total number of anatomical views the participants were exposed to.

Given the small effect size of stereopsis alone on anatomical learning, and the low ecological validity of the experiment reported here (simplified anatomical learning task, no participants of a medical background), judgment has to be postponed on the advisability of implementing stereopsis enabling hardware in medical study settings. A study geared towards medical professionals, with more realistic learning tasks, would be a necessary step before any solid recommendations can be made with respect to the practical implementation of this technology. Studies similar to the one reported here, but additionally manipulating task difficulty would be very useful too.

An important topic for future research also would be investigating the social aspects of VLE use, i.e., to what extent does having to wear special headgear interfere with normal communication between users. Case studies reported by Montgomery et al. (2005) suggest that being able to make eye contact is essential in social situations (such as preoperative planning, or surgical practice), restricting the use of specialized headgear to specific, single-user scenarios. At the moment of writing, autostereoptic monitors are becoming available, but do not yet offer the specifications necessary for serious use in a professional setting.

The role of dynamic exploration alone in virtual anatomical learning warrants further exploration too. A new study is in progress to investigate the importance of dynamic exploration for virtual anatomical learning.

Concluding, the implementation of stereopsis in VLEs is not just beneficial for movement execution in endoscopic surgery (and by implication for the training of surgical skills), but also impacts the construction of visuo-spatial mental representations, a cognitive skill that forms the backbone of anatomical learning. The slight, but positive, contribution of stereopsis to aspects of visuo-spatial learning is a novel find, and potentially of great practical value, if corroborated and mapped out by future studies.

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