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Optimizing conditions for computer-assisted anatomical learning

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Abstract

An experiment evaluated the impact of two typical features of virtual learning environments on anatomical learning for users of differing visuo-spatial ability. The two features studied are computer-implemented *stereopsis* (the spatial information that is based on differences in visual patterns projected in both eyes) and *interactivity* (the possibility to actively and continuously change one's view of computer-mediated objects). Participants of differing visuo-spatial ability learned about human abdominal organs via anatomical three-dimensional (3D) reconstructions using either a stereoptic study phase (involving stereopsis and interactivity) or using a biocular study phase that involved neither stereopsis nor interactivity. Subsequent tests assessed the acquired knowledge in tasks involving (a) identification of anatomical structures in anatomical 2D cross-sections (i.e. typical Computed Tomography pictures) in an *identification task*, and (b) localization of these cross-sections in a frontal view of the anatomy in a *localization task*. The results show that the stereoptic group performed significantly better on both tasks and that participants of low visuo-spatial ability benefited more from the stereoptic study phase than those of high visuo-spatial ability.

Keywords: Visuo-spatial ability; Stereopsis; Anatomical learning; Virtual learning environments; Interactivity

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1. Introduction

1.1. Anatomical learning

A recurring theme in medical practice is the necessity to form a visuo-spatial mental representation of a patient's anatomy based on two-dimensional (2D) images. During diagnosis, practitioners review patient-specific cross sections made by non-invasive imaging technologies (Fig. 1), endoscopic surgeons get 2-dimensional video feedback on their actions (often presenting a viewing angle that is not aligned with the surgeon's view), and medical students learn anatomy by studying illustrated texts. *Visuo-spatial ability*, the capacity to construct and manipulate mental, visuo-spatial representations of objects and environments, allows people to transform 2D images to visuo-spatial mental representations and to mentally rotate these representations (Gordon, 1986; Kozhevnikov and Hegarty, 2001). This capacity is therefore likely to play an important part in being a successful medical practitioner. This is supported by several studies that found visuo-spatial ability to be highly correlated with success as an endoscopic surgeon (e.g. Risucci, 2002; Wanzel et al., 2002). Rochford (1985) found a correlation between spatial learning disabilities and underachievement in an anatomy course for second-year medical students at Cape Town University. Additional support comes from Schueneman et al. (1984), who found that visuo-spatial ability is one of three factors in standard aptitude tests that predict success as a surgeon (the other two being visuo-motor skills and sensitivity to stress).

Two phases that bear upon the use of mental representations can be distinguished: an acquisition phase and a manipulation phase. The acquisition phase refers to the construction of a visuo-spatial mental representation, e.g. during anatomical learning or medical diagnosis, the manipulation phase refers to the mental manipulation of these representations, e.g. during pre-surgical planning or endoscopic surgery. Having acquired a visuo-spatial mental representation (from this point called a 'mental representation') is evidently a prerequisite to mentally manipulate such a representation. This distinction between acquiring a mental representation and manipulating a mental representation leads to a number of questions: What is the role of visuo-spatial ability in each of these phases? Do medical practitioners of low visuo-spatial ability perform worse because of a deficiency in their mental representations or because of an inability to manipulate these representations? Is there a way to optimally help learners acquire mental representations? Several practices in anatomical learning can be distinguished.

Traditionally, anatomical learning takes place in the dissection room, with the help of anatomical manikins or self study with anatomical atlases. Each of these methods has its drawbacks: a dissection room is expensive and arduous to maintain, both manikins and dissection rooms are not readily available, anatomical variety in manikins is limited, anatomical atlases are limited to 2D representations and offer neither interactivity nor feedback. These limitations can be largely

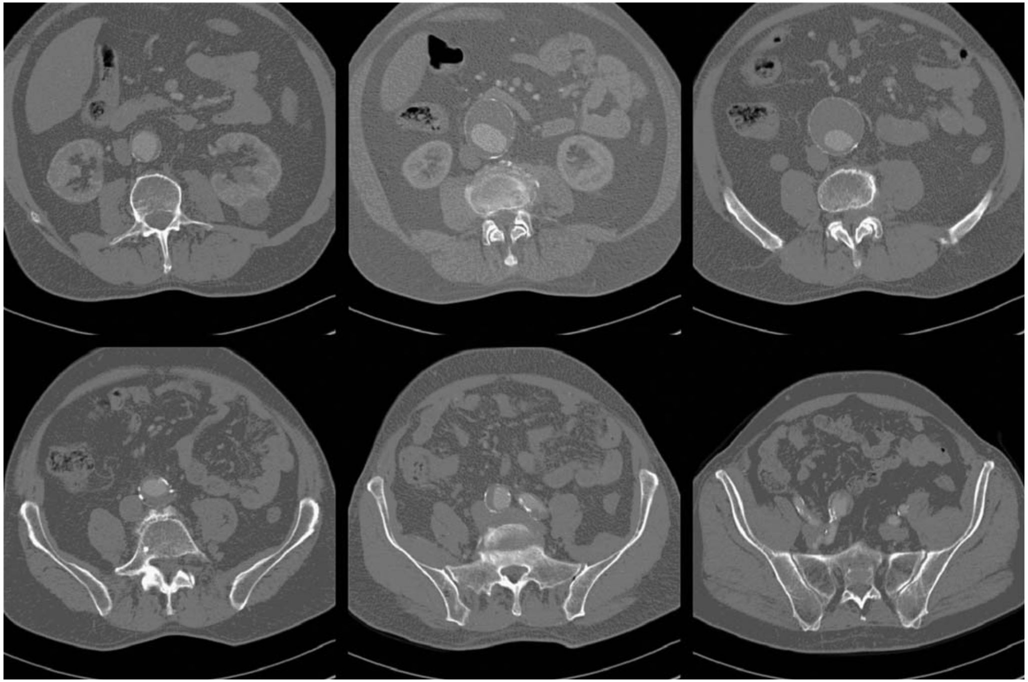

Fig. 1. Examples of anatomical cross-sections derived from CT-imaging of the lower abdominal region.

overcome by the relatively recent alternative found in virtual learning environments (e.g. see Jastrow and Vollrath, 2003, who give an overview of anatomically oriented virtual learning environments based on the visible human project). Basic questions with respect to the transfer of skills and/or knowledge acquired in a virtual learning environment however are largely unanswered (Stanney, 2002; Verwey et al., 2005), and one wonders to what extent these systems can be made more efficient by adjusting them to the learning styles and capacities of the trainees. Especially relevant to the capacity of visuo-spatial ability is the implementation of stereopsis and interactivity.

1.2. Stereopsis and interactivity

People have various mechanisms that contribute to the depth perception of the world around them. One mechanism, the disparity of visual information entering the left and right eye, is especially important for objects within an arm's reach (Cutting and Vishton, 1995). This mechanism is known as s*tereopsis*. When direct visual feedback from a 3D object or environment is received through mediation by a standard computer screen (or other 2D visual feedback device) people are said to receive *biocular* visual feedback, meaning that both eyes are exposed to the same image. There is substantial evidence that stereoptic feedback benefits the execution of endoscopic tasks (Wanzel et al., 2002; Falk et al., 2001; IJsselstein et al., 2001). Whether stereoptic feedback benefits the acquisition of anatomical knowledge in the context of virtual learning environments is as yet uncertain. The resolution of this question has implications for the way anatomical information is best presented in learning situations. Several technologies exist that allow the experience of stereopsis, such as head-mounted displays that uses different display channels for each eye, or displays coupled to shutter-glasses that make odd and even numbered images reach the left and right eye separately. The higher costs associated with the implementation and maintenance of such systems will have to be balanced against their usefulness.

A second way to improve the acquisition of anatomical knowledge is allowing people to explore the presented anatomy by giving them the possibility to change the perspective shown. Such systems can be considered systems with high *interactivity*. In contrast, systems with one or just a few alternative perspectives are systems with low interactivity. A recent study by James et al. (2001) suggests that interactivity helps people to develop visuo-spatial mental representations. In their study, interactivity consisted of the possibility to freely rotate computer-mediated, non-stereoptic 3D objects. Each participant explored some objects actively and other objects passively. Each participant in the passive condition watched the recorded explorations of an active participant. Later all participants made same/different judgments on a series of 2D views of these objects from various perspectives. James et al. found that participants from the active condition recognized objects faster. So, it seems that both stereopsis and interactivity support people in creating visuo-spatial mental representations of objects in the real world. This may well benefit students' learning of human anatomy too, especially those of low visuo-spatial ability.

The present study examined whether stereopsis and interactivity contribute to the development of flexible visuo-spatial mental representations of human abdominal anatomy, and whether this might help overcome the disadvantage low visuo-spatial individuals have in developing such representations. To that end, the following experiment was performed. First, participants' visuo-spatial ability was determined by a mental rotation test, the outcome of which was used to form matched pairs over two learning conditions. The *stereoptic group* studied human abdominal anatomy in a condition involving stereopsis and extensive interactivity. The *biocular group* studied the same anatomy in a condition with biocular information presentation and with limited interactivity. Subsequently, knowledge of the abdominal anatomy was tested by two tasks that are assumed to require mental manipulation of 3D representations. The *identification task* required participants from both groups to identify anatomical structures in 2D cross-sections (typical Computed Tomography, or CT, pictures) they had not seen before. The *localization task* required them to indicate the level in a front side view of the human abdomen, from which a presented cross section was taken. We expected that the stereoptic group would outperform the biocular group, and that this difference would be larger for participants of low visuo-spatial ability than for participants of high visuo-spatial ability.

2. Method

2.1. Participants

Participants were Dutch university students and employees from the faculty of Behavioral Sciences. All had limited knowledge of human abdominal anatomy. Participants were between 18 and 50 years of age. A total of 36 participants took part (21 women and 15 men). All reported normal or corrected to normal vision. The participants were selected from a pool of 73 potential participants on the basis of pretest-results (see below).

2.2. Procedure

Before the actual experiment, the 73 participants took part in two pretests, a stereoscopic vision test to ascertain that they could see stereoptically, and a test for visuo-spatial ability. The first test involved the TNO-test for stereoscopic vision which requires participants to distinguish figures from a background in random-dot figures within one minute (Okuda and Wanters, 1977). On the basis of this test result, four subjects were excluded from further participation. The remaining 69 participants were tested for visuo-spatial ability using Vandenberg and Kruse's mental rotation test (Vandenberg and Kuse, 1978; Peters et al., 1995). Starting from the low end of the resulting scale, 18 participants (16 females and 2 males) were matched in pairs over two groups. One member of each matched pair was randomly assigned to the biocular group; the other to the stereoptic group. The same procedure was followed starting from the high end of the scale resulting from the pretest (5 females and 13 males). Participants who scored in the mean region of the pretests' scale were excluded from the experiment. After a study phase that differed for the two groups, performance was measured in an identification task and a localization task. Apart from the study phase, the experiment was identical for all participants. The study phase and both tests were administered to each participant individually in a specially prepared cubicle in the presence of a researcher. The cubicle contained the hardware and software necessary for the experiment and was shut of from possible disturbances during the experiment. All explanations were provided on screen, subjects were only verbally prompted to use the possibility of interactive rotation or clickable thumbnails (during one of either study phases) if they did not start using this possibility on their own accord. After the experiment, participants were asked to describe their problem solving strategies for each task.

2.3. Study phase

A short example of the study phase, identification task and localization task were presented to participants at the beginning of the experiment. They were told to use the study phase to prepare for these two tasks (Fig. 2). Both study phases contained labeled reference figures for the eleven anatomical parts of the abdomen relevant to the tasks (Upper part of Fig. 3). In the study phase, the *biocular group* (9 women and 9 men) explored 2D stills of this abdominal anatomy. They had limited interactivity in that they could change between just three views (frontal, side and top). The *stereoptic group* (12 women and 6 men) explored computerized 3D-reconstructions of the same abdominal anatomy in a condition that provided stereopsis and extended interactivity. In contrast to the biocular participants, stereoptic participants wore shutter-glasses to perceive depth (stereopsis). Extended interactivity involved the possibility to rotate the virtual 3D anatomy in any direction using the mouse. All participants were given four minutes to learn the form and location of these eleven anatomical parts of the abdomen, during which time they were free to manipulate the provided representation.

2.4. Identification task

The identification task (see upper frame of Fig. 3) consisted of four familiarization trials and twenty test trials. Participants were told 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 with a highlighted anatomical structure appear, as well as a list with names of the eleven anatomical structures. With the release of the '5' button the picture of the cross-section disappeared. The anatomical cross-sections used for this task 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 '5' button only when they had identified the highlighted structure, and then to mouse-click the corresponding name in the list at their own pace. Reaction times were defined as the time the '5' button was pressed during each trial. If after 10 s the '5' button had not been released, the picture with the cross-section disappeared

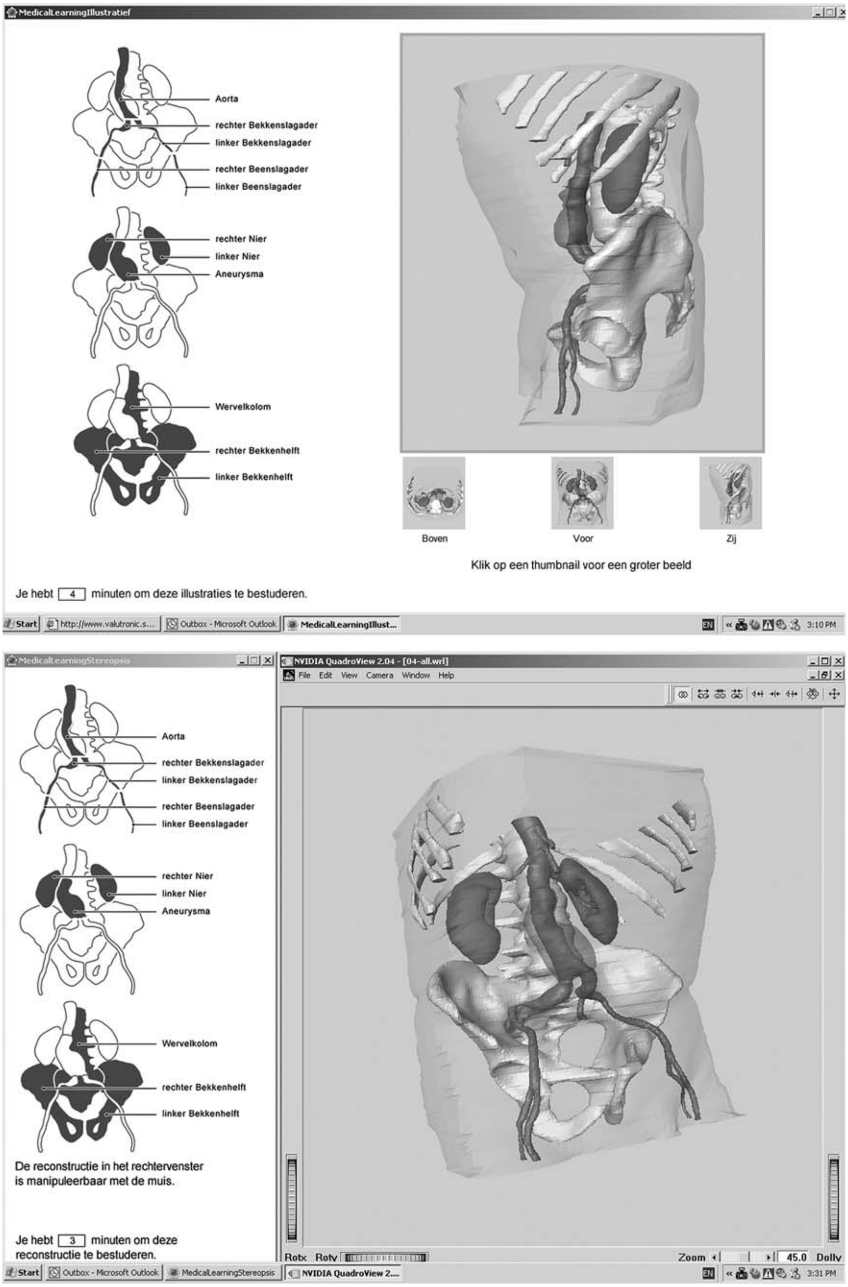

Fig. 2. The biocular (top) and stereoptic study phases of the experiment. The biocular study phase allowed participants to alternate between three, two-dimensional screenshots of the anatomical objects by clicking one of the three thumbnails below the image. The stereoptic study phase provided stereopsis and interactivity involving free, mouse-controlled rotation of the anatomical objects.

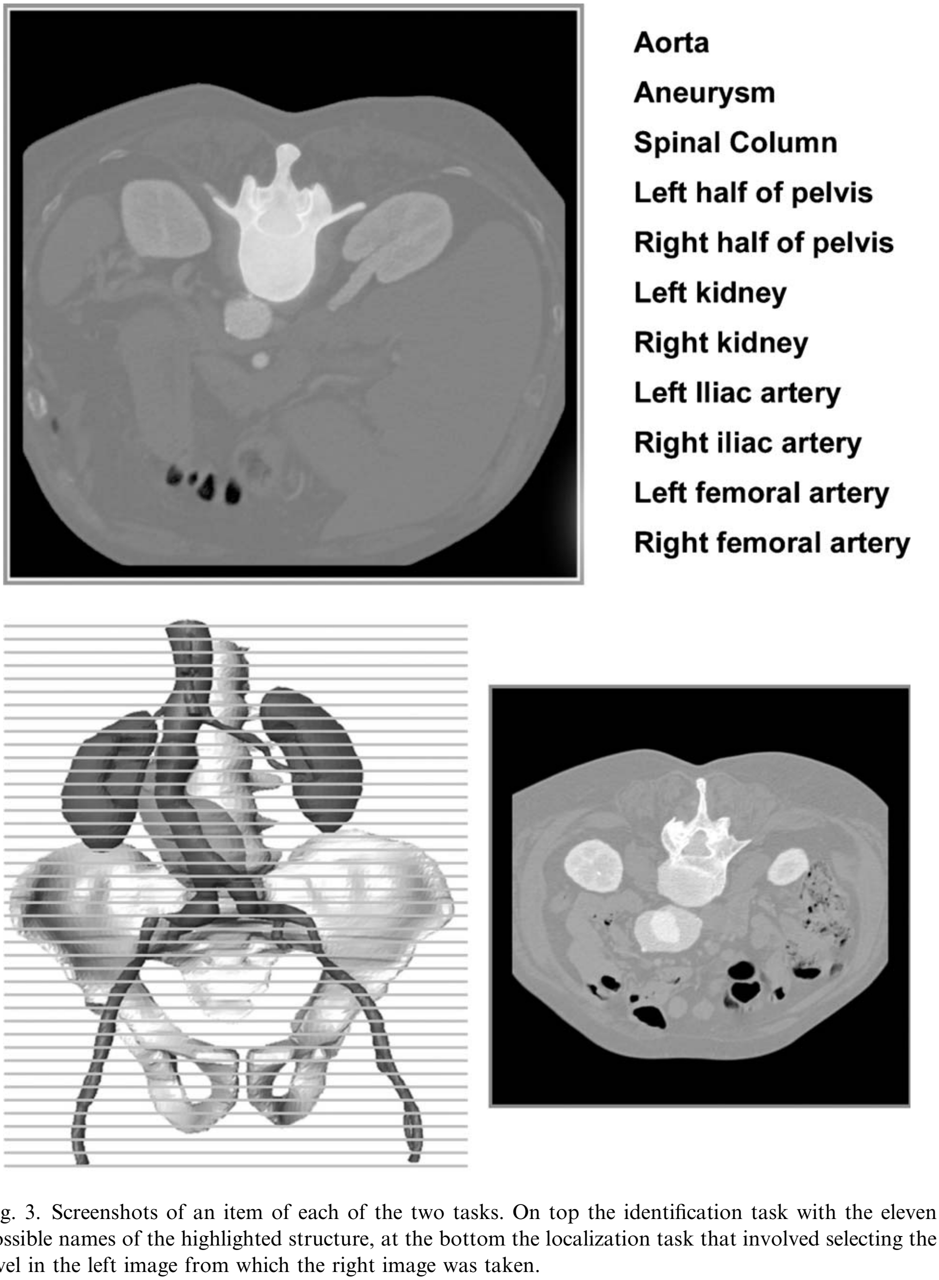

Fig. 3. Screenshots of an item of each of the two tasks. On top the identification task with the eleven possible names of the highlighted structure, at the bottom the localization task that involved selecting the level in the left image from which the right image was taken.

anyway. Errors were defined as clicking an incorrect name or no name at all. After each trial error feedback was given. When a participant verbally indicated they released the '5' key accidentally, or that they wished to change their answer, the trial was excluded from further analysis. No shutter-glasses were worn during this task.

2.5. Localization task

The localization task consisted of three familiarization trials and eighteen test trials. Participants were asked to indicate on a frontal-view screenshot of the studied anatomy, the correct horizontal level of a CT-based anatomical cross-section (lower frame of Fig. 3). 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 for each participant. 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 '5' button the picture of the cross-section disappeared. They were further instructed to release the '5' button 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 '5' button was not released, the cross-section disappeared and an error was scored. Reaction time was defined as the time the '5' 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. When, as in the identification task, a participant verbally indicated they released the '5' key accidentally, or wished to correct the given answer, this trial was excluded from further analysis. This task did not involve the use of shutter-glasses either.

2.6. 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 StereoEnabler, a Pentium 4 computer running Windows XP, a 19″ 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 with left and right alternating shutter-glasses. This enabled participants in both conditions to study the anatomical objects without a 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 models were post-processed in 3D Max and Cosmoworlds, after which the resulting VRML models were ready for use in the stereoptic study phase. In this study phase, they could be explored by means of the Nvidia QuadroView 2.04 application. The images used in the biocular study phase were derived from these models by means of screenshots and further processing in Adobe Photoshop. 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.

2.7. Software used in this experiment

In this experiment, we sought to optimize conditions for the visuo-spatial component of anatomical learning. This was reflected in the software built for this experiment: we ignored the integration with other than anatomical knowledge domains (e.g. physiology, pathology) necessary for real-world medical learning software. Also, in order to be able to test a sufficient number of participants, we created a simple anatomical model that would not be particularly useful for medical students, but that was sufficiently challenging for students of behavioral sciences. Consequently, there are no plans to further develop this software for other than experimental purposes.

3. Results

For the localization task, one of the matched participant pairs was removed from the analyses because one of the two had not understood the task correctly. For the identification task all pairs were kept. Pretest score correlations between matched pairs were high, $r(16) = .975$, $p < .001$. For each participant, three correct-answer proportion scores were calculated by dividing the total number of good answers for each test by the total number of test items for each test, the three tests being the pretest, the identification task and the localization task. Descriptive statistics for the identification task and the localization task are shown in Fig. 4.

Across biocular participants, there was a positive correlation between the correct-answer proportion scores of the prestest (assessing visuo-spatial ability) and each experimental task: identification task: $r(16) = .48$, $p < .05$, localization task: $r(15) = .72$, $p < .001$. This confirms that performance in the experimental tasks increased with visuo-spatial ability for the biocular group. In contrast, across stereoptic participants these correlations did not reach significance, identification task: $r(16) = .014$, $p > .95$, localization task: $r(15) = .41$, $p > .1$. These data show that visuo-spatial ability increased learning in the biocular group but not significantly in the stereoptic group.

Two multiple linear regression analyses were used to further evaluate the data, separately for each experimental task. Independent variables were pretest correct-answer proportion scores, experimental treatment (biocular versus stereoptical, rendered as a dichotomous variable of zero or one), and an interaction variable (pretest correct-answer proportion scores×experimental treatment). In the first analysis, the dependent variable consisted of the correct-answer proportion scores on the identification task, in the second analysis the dependent variable consisted of the correct-answer proportion scores on the localization task.

3.1. Results for the identification task

The F statistic $F(3,32)$ was 4.59, $p < .01$, demonstrating that together the independent variables accounted for most of the observed variance in this task. Effect for experimental treatment (single-tailed) was $t(32) = 2.8$, $p < .005$, confirming that the stereoptic group as a whole outperformed the biocular group. Effect for interaction

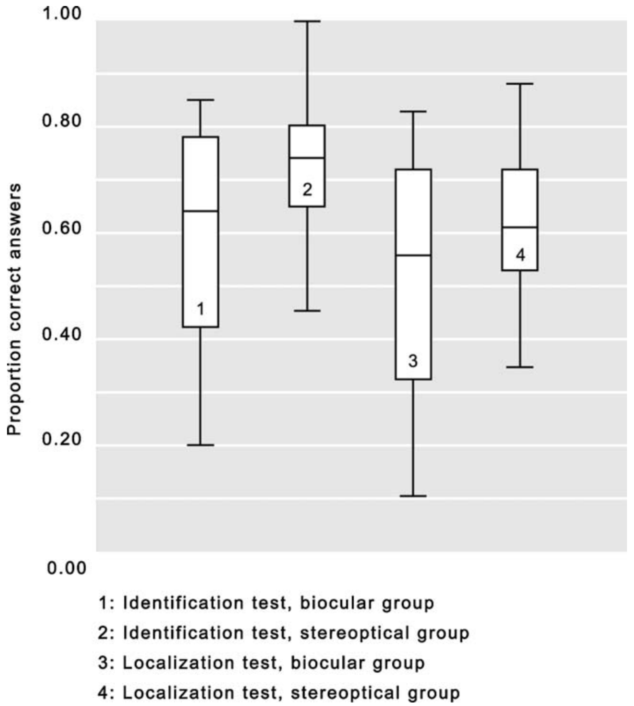

Fig. 4. Median, interquartile range and extreme values of correct answers per group and task.

(single-tailed) was $t(32) = 1.75$, $p < .05$ (Fig. 5), which shows that participants of low visuo-spatial ability (as measured by the mental rotation pretest) benefited significantly more from the stereoptic study-phase than participants of high visuo-spatial ability (left side of Fig. 5).

3.2. Results for the localization task

The F statistic $F(3,30)$ was 8.08, $p < .001$, showing that together the independent variables accounted for most of the observed variance in the localization task as well. Effect for experimental treatment (single-tailed) was $t(30) = 2.59$, $p < .01$, demonstrating superior performance for the stereoptic group on this task. Effect for interaction (single-tailed) was $t(30) = 2.08$, $p < .03$, again showing that participants of low visuo-spatial ability (as measured by the mental rotation pretest) benefited significantly more from the stereoptic study-phase than participants of high visuo-spatial ability did (right side of Fig. 5).

A large effect size (magnitude of treatment effect) was found on the identification task, Cohen's $d = .87$, whereas effect size on the localization task was moderate, Cohen's $d = .44$.

No significant correlations were found between reaction time and correct-answer proportions, ruling out a speed-accuracy trade-off. Finally, the experimental tasks

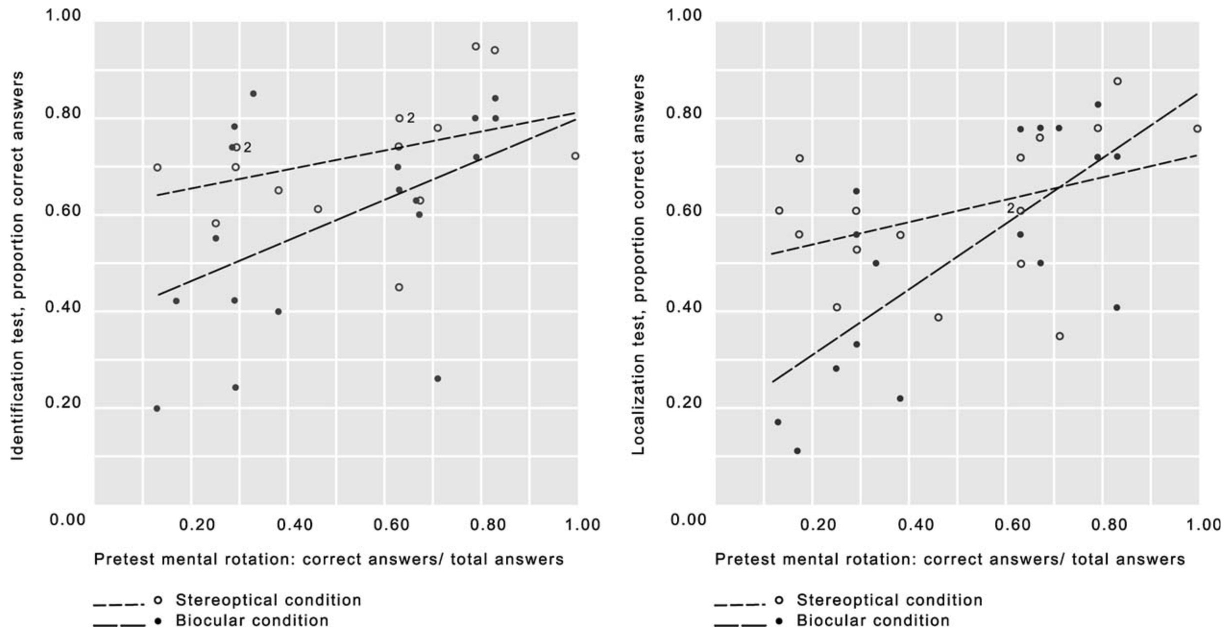

Fig. 5. Regression lines for the biocular and stereoptic groups depicting the relationship between the results of the pretest and the results of the identification task (left panel) and the localization task (right panel).

were subjected to a reliability analysis. The identification task (20 multiple choice items, eleven choices per item) was reliable at a Cronbach's α of .75. The localization task (20 multiple choice items, 14 choices per item) was reliable at a Cronbach's α of .80. This indicates that the items in each task were of similar difficulty and measured the same construct.

4. Discussion

4.1. Discussion of the results

The present study tested whether (a) interactivity (implemented as mouse-controlled object rotation) and stereopsis (depth perception enabled by the use of shutter-glasses) improves anatomical learning, and (b) whether participants of low visuo-spatial ability benefit more from these features than participants of high visuo-spatial ability. Towards that end, participants inexperienced with human anatomy learned about the human abdominal parts in a study phase that involved either both stereopsis and interactivity (i.e. the stereoptic group), or neither of these (i.e. the biocular group). Learning was assessed in an identification task and in a localization task.

Performance was better in the stereoptic group than in the biocular group for both tasks, suggesting better anatomical learning for the stereoptic group. The data also confirmed our expectation that participants of low visuo-spatial ability benefit more from the combination of stereopsis and interactivity in the stereoptic study condition than participants of high visuo-spatial ability. This is an important finding as it suggests that, given the proper learning conditions, low visuo-spatial ability is less of a problem for developing visuo-spatial representations of anatomy and, perhaps even, for becoming a skilled endoscopist/ laparoscopist. This suggests that subjects of low visuo-spatial ability have difficulty constructing visuo-spatial representations, but are quite able to mentally manipulate these representations once formed. The finding that a combination of 3D reconstructions and interactivity benefits learning, and benefits learning especially for subjects of low visuo-spatial ability contradicts earlier findings by Garg et al, who report no benefits for either 3D reconstructions, or interactivity. This will be explored further in the following paragraphs.

Garg et al. (1999, 2001, 2002) reported a series of experiments that investigated the usefulness in anatomical learning of computer mediated anatomical 3D reconstructions, and active control of these reconstructions. In the first of these studies they used an anatomical learning task that compared a multiple view condition (anatomy rotating 15 degrees every twenty seconds) with a key view condition (front view and back view exchanged every 20 s). After this study phase, an anatomical knowledge test assessed the participants' learning. They found that learners of low visuo-spatial ability performed worse on the anatomical knowledge test following the multiple view condition, compared to the key view condition. However, in a second experiment, where learners were allowed active control of the rotation, they found a significant benefit for the multiple view condition for all learners. In a third experiment they compared a learner-controlled multiple view condition with a learner-controlled condition that only allowed a front and a back view with a ‘wiggle’ of ten percent around either view. This effectively cancelled out the benefits of the multiple view condition, which Garg and his colleagues took to support the view that visuo-spatial memory basically uses key-views that are then transformed to match a novel view. One is then tempted to conclude that neither 3D anatomical models nor interactivity seem to benefit anatomical learning beyond traditional anatomical atlases.

To explain the contradicting outcomes of Garg et al’s experiments and the experiment reported here four points come to mind. Firstly, the most important visuo spatial depth cue for near (< 2 m) objects is stereopsis (Cutting and Vishton, 1995), which was not implemented in Garg et al.’s studies. The lack of stereopsis could add extra difficulty for participants of low visuo-spatial ability to build a mental model from the material presented. Secondly, the conditions in Garg et al’s experiments did not allow for a continuous visual transformation between views, possibly adding further difficulty to forming an appropriate mental model. Thirdly, their very observation that introducing a ‘wiggle’ (a ten percent rotation around the y-axis on both sides of the key-view) apparantly adds structural 3D information to the key-view based mental model lends support to the alternative hypothesis that spatial mental models contain structural 3D information. Lastly, the material Garg et al. used in their studies (carpal bones of the hand) contains very little relevant 3D information as it consists essentially of two rows of four bones in a flat plane.

Further experiments should assess the relative importance of stereopsis and interactivity in the development of visuo-spatial mental representations, and why these features contribute to learning. Perhaps, interactivity increases attention to the material studied (e.g. because questions can be explored and answered immediately). The possible benefits of stereopsis are more difficult to explain, given the amount of alternative (monocular) depth cues available in the study phase material. If stereopsis turns out to be a critical factor in learning, this would lend support to the hypothesis that mental representations can include structural 3D information, a notion that is debated in the literature (Christou and Bülthoff, 2000; Tarr and Bülthoff, 1998). Basically, two views are held: one view holds that mental representations are essentially flat ‘key-views’ that are somehow mentally transformed to match a novel view of the same object, the other view holds that mental representations can include spatial information. These two views of visuo spatial mental models that are debated in the literature are not necessarily mutually exclusive however (Tarr and Bülthoff, 1998). Two ideas come to mind that could reconcile these models. One is that the qualities of the mental model formed depend on the nature of the input (Jolicoeur and Milliken, 1989. Kourtzi et al., 2003). In the present context this would mean that multiple views stimulate a key view based mental model, and stereoptical 3D models stimulate a structural 3D mental model. A second idea is that the qualities of the mental model depend on the use a participant expects to make of these models: a recognition task would stimulate key view mental models, a mental rotation task or perceptual motor task would stimulate a structural 3D mental model. In short, goal orientation could be an important variable in constructing (or constricting) mental models.

The observation that visuo-spatial ability allows participants to correlate anatomical cross-sections that are new to them with the anatomical 3D reconstructions that were studied, supports the view that mental representations can include spatial information. Another area for future research would be to assess the effect of these higher quality mental representations on surgical performance, especially in the fields of endoscopic and laparoscopic surgery. In conclusion, virtual learning environments hold great promise as an alternative to traditional anatomical learning, and a combination of stereopsis and interactivity makes an important contribution to their effectiveness.

4.2. Observations made during the experiment

Additional qualitative data were gathered by means of a one-question interview at the end of each experimental session. When asked about their problem solving strategies, participants usually reported one or more of the following:

- In the identification task, participants had to realize that in the cross sections shown, the one highlighted member of a pair of bilaterally symmetrical organs had to be reversed in its left–right orientation for the correct answer. After an initial mental rotation strategy, most participants switched to a rule-based strategy (left on screen is right for the anatomical part and vice-versa).
- In the localization task, the cross-section view was compared with the frontal anatomical view in several passes, first comparing the anatomical parts presented in the anatomical view with those in the cross-section view, then, after identification of identical organs, comparing details of shape of those organs between the two views, until a decision was made. This suggests that other strategies than strictly visuo-spatial ones might play a role in performance on this task.
- In the localization task, some participants projected the cross-section view in their own body, and compared that mental model with the anatomical view (to identify the correct height). If this is a common strategy, results from similar experiments might differ over different knowledge domains.

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