How Spatial Abilities and Dynamic Visualizations Interplay When Learning Functional Anatomy With 3D Anatomical Models

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The emergence of dynamic visualizations of three-dimensional (3D) models in anatomy curricula may be an adequate solution for spatial difficulties encountered with traditional static learning, as they provide direct visualization of change throughout the viewpoints. However, little research has explored the interplay between learning material presentation formats, spatial abilities, and anatomical tasks. First, to understand the cognitive challenges a novice learner would be faced with when first exposed to 3D anatomical content, a six-step cognitive task analysis was developed. Following this, an experimental study was conducted to explore how presentation formats (dynamic vs. static visualizations) support learning of functional anatomy, and affect subsequent anatomical tasks derived from the cognitive task analysis. A second aim was to investigate the interplay between spatial abilities (spatial visualization and spatial relation) and presentation formats when the functional anatomy of a 3D scapula and the associated shoulder flexion movement are learned. Findings showed no main effect of the presentation formats on performances, but revealed the predictive influence of spatial visualization and spatial relation abilities on performance. However, an interesting interaction between presentation formats and spatial relation ability for a specific anatomical task was found. This result highlighted the influence of presentation formats when spatial abilities are involved as well as the differentiated influence of spatial abilities on anatomical tasks.

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INTRODUCTION

Functional anatomy is a domain that involves complex spatial mental transformations of anatomical structures and movements. It is thus an ideal learning domain to investigate the use of dynamic visualizations and individual visuospatial abilities. The recent evolution in anatomy curricula toward more computer-based instructions (Sugand et al., 2010) raises the issue of the influence of dynamic computer visualizations and spatial abilities on this format of learning. With traditional static visualizations, students need to mentally manipulate three-dimensional (3D) relationships from what they see in two-dimensional (2D) representations (Pedersen, 2012). Conversely, dynamic visualizations may help learners to acquire information and/or build mental representations that would be otherwise challenging. Dynamic visualizations specify the spatial organization of elements and how they change with time (Bétrancourt et al., 2001; Schnotz and Lowe, 2003). The dynamic visualization of a three-dimensional rotating model gives additional spatial information about the 3D model, such as supplementary depth and spatial cues (Huk, 2006; Stieff, 2007). It also provides multiple anatomical views as well as different perspectives of the model's position within the space, aspects that are believed to support

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learners' perception of the complex configuration of the three-dimensional object (Hoyek et al., 2009). Even though dynamic visualizations of 2D or 3D models might help resolve spatial difficulties encountered when learning anatomy through static visualizations (Guillot et al., 2007; Hoyek et al., 2009, 2014), they may be difficult for novices to process.

The importance of individual visuospatial abilities when processing complex information is well documented in the literature. Essentially, students with low spatial abilities make more errors (Hegarty, 2004; Hegarty and Waller, 2005), whereas students with high spatial abilities perform better (Yang et al., 2003; Höffler, 2010). Several related spatial components or factors (Linn and Peterson, 1985; Carroll, 1993) predicting differential performance on specific tasks were identified. Spatial visualization and spatial relation are the two of most frequently cited factors in the literature (Colom et al., 2001; Höffler, 2010). The spatial visualization ability (Vz) refers to the ability to apprehend, encode, and manipulate mental representations (Carroll, 1993). Operationalization of mental representations includes mental transformations of complex spatial forms (Hegarty and Kozhevnikov, 1999; Miyake et al., 2001; Höffler, 2010), and the imagining of spatial movements (Hegarty and Waller, 2004) in a 3D space (Colom et al., 2001). Somewhat comparable to Vz, spatial relation ability (SR) refers to the ability to rapidly and accurately rotate 2D and 3D information. It implies a higher speed of execution, as the mental manipulations of the visuospatial information are simpler (Carroll, 1993; Miyake et al., 2001). It is sometimes difficult to distinguish the processes involved in Vz and SR abilities, as they both imply mental rotations of objects (Carroll, 1993; Colom et al., 2001) and are somewhat correlated with one another (Carroll, 1993; Miyake et al., 2001).

Currently, the interaction between spatial abilities and dynamic visualization processing is addressed by two hypotheses. The compensating hypothesis (Mayer and Sims, 1994; Hays, 1996; Mayer, 2002) claims that dynamic visualization can compensate for learners' low spatial abilities. According to this hypothesis, low spatial learners benefit from dynamic visualization as it offers an explicit external representation of the system. In return, this explicit representation allows these low spatial learners to build a more adequate, sufficient, and efficient mental model of the to-be-learned content. This enables their performance to improve to the level of their high spatial abilities counterparts, in which case the dynamic visualization acts as a "cognitive prosthetic" (Hegarty and Kriz, 2008). Conversely, the enhancer hypothesis (Hegarty and Sims, 1994; Hegarty, 2005; Huk, 2006; Höffler, 2010) states that high spatial learners are better equipped to process dynamic visualizations as they have enough cognitive capabilities left for building an adequate mental model of the content to-be-learned. According to this hypothesis, learning with dynamic visualization leads to high spatial learners performing better. The interaction between spatial abilities and performance suggests that high and low spatial learners differ in their processing of instructional materials containing dynamic visualizations. For example, in Höffler and Leutner's chemistry study, participants learned the role of surfactants during the washing process either from static or dynamic visualizations (Höffler and Leutner, 2011). Spatial visualization ability and SR were assessed with the Paper Folding test (Ekstrom et al., 1976) and the Card Rotation test (Ekstrom et al., 1976), respectively. Results of their study showed an interaction effect between Vz and the presentation format. When learning from static pictures, high Vz learners performed better than low Vz students. Conversely, when learning from dynamic visualizations, Vz did not correlate with performance as low and high Vz students performed equally (Höffler and Leutner, 2011). In a domain closer to anatomy, Hegarty and colleagues conducted a study on spatial inferences on a 3D anatomy-like structure (Hegarty et al., 2007). Students had to infer and draw cross-sections of the 3D egg-shaped structure, with a transparent exterior that revealed an internal network of duct structures. Participants' spatial abilities, more specifically SR, were assessed with the Vandenberg and Kuse (1978) mental rotation test (MRT). The results showed that performance on cross-section accuracy was predicted by the use of the interactive visualizations, but the use of interactive visualizations mediated the relationship between spatial ability and cross-section accuracy. In sum, these examples highlighted that Vz may compensate the challenge brought by the static visualizations, and that SR interplayed in the performance when participants need to form an internal mental representation of a 3D object.

Do Spatial Abilities Affect Anatomy Learning?

By documenting the cause behind medical students' underachievement in anatomy, Rochford's study (1985) sheds light on the underlying spatial ability components of the anatomy learning process. Students, who struggled to remember, to mentally operate or to perceive three-dimensional configurations or changes, scored lower on practical anatomical tests. Conversely, students with differentiated spatial abilities performed equally on non-spatial anatomical knowledge. Rochford (1985) provided evidence that anatomical knowledge involves spatial reasoning in three dimensions as well as different components of spatial abilities, such as Vz and SR. Numerous studies evidence that spatial abilities are related to successful performance in anatomy that makes use of traditional static displays (Rochford, 1985; Lufler et al., 2012), as well as with dynamic visualizations of 2D or 3D models (Garg et al., 1999, 2001; Keehner and Khooshabeh, 2002; Keehner et al., 2004; Huk, 2006; Cohen and Hegarty, 2007; Guillot et al., 2007; Luursema et al., 2008; Hoyek et al., 2009; Stull et al., 2009, 2010; Luursema and Verwey, 2011; Nguyen et al., 2012, 2013; Tan et al., 2012; Hoyek et al., 2014).

In a study by Garg et al. (2001), medical students were instructed to learn the spatial relationships of the carpal bones. They studied a self-paced 3D hand model either with key views or multiple views of the bones. The mental rotation test (MRT) assessed students' spatial relation ability, and the carpal knowledge was assessed through 50 multiple-choice questions requiring the identification of carpal bones intersections from various angles. The authors found a significant effect of the MRT on the learning performance. High spatial ability and access to multiple views enhanced the spatial understanding of the carpal bones. When questioned about their strategy, students "confirmed they remembered a key view, and rotated this image to answer the questions" (Garg et al., 2001).

Luursema and colleagues examined the contribution of stereopsis to anatomy learning (Luursema et al., 2008). Participants studied abdominal anatomy with an auto-rotating 3D model either with shutter glasses (stereoptically) or without shutter glasses (binocularly). Anatomical knowledge was assessed through the use of an identification task, which involved naming highlighted structures on cross-sectional images, and a localization task, which involved the selection of the correct cross-section levels. The authors tested the spatial relation ability with the MRT. They found that spatial relation ability proved to be beneficial for the performances on the identification task as well as on the localization task (Luursema et al., 2008).

In another study examining spatial ability and functional anatomy, Guillot and colleagues' (2007) results indicated that the two spatial ability subcomponents, spatial visualization measured by the Group Embedded Figures Test (GEFT, Witkin et al., 1971) and spatial relations measured by the MRT, highly correlated with the anatomy examination, a 220 multiple-choice questionnaire.

Without being exhaustive, a closer look at the exact nature of relevant spatial ability components involved in anatomy sheds light on their contribution to the many visual processes required while learning anatomy with dynamic visualizations of 3D models. Spatial relation ability, measured with the MRT, was evidenced as being involved in the building of an internal representation of a 3D structure, in specific processes or tasks such as understanding the relationship between the bones and the skin (Garg et al., 2001), inferring names and locations of structures in cross-sections views (Luursema et al., 2008), and in mentally rotating a structure in order to find a matched perspective (Guillot et al., 2007). Conversely, spatial visualization ability, measured with the GEFT, seemed to be involved more specifically with the identification and the visual disembedding of a structure from a complex 3D environment (Guillot et al., 2007). Although the effective relationships of SR and Vz on successful anatomy learning are well documented, their relative contributions to the different cognitive operations needed to learn functional anatomy are less known.

Cognitive Operations Involved in Learning Functional Anatomy With 3D Dynamic Visualizations

Anatomy is a highly spatial instructional domain in which it is vital not to dissociate the understanding of a structure from its location or position within the 3D body space. Complete and efficient learning includes a configurational as well as a functional understanding of the anatomical structure and its movement within the three-dimensional body space. Note that a comprehensive knowledge of functional anatomy is not merely the study of osteology. It is far more complex and includes syndesmology, myology, angiology, and biomechanics. However, in this study, the term functional anatomy refers only to the study of anatomical structures and their relative behaviors or movements.

Although the use of 3D dynamic visualizations for learning anatomy has become widespread, the assessment of this specific 3D information has rarely been examined. A framework allowing the understanding of the cognitive operations or steps involved in the learning of 3D structures or objects is not yet available. Essentially, a cognitive task analysis, aiming at describing the processes required to solve specific complex tasks and/or achieve a goal (Clark et al., 2008), generates detailed and precise information regarding the nature of the cognitive operations of the task of interest. It can also provide support for the interpretation of the interplay between learning objectives, visualizations, and participants' spatial abilities. Based on the literature (Thiriet, 1982; Marks, 2000; Van Sint Jan et al., 2003; Hegarty et al., 2007; Tan et al., 2012) an informal cognitive task analysis, was developed describing the steps learners need to accomplish to achieve an understanding of a 3D structure as well as its 3D movements within the body space. The aim of this cognitive task analysis, presented in Figure 1, was also to highlight the contribution of static and dynamic visualizations to each of the cognitive operations to be achieved.

Step 1, isolate the structure from its context, is mainly driven by the perception and should lead to the extraction of pertinent and relevant information about the structure as the object-to-learn. The processing of this step from either static or dynamic visualizations would be identical. Learners should pay particular attention to the perceptibility profile of the content (Lowe, 1999; Lowe and Boucheix, 2009; Boucheix and Lowe, 2010), which may wrongly induce them to extract salient but irrelevant information. The visuospatial salience of elements may lead to confusion, as what is bigger, brighter, or more visible is not necessary more thematically pertinent. As a result, the discrepancy between perceptual salience and thematic relevance distorts learners' comprehension, novice learners tending to focus more on perceptually salient information and therefore to build an erroneous mental model (Boucheix and Lowe, 2010). The learner would succeed in building a disembedded but basic mental representation of the structure.

Once the pertinent and relevant structure is visually extracted, Step 2 involves learning the 2D shape of this structure from all perspectives. Whereas static visualizations may not provide all the anatomical view planes, the dynamic visualization with a 3D rotating model will provide continuous viewpoints and different perspectives of the structure. The learner would thus build a series of simple mental representations of 2D configurations of the structure on one anatomical plane (Narayanan and Hegarty, 2002).

During step 3, a reconstruction of the three-dimensional structure will be established. From a focused viewpoint, learners need to "think big," in three dimensions. Learners with a 3D dynamic visualization would need to gather all the perceived views from the previous stage to form a unique 3D structure. From static visualizations, learners would need to infer the missing views of the 3D structure by transforming the few stored views (Tarr and Pinker, 1989). The learner would build a mental representation of a more complete 3D configuration of the structure.

Step 4 would enable the learners to reconstruct the spatial relationships between the 3D structure and its environment to apprehend the body space. This step is definitely based on the understanding of the organization of the body space related to the orientation reference system of the human body. Learners with the 3D dynamic visualization may have an advantage. This type of visualization provides additional depth and spatial information as the 3D model is fully rotating on different anatomical planes, in contrast with the static 2D "flat" visualization. The learner would build a mental representation on 3D spatial surroundings of the structure, including location and position of the structure in the 3D body space.

The following two steps focus on understanding the behavior of the structure. Step 5 involves learning the dynamics of the structure. The dynamic functions of the structure involve displacements and/or deformations of the structure (Van Sint Jan et al., 2003) and might be structure-specific or

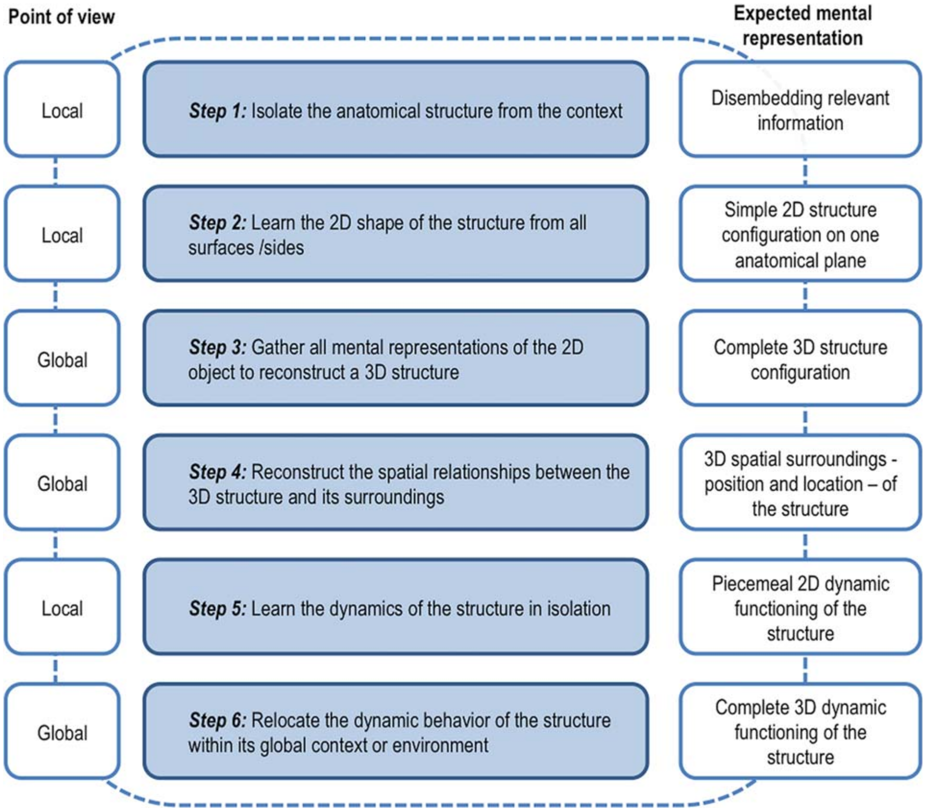

Figure 1.

Cognitive task analysis of learning functional anatomy. The left column defines the learners' point of view, whether it is localized in a particular body area or global with a general overview on different planes. The right column specifies the expected mental representations built from the cognitive processing steps (middle column).

at least joint-specific. In which case, dynamic visualizations will confer an advantage over the static visualizations, as they explicitly convey and depict changes over time (Bétrancourt and Tversky, 2000; Schnotz and Lowe, 2003). The learner would obtain a piecemeal mental representation of the 2D dynamic functioning of the structure.

Once the dynamic behavior of the structure is understood, step 6 is to relocate it within the global body space. From a local one-plane view, the learner has to relocate the behavior in all anatomical spaces or planes in order to understand the 3D movement. Again, in this step, learning from 3D dynamic visualization may benefit the learner by providing depth and spatial cues. Yet the learner would build a mental representation of a more complete 3D dynamic functioning of the structure.

Note that this task analysis lists distinct but interrelated cognitive steps that might be processed in a different order, in accordance with the needs of the learning objectives. Considering these steps, it is important to question the ways in which Vz and SR contribute to cognitive demands when learning functional anatomy.

The purpose of this study was to investigate whether 3D dynamic visualizations support functional anatomy learning. Students studying with dynamic visualizations of 3D models were expected to perform better than their counterparts studying with static visualizations of the same 3D models. Another key objective of this study was to explore how spatial abilities—Vz and SR—and presentation formats—dynamic versus static—interplay when the functional anatomy of a 3D scapula and the associated shoulder flexion movement are learned. One way to observe this interaction was to examine performance on five anatomical tasks derived from the cognitive task analysis.

METHODS

Participants

Eighty-six students aged between 18 and 22 years old enrolled in first-year kinesiology degree at the University of Lyon 1, France, voluntarily participated in the study. Because of a technical problem, incomplete data from 37 participants had to be excluded, leaving the sample of this study with 49 students (9 women, 40 men, mean age = 18.9 ± 1.82 [SD] years). Participants with no prior courses in anatomy were asked to understand the anatomy of the scapula, its structure, and its movement during shoulder flexion by studying two multimedia instructional learning materials. All participants were blind to the tasks and content. They were randomly assigned to one of two presentation format conditions:

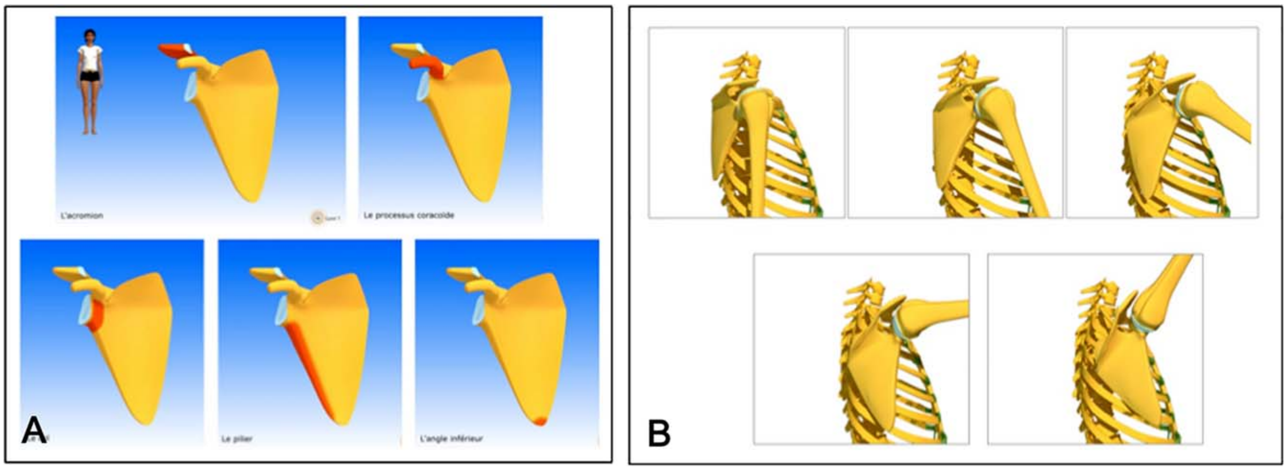

Figure 2.

Snapshot of the static condition of the learning material of the structure and the movement of the scapula. **A**, static condition presenting the scapula and its features in the anterior anatomical view; **B**, static condition of the scapula shoulder flexion movement in the lateral view.

dynamic visualization ($n = 22$), or static visualization ($n = 27$).

MATERIALS

The computer-based instructional material consisted of two 3D dynamic visualizations developed at the University of Lyon 1, France and addressed two learning objectives, namely (1) the structure of the scapula and six of its features (acromion process, inferior angle, coracoid process, lateral border, spine, and neck), and (2) the scapula movement during shoulder flexion, which is when the arm is moving from the standard anatomical position (arm along the body) upward to the front and downward back to the standard position. Four anatomical orientation views—posterior, lateral, anterior, and superior—were sequentially displayed in all the materials. Two versions of the material were created.

Dynamic Visualizations

The dynamic version of the scapula structure (84 seconds) presented the 3D scapula and a small human-like character acting as a permanent spatial anatomical reference. An emphasis of the scapula configuration was made by color-cueing the six anatomical features for 3 seconds. The dynamic version of the scapula shoulder flexion movement (118 seconds) consisted of the successive presentation of upward and downward movements.

Static Visualizations

The static materials were extracted from the corresponding dynamic visualizations. The static version of the scapula structure (Fig. 2A) consisted of the simultaneous presentation of the visible and color-cued features. The static version of the scapula shoulder flexion movement (Fig. 2B) consisted in the simultaneous presentation of a five-step upward movement. The duration of the static visualizations was identical to the duration of the corresponding dynamic visualizations.

Procedure

Participants were tested in groups of 14–15 students in a computer lab. After providing a signed consent, participants began the computer-based experiment. The entire experiment was conducted on E-Prime® software, version 2.0 (Psychology Software Tools, Pittsburgh, PA) that was system-paced. Participants were asked to pay close attention when studying and reading the displays, and to answer five assessment tasks as accurately and as fast as possible. All participants were first presented with a two-minute general introduction of the scapula, an 86-word text coupled with a scapula labeled picture. Hereafter, they studied the instructional structure material and answered three assessment tasks. Then, they studied the movement material and answered the last two assessment tasks. All learning material was presented twice. Online gaming experience was examined with a five-point Likert scale, ranging from never to very often. Additional cognitive measures were assessed at the end of the experiment: the MRT (Vandenberg and Kuse, 1978) and the GEFT (Witkin et al., 1971). Participants completed all tasks and questionnaires, and the complete experimental session lasted approximately 60 minutes.

Assessment Tasks

Based on the cognitive task analysis (Fig. 1), five assessment tasks, matching Steps 2–6, were developed. These tasks, mainly pictorial, were designed to investigate students mental representations involved in learning functional anatomy, namely (1) the simple 2D structure configuration on one anatomical plane, (2) the complete 3D structure configuration, (3) the spatial relationship between structure and body space, (4) the dynamic functioning of the structure on one anatomical plane, and (5) the complete 3D dynamic functioning of the structure. To illustrate the five assessment tasks, example items are shown in Figure 3.

The feature identification task (Fig. 3A), with 36 multiple-choice questions, consisted in recalling the scapula's features spatially distributed on the structure. The scapula relative rotations task (Fig. 3B) assessed, through 27 true/false statements, the recognition of the relative rotations of the scapula. Each item presented first the scapula (model) in a specific position, then a second scapula image with a rotation amplitude statement. Participants had to determine whether the second image was a congruent rotation of the model in accordance with the amplitude statement. The orientation reference task (Fig. 3C), by means of 38 true/false questions, consisted in the understanding of the anatomical 3D space with regard to the scapula's relative position and the orientation reference character. Participants had to decide whether the anatomical positioning of the two images was congruent. The movement sequence identification task (Fig. 3D), made up of 36 true/false questions, consisted in dynamic excerpts recognition of dis/similar phases of the shoulder flexion movement. The movement sequence order task (Fig. 3E) assessed, through 16 test items, the recognition of the scapula movement during shoulder flexion by ordering five static images of different motion states and different anatomical plane views. Participants responded by typing the numerical ordered sequence of images. For all fives tasks, accuracy scores were measured as the number of items correctly answered. Response time measures were calculated as the average time for the correct items only.

Testing Visuospatial Abilities

The mental rotation test (MRT; Vandenberg and Kuse, 1978) was used as the spatial relation ability measure. The MRT used in this experiment was a revised version (Peters et al., 1995), which was computerized for the experiment. It contains two series of 12 problem sets, with a total of 24 problem sets. Each problem set consists of one model and four alternatives (two correct and two incorrect ones). One point is scored only if both choices are correct. No credit is given for a single correct answer. The possible score ranges from 0 to 24. The group embedded figures test (GEFT; Witkin et al., 1977) was used in this experiment as the spatial visualization ability measure. In a booklet form, GEFT is a 25-item assessment comprising three sections, one simple and two complex figure sections. Within each larger complex figure is an obscured or embedded one of eight simple figures. Participants were asked to locate and trace with a pencil a previously seen simple figure. The test was administered according to instructions. The score consisted of the total number of correct answers from sections 2 and 3 only. The first section, composed of seven items, served as practice. The range of score is 0–18, with a high score indicating a field independency. Both spatial ability measures were used in the statistical analyses as continuous factors.

Data Analyses

A multiple analysis of covariance (MANCOVA) was performed to determine the relationship between the five anatomical tasks performance and online gaming according to the presentation format conditions. Performance in the five anatomical tasks was

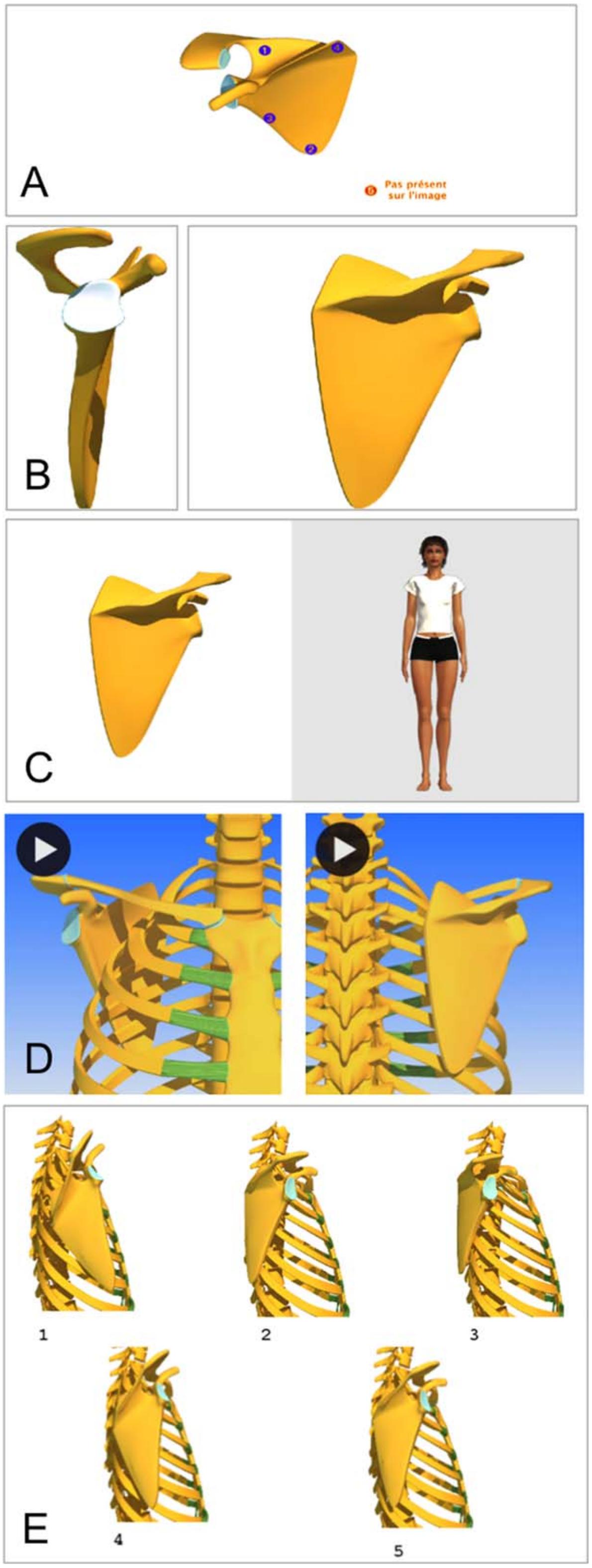

Figure 3.

Graphic illustration of five assessment tasks: **A**, Example items from the feature identification task; **B**, the scapula relative rotations task; **C**, the orientation reference task; **D**, the movement sequence identification task; and **E**, the movement sequence order task.

Table 1.

Means and Standard Deviation for the Performances and Response Times for the Five Assessment Tasks and Spatial Ability Measures According to Conditions

Assessment tasks	Dynamic Condition ($n = 22$) Mean (±SD)	Static Condition ($n = 27$) Mean (±SD)
Structure tasks		
(1) Feature identification		
Accuracy (max = 36)	24.55 (±5.28)	23.07 (±5.98)
Responses time (ms)	4,947.12 (±1,468.8)	4,654.52 (±1,353.2)
(2) Rotation of the scapula		
Accuracy (max = 27)	18.86 (±2.78)	17.78 (±2.80)
Response time (ms)	6,363.04 (±3,527.6)	6,314.26 (±2,633.2)
(3) Orientation references		
Accuracy (max = 38)	23.05 (±3.98)	24.11 (±4.25)
Response time (ms)	3,826.45 (±1,358.7)	3,522.03 (±1,802.1)
Movement tasks		
(4) Movement identification		
Accuracy (max = 36)	25.36 (±3.56)	26.44 (±2.97)
Response time (ms)	2,364.84 (±576.3)	2,283.99 (±344.35)
(5) Movement order		
Accuracy (max = 16)	5.82 (±3.20)	5.74 (±3.05)
Response time (ms)	20,116.83 (±6,397.4)	18,634.03 (±7,634.7)
Spatial ability measures		
MRT	5.32 (±2.27)	4.93 (±2.67)
GEFT	12.95 (±4.30)	14.19 (±3.57)

ms, milliseconds; MRT, mental rotation test; GEFT, group embedded figures test.

then analyzed using a MANOVA with presentation format conditions as a between-subjects factor (dynamic vs. static visualizations). Because of technical problems, the computerized MRT was not recorded in the second set of 12 items. Final scoring only applied to the first 12-item set. Multiple linear regression analyses were used to explore the relationship between the performance on the five anatomical tasks and presentation formats, spatial abilities (centered-MRT, centered-GEFT), and their interaction terms with presentation formats.

RESULTS

Do 3D Dynamic Visualizations Favor the Learning of Functional Anatomy?

Students self-reported their online gaming as a moderated frequency ($M = 1.94$, $\pm SD = 1.29$). Results of the MANCOVA (between-subjects factor: presentation formats, covariate: online gaming) revealed no effect of online gaming (Wilks' Lambda $\lambda = 0.856$, $F(5, 42) = 1.414$, $P = 0.239$). This variable was thus excluded from later analyses. Table 1 presents the descriptive statistics that include mean scores (and ±SD) and proportion of correct answers (and SD) for the five tasks according to presentation format conditions.

The results of the MANOVA yielded no overall advantage when learning with dynamic visualizations, neither for the accuracy (Wilks' λ (λ) = 0.88, $F(5, 43) = 1.11$, $P = 0.366$), nor the overall response times ($\lambda = 0.95$, $F(5, 43) = 0.39$, $P = 0.85$). Consecutive ANOVAs were all non-significant ($F < 1$).

Do Spatial Abilities Interact With Visualization Conditions?

Descriptive statistics for the MRT and GEFT measures are presented in Table 1. The spatial ability scores—MRT and GEFT—were not significantly different between the presentation formats ($F < 2$, $P > 0.28$), neither between sex ($F < 1$, $P > 0.45$).

For all five regressions, no main effect of presentation formats (dynamic vs. static) could be obtained ($t < 1.695$, $P > 0.09$). The MRT was a significant predictor of performance for three tasks: feature identification task ($ß = 0.418$, $t(41) = 3.157$, $P = 0.003$), movement identification task ($ß = 0.493$, $t(41) = 3.136$, $P = 0.003$), and movement order task ($ß = 0.415$, $t(41) = 2.771$, $P = 0.008$). Additionally, the MRT marginally predicted the scapula relative rotations task ($ß = 0.317$, $t(41) = 2.003$, $P = 0.052$). Admitting a $P = 0.053$ as significant, an interaction effect was found with the feature identification task between the presentation formats and the MRT scores ($ß = 0.263$, $t(41) = 1.991$, $P = 0.053$). The slopes of the regression (Fig. 4) yield to different patterns

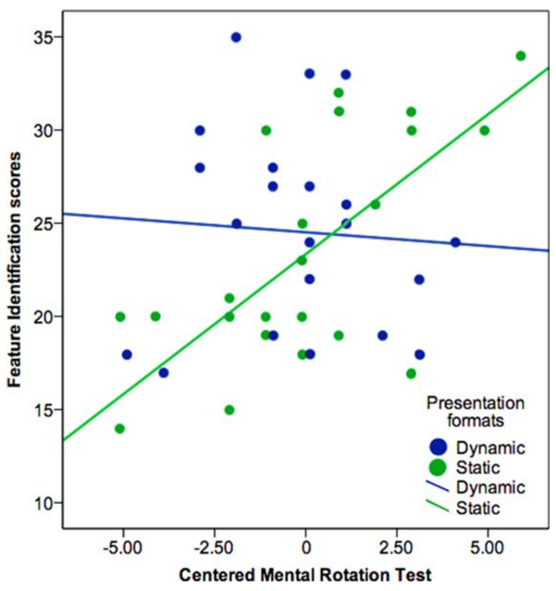

Figure 4.

Feature identification score as a function of mental rotation test (MRT) interaction depending on presentation formats (dynamic vs. static condition).

between the dynamic and static visualization conditions. As shown in Figure 4, the slope for the static group was positive ($R^2 = 0.451$), whereas it was null ($R^2 = 0.004$) for the dynamic condition. In other words, the MRT did not moderate both learning conditions in the same way.

Regarding the GEFT, it was a significant predictor only for the structure tasks: the feature identification task ($ß = 0.286$, $t(41) = 2.290$, $P = 0.027$), and the scapula relative rotations task ($ß = 0.315$, $t(41) = 2.111$, $P = 0.041$). GEFT did not predict the movement tasks ($t < 1.4$, $P > 0.16$).

Surprisingly, no main effect of spatial abilities on the orientation references task was obtained (MRT: $ß = 0.272$, $t(41) = 1.628$, $P = 0.111$, GEFT: $ß = 0.221$, $t(41) = 1.403$, $P = 0.168$).

DISCUSSION

This study focused on two main goals. The first was to examine whether presentation formats influence the building of efficient and effective mental representations when learning the functional anatomy of a structure and its movements. The second goal was to investigate the role of spatial abilities, more specifically the spatial relation and spatial visualization abilities measured with the MRT and the GEFT, respectively, and their interplay with presentation formats when learning the scapula, its shoulder flexion movement, and their relative location within body space.

Do Dynamic 3D Visualizations Support Learning Functional Anatomy?

It was expected that studying the scapula and its associated shoulder flexion movement with 3D dynamic visualizations would lead to better performance as compared to learning with static visualizations. However, the findings demonstrated that this was not the case, as there were no obvious global performance differences for learning functional anatomy from 3D dynamic or static visualizations. This replicates the findings of Khot and colleagues that computer-based resources were not more effective than traditional models for the self-study of pelvic anatomy (Khot et al., 2013). These findings are also consistent with previous studies (Hegarty et al., 2003 [study 3]; Mayer et al., 2005; Schneider, 2007; Boucheix and Schneider, 2009; Imhof et al., 2012) suggesting that dynamic visualizations are not the only way to effectively convey complex and dynamic information, and that particular spatial layouts (Imhof et al., 2012) may be as efficient. Indeed, the static condition in this study combined two effective spatial layouts. It was a simultaneous presentation of the scapula's highlighted features (or different motion states of the shoulder flexion movement, respectively) embedded in a sequential presentation of the different anatomical plane views (posterior, lateral, anterior, and superior views). Without claiming that the information was strictly alike in both presentation format conditions, the static pictures proposed the same anatomical plane views of the content, yet with only one picture per plane. The perspectives were definitively not dynamically continuous, as they were in the 3D rotating model of the dynamic visualization, but rather sequential-simultaneous. This static format allowed the comparison between states and supported mental simulation of movement (Mayer et al., 2005). It did not prevent the static learners from inferring the "missing" plane-views to reconstruct the 3D information, that is, the 3D structure, its location or position within the 3D space, and to a lesser extent, the 3D movement.

Taken together, these results indicate that the building of effective mental representations of a 3D scapula and the associated 3D movement following the initial processing of the learning material was possible for learners, regardless of the presentation format conditions. They perceived and extracted key information from the content-to-be-learned, avoiding a perceptual salience-thematic relevance discrepancy, which is more frequent among novices (Boucheix and Lowe, 2010).

Does Learning Functional Anatomy of a Structure and Its Associated Movements Involve Spatial Abilities?

Spatial abilities have been shown to be relevant predictors for learning anatomy outcomes. This was especially true of the MRT, being a broader predictor than the GEFT. The MRT could predict performance when learning an anatomical structure (steps 2 and 3 of the cognitive task analysis) as well as its associated movement (tasks 5 and 6). These tasks implied effective and somewhat incremental mental representations of the structure and movement, respectively. They required participants to use some forms of mental rotation processing, and/or to spatially manipulate and transform representations of the 3D scapula structure. This is consistent with previous studies (e.g., Rochford, 1985; Garg et al., 2001, 2002; Guillot et al., 2007; Langlois et al., 2015) that have underlined the MRT as a good predictor of success in learning anatomy.

Paradoxically, the GEFT predicted performance exclusively on structure tasks (the feature identification and the rotation of the scapula tasks), involving the building of a mental representation of the 3D structure from a 2D shape (steps 2 and 3 of the cognitive task analysis, respectively). It would have been expected that the GEFT, which reflects a perceptual disembedding ability, would have played a more important role in the movement tasks and the preceding processing of the movement visualization. Indeed the shoulder flexion movement learning material, irrespective of the presentation formats, was of greater perceptual complexity. It included more configurationally detailed components (presence of the humerus, clavicle, skull, vertebral column, and rib cage), as compared to the scapula visualization, which contained a single element. These findings are consistent with previous studies (Garg et al., 2001; Huk, 2006; Guillot et al., 2007), suggesting strong but independent relationships between anatomy performance and SR and Vz, respectively.

Contrary to all expectations, none of the spatial ability measures interacted with the anatomical 3D body space task (orientation references task), where students had to judge whether the viewpoints of the scapula and the orientation reference were identical. This suggests that performing this task might call upon other spatial ability components or factors, such as spatial orientation, which is defined by McGee (1979) as the ability to imagine the appearance of an object from another perspective and to make a judgment from this imagined view. Alternative strategies, such as embodied cognition, should also be considered for performing this task in light of research on learning with dynamic visualizations (Van Gog et al., 2009; de Koning and Tabbers, 2011). That is, besides the brain, the body may also be involved in cognition and play a crucial role in learning (Lakoff and Johnson, 1999). The importance of being able to distinguish a simple form within a more complex form when learning anatomy may not be as revealing as the ability to perform mental rotations. Indeed, our findings suggest that the spatial relation ability may be involved both in extracting pertinent anatomical information as well as in performing anatomical tasks. In the former case, the interplay between the MRT scores and presentation formats sheds light on the role of the spatial relation ability during the visualization processing. In the latter case, the predicting role of the MRT scores for successful anatomy performance replicated evidence provided by numerous studies relevant to the literature in the anatomy domain (e.g., Rochford, 1985; Garg et al., 2001, 2002; Guillot et al., 2007; Langlois et al., 2015).

Spatial abilities have proven to be much stronger predictors of successful functional anatomy performance than dynamic versus static visualization grouping. However, an interesting interaction between the MRT scores and presentation formats was found in the feature identification task. Whereas the dynamic visualization group, either for students with high or low MRT scores, performed equally well on this task, students of the static condition with high MRT scores outperformed their counterparts with low MRT scores. This interaction, indicating that the effect of spatial relation ability is different for dynamic or static learners, can be explained in two ways.

On one hand, the interaction is in line with the compensating hypothesis (Mayer and Sims, 1994; Hays, 1996; Mayer, 2002). Studying with dynamic visualization enabled learners with low spatial ability to build effective mental representations of the scapula structure while processing the scapula visualization, resulting in identical performances on the feature identification task for both learners with high and low spatial ability. Conversely, learners of the static condition processed the scapula visualization differently, depending on their MRT abilities. This in turn led to the building of qualitatively different mental representations. In terms of presentation formats, studying with dynamic visualization helped students with low MRT scores to compensate for their spatial weaknesses. In terms of spatial ability, this interaction suggested that spatial relation ability could compensate for static instructional material. Key differences between the two types of visualization are the transitions between the multiple anatomical views. Indeed, dynamic visualizations offer the explicit and external motion of the scapula moving between the views. Whereas learners with dynamic visualizations only had to "watch" to build analogous mental representations of the structure, learners with static visualizations had to infer these translational views. Results are in line with Höffler and Leutner's study, suggesting a possible compensating hypothesis effect of the dynamic visualization with the MRT (Höffler and Leutner, 2011). It is worth noting that in this study, the compensating hypothesis effect was found with the MRT, a SR measure, whereas in Höffler and Leutner's (2011) study, this effect was found with the Paper Folding test, which is a Vz measure. In light of Höffler and Leutner's study, the findings suggest that the compensating effect might occur independently with different spatial ability components when studying with dynamic visualizations (Höffler and Leutner, 2011).

On the other hand, the interaction from learners with high spatial ability suggests an alternative explanation. The discrepant performance of the students with high MRT scores may be discussed in terms of an expertise reversal effect, where learners with high MRT scores in the dynamic condition could have been hindered by dynamic visualizations. Indeed, Khacharem et al. (2013) showed that expert learners invested less mental effort to process dynamic visualizations and did not benefit from such a display, whereas novice learners were able to take advantage of the dynamic visualizations to produce better learning outcomes. These findings definitively highlighted the influence of presentation formats when spatial abilities were involved.

Although this study was not focused on the validation of the cognitive task analysis, the empirical data provided some insights to enrich the understanding of cognitive challenges involved in learning the functional anatomy of 3D structures and their movements. The interaction between visuospatial abilities and anatomical tasks underlined two essential findings. First, different anatomical tasks involved distinct and specific cognitive operations as claimed in the cognitive task analysis. Second, distinct dimensions of spatial abilities—here Vz and SR—differentially affected or influenced learners' performance in those (post)tasks. In addition, this interaction may also describe why some anatomical structures, depending on their perceptual characteristics, may be easier to process than others. Moreover, it is important to bear in mind that performing the (post) tasks involved and required mental transformations elaborated on the newly acquired mental representations. A clear distinction between spatial abilities involved in the initial visualization processing and those subsequently involved in performing the (post) tasks would help to understand the interplay between dynamic visualizations and spatial ability in a learning context. This calls upon the need to address these aspects when studying a spatially complex instructional domain, such as anatomy. Moreover, further studies should extend the interrelationship between the instructional anatomy domain and relevant spatial abilities, the question being whether spatial abilities enhance anatomy learning, or the other way round.

Limitations

This study has certain limitations. First, due to technical problem, half of the participants' data could not be taken into consideration, which could have reduced the statistical power of the analyses. Second, the study population was restricted to first-year kinesiology students. Whether these findings could be generalized to all medical-related students or more senior students needs to be determined. It has been shown in the literature that expertise could compensate for low visuospatial abilities, as prior knowledge orientates visual attention and cognitive processes in a top-down manner (Hegarty and Kriz, 2008). Third, during the time dedicated to learning, about 10 minutes, participants were asked to study the displays. It was not clear whether they actively processed the material, or only passively "watched" it, especially with dynamic visualizations that appear self-explanatory (Hegarty et al., 2003; Lowe, 2003). Asking learners to perform an activity during the learning phase, such as inferring the different perspectives or the movements of a 3D structure, might engage them in active learning and foster the "mental interaction needed [...] in the process of understanding." (Moreno and Mayer, 2000). Finally, only two different spatial ability factors were explored through the study. It would be of importance to investigate factors other than Vz and SR as well as to use other tests to understand their specific role. Future research should investigate the impact of other visuospatial dimensions, such as the perspective taking ability (Kozhevnikov and Hegarty, 2001), a measure of the spatial orientation factor as well as the impact of perceptual profile of different anatomical structures.

CONCLUSION

It is clear from this present research that learning 3D structures and 3D movements was possible for novices independently from the learning displays and within a rather short learning period. The interaction between the MRT scores, measuring spatial relation ability, and presentation formats suggested a compensating hypothesis effect of dynamic visualizations, enabling learners with low spatial ability to build adequate and effective mental representations of a 3D structure. On another note, this interaction also underlined the potential hindrance of dynamic visualizations for learners with high spatial ability, suggesting an expertise reversal effect. However, the findings clearly demonstrated that the interaction between visuospatial abilities, at least spatial relation, and instructional material depends on the subsequent tasks participants have to perform. This calls upon the necessity to take into consideration the cognitive operations involved in the anatomical tasks targeted by the learning objectives when designing or proposing instructional material to novice anatomy students.

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