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Experimental Evidence for Improved Neuroimaging Interpretation Using Three-Dimensional Graphic Models

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Three-dimensional (3D) or volumetric visualization is a useful resource for learning about the anatomy of the human brain. However, the effectiveness of 3D spatial visualization has not yet been assessed systematically. This report analyzes whether 3D volumetric visualization helps learners to identify and locate subcortical structures more precisely than classical cross-sectional images based on a two dimensional (2D) approach. Eighty participants were assigned to each experimental condition: 2D cross-sectional visualization vs. 3D volumetric visualization. Both groups were matched for age, gender, visual-spatial ability, and previous knowledge of neuroanatomy. Accuracy in identifying brain structures, execution time, and level of confidence in the response were taken as outcome measures. Moreover, interactive effects between the experimental conditions (2D vs. 3D) and factors such as level of competence (novice vs. expert), image modality (morphological and functional), and difficulty of the structures were analyzed. The percentage of correct answers (hit rate) and level of confidence in responses were significantly higher in the 3D visualization condition than in the 2D. In addition, the response time was significantly lower for the 3D visualization condition in comparison with the 2D. The interaction between the experimental condition (2D vs. 3D) and difficulty was significant, and the 3D condition facilitated the location of difficult images more than the 2D condition. 3D volumetric visualization helps to identify brain structures such as the hippocampus and amygdala, more accurately and rapidly than conventional 2D visualization. This paper discusses the implications of these results with regards to the learning process involved in neuroimaging interpretation. Anat Sci Educ 5: 132–137. © 2012 American Association of Anatomists.

Key words: neuroanatomy education; gross anatomy education; medical education; brain; neuroimaging; volumetric visualization; visual-spatial abilities; 2D/3D testing; learning

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INTRODUCTION

Neuroscience students experience difficulty in identifying and locating neuroanatomical structures in the brain (Giles, 2010; Zincet al., 2010) since the interpretation of cross-sectional images (morphological and functional) is extremely complex (Zinchuk et al., 2010). Three reasons may explain this phenomenon. First, although it is possible to render cerebrospinal fluid, cerebral vasculature (Nowinski et al., 2009), and white and gray matter (Hu et al., 2005; Gupta et al., 2010), current algorithms are insufficient for independent rendering of brain structures with a homogeneous composition. Consequently, highly demanding cognitive processes are required to reconstruct three-dimensional (3D) mental images of subcortical brain structures based on cross-sectional images (Pillay, 1994). Second, the structures of the brain not only are packed within a small area in 2D visualizations, but they also show a great topographic variability among participants and sections (Thompson and Toga, 1997). Third and last, the spatial resolution in 2D visualizations is often low, particularly for functional images (Mizumura, 2010).

Although the classical approach for studying brain neuroanatomy is based on cadaver dissections and orthogonal 2D projections (Moon et al., 2010), there has been an exponential growth in the use of digital images, such as 3D graphic models (Drake et al., 2009; Nowinski, 2009; Petersson et al., 2009; Estévez et al., 2010; Grauke et al., 2010; Venail et al., 2010; Chariker et al. 2011; Yeung et al., 2011). For the most part, these techniques optimize the visualization of subcortical structures and their spatial relations, which may facilitate the learning of neuroanatomy (Silén et al., 2008; Svirko and Mellanby, 2008; Chariker et al., 2011).

The benefits of volumetric visualization for learning neuroanatomy may be determined by variables such as the participant's individual abilities or the specific properties of the tasks to be performed, such as difficulty (Fernández et al., 2011; Nguyen et al., 2012). Thus, a relationship may be expected between the level of competence (novice vs. expert) and performance on tasks related to the identification and location of complex brain structures (Fernández et al., 2011). However, the effect of some variables, such as visual-spatial aptitude, is controversial (Garg et al., 2001). Some authors believe that visual-spatial aptitude can predict the level of learning in neuroanatomy (Wanzel et al., 2002; Fernández et al., 2011), whereas other researchers do not support this association (Hegarty et al., 2009).

In this context, empirical studies aimed at evaluating computer-based teaching resources have shown a high degree of variability in their procedures and outcomes (Chariker et al., 2012). Moreover, the effect of the type of image (morphological vs. functional) and the level of task difficulty (easy vs. complex) on 3D volumetric visualization of subcortical brain structures is almost unknown.

The objective of this study is to analyze the efficacy of volumetric visualization (3D graphic models embedded in 2D cross-sections) vs. conventional visualization (based on 2D cross-sections) for the identification and location of subcortical brain structures. Specifically, the goal of the present study is to determine whether the benefits of 3D volumetric visualization depend upon other variables, such as the type of image and the difficulty of the brain structure to be identified.

MATERIALS AND METHODS

Participants

The sample was comprised of 80 volunteers with ages ranging from 23 to 48 (Mean = 34.2 ± 4.31). These volunteers were recruited from different universities and medical centers located in Central Spain (Madrid), Northwestern Spain (Salamanca and Valladolid), and Northeastern Spain (Pamplona and Barcelona). All participants gave their informed consent to participate in the study, which was approved by the local ethics committee following the principles established in the Declaration of Helsinki.

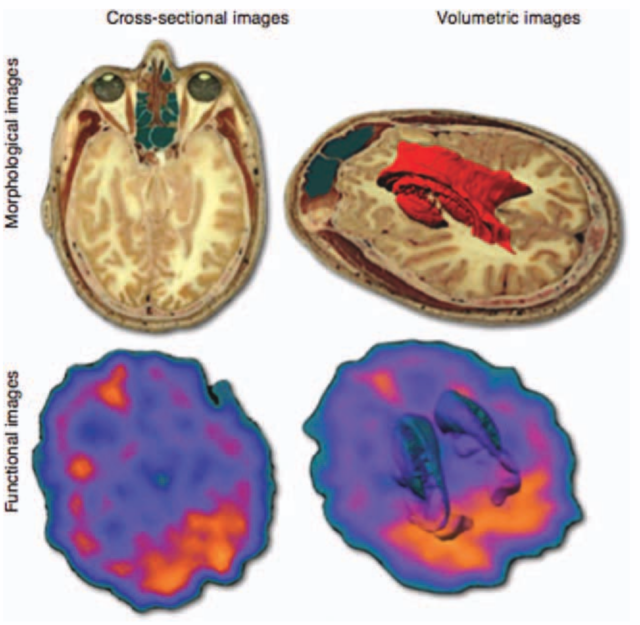

Figure 1.

Morphological and functional images for both cross-sectional and volumetric experimental conditions.

The participants' level of education was classified as follows: (1) novices, participants who obtained their degree in psychology (*n* = 20) or medicine (*n* = 20) and (2) experts, neuropsychologists (*n* = 20) and neuroanatomists (*n* = 20). All experts had completed a postgraduate course (masters or doctoral degree) and had at least one year of professional experience in their field (experience range: 1–10 years).

Materials

Morphological images were obtained with the Visible Human Project (Male CD-ROM), version 2.0, (Research Systems Inc., Munroe Falls, OH); in particular, high quality images were obtained from sections Hi1001 to Hi1160. Meanwhile, functional positron emission tomography (PET) scan images using two different tracers—fluorine-18 (^{18}F) fluorodeoxyglucose (FDG), called ^{18}FDG-PET scans, and 18-fluoro-L-DOPA, called ^{18}F-DOPA-PET scans—were obtained from healthy adult individuals. All images were optimized for a resolution of 800 × 600 pixels and were presented using a full screen web-navigator for two experimental conditions: (1) 2D cross-sections of the brain, and (2) volumetric images with embedded 3D graphic models. These 3D models were generated from the same sections used in the 2D visualizations; thus, similar brain structures were selected for both conditions. The brain structures that participants were asked to identify included the hippocampus, caudate nucleus, putamen, amygdala, thalamus, and subthalamic nucleus. Figure 1 shows some examples of the images for both the 2D and 3D visualizations.

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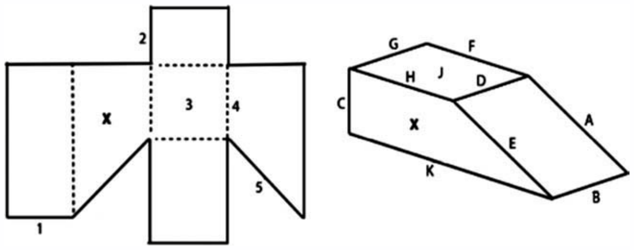

Figure 2.

Example of stimulus item used in Yela's visuospatial test. (Reproduced with permission from Yela Desarrollo de Superficies/ L.L. Thurstone. Adaptación M. Yela. 1st Ed., 1969, 12 p, ©Técnicos Especialistas Asociados).

Procedure

The procedure used to create the 3D graphic models embedded in 2D cross-sections are described as follows. First, morphological and functional ^{18}FDG-PET and ^{18}F-DOPA-PET images were obtained from the Visible Human Project and healthy individuals, respectively. Thirty-six images (three morphological and three functional images from each structure) were selected according to the target brain structures for this study. Second, volumetric graphic models for brain structures corresponding to different subcortical regions of the brain were developed using the Amira® software program, version 5.3 (Mercury Computer Systems/TGS, San Diego, CA). This started with the segmentation of regions of interest from the selected 2D images. After this phase, the surface was extracted, and each brain structure was rendered.

The difficulty in locating each brain structure was established by expert consensus. Three skilled neuroanatomists classified the brain structures with a forced-choice question format (easy or difficult) based on two basic criteria: the size and the facility to establish the limits of the structure, which were indicated before starting the classification process. The structures were classified as follows: (a) high (amygdala, hippocampus, and subthalamic nucleus) and (b) low (caudate nucleus, thalamus, and putamen nucleus). The 36-question examination was given to a panel of skilled neuroanatomists (different from the ones used to create the 3D volumetric models) to ensure that they were able to answer the questions. Every 3D image was correctly identified by at least one of the three members of the panel.

Finally, a quasi-experimental design (participants were assigned of to each condition without a random process) was implemented in computerized form to study the effect of the visualization conditions on the outcome measures. All centers had a coordinator who contacted potential participants (e.g., staff members, postgraduate students) by e-mail. Volunteers were assigned to one of two experimental groups and were matched for gender distribution and level of competence in neuroanatomy. The control group completed the identification task of subcortical structures in 2D cross-sections. The experimental group completed this same task using volumetric graphic models (volumetric visualization).

The test consisted of 36 items randomly presented to avoid possible effects of the stimulus order. Initially, instructions were presented and one item was provided as an example to test that the participant understood the objective of the task and the response procedure. The participants were asked to identify one specific structure (e.g., "identify the amygdala in the following image") by clicking on a particular target area on the screen. This area was defined by the technical staff using coordinates (*x-y*, range: from 50 to 500) on each image. The correct answers and errors were automatically registered for both 2D and 3D conditions when the participant clicked on the screen. The total length of the session was ∼15 minutes. After a five-minute break, the participants' visual-spatial ability was assessed with the computerized version of Yela's test (Yela, 1969).

Outcome measures. The percentage of structures that were correctly identified (hit rate) and response time (milliseconds) were considered the main outcome measures for testing performance in both experimental conditions (2D and 3D). In addition, the participant's confidence in the response and satisfaction with each visualization condition were evaluated with two rating scales which were tested in a pilot study (Ruisoto et al., 2011).

On the scale of confidence (score range: 0–10), higher scores indicated a greater certainty of response. Meanwhile, satisfaction was analyzed using a simple scale of two items, (1) "Volumetric visualization made it easier to identify/locate brain structures," and (2) "I would recommend using volumetric visualization for teaching/learning neuroanatomy"), with a five-point Likert scale format: 1 = strongly disagree, 2 = partially disagree, 3 = neither agree nor disagree, 4 = partially agree, and 5 = strongly agree.

Finally, a computerized version of the Surface Development Test (Yela, 1969), originally developed by Thurstone (1938), was used to measure the visual-spatial ability of the participants. The participants had to complete a surface development task. The task consisted of an association between the numbers in a 2D geometric image and the corresponding letters on a concrete surface in a 3D figure. The test contained 12 items and the maximum time was 14 minutes. Figure 2 provides an example.

Statistical analyses. Statistical analysis was performed using SPSS statistical package, version 18.0 for Windows

Table 1.

Sociodemographic and Visuo-Spatial Characteristics for Participants in Both Cross-Sectional (2D) and Volumetric (3D) Experimental Conditions

Characteristics of participants	2D–Cross-sectional (*n* = 40)	2D–Volumetric (*n* = 40)
Age[a] (± SD)	30.80 (± 6.83)	29.40 (± 6.40)
Gender (male/female ratio)	20/20	20/20
Competence (novices/experts ratio)	20/20	20/20
Visual-spatial test[a] (± SD)	20.08 (± 2.96)	21.35 (± 3.38)

[a] Non-significant differences between groups.

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Table 2.

Statistical Analysis of Outcome Measures for Participants in Both Cross-Sectional (2D) and Volumetric (3D) Experimental Conditions

Measured parameters	2D–Cross-sectional ($n = 40$)	3D–Volumetric ($n = 40$)	Student's *t*-test	*P* value
Hit rate[a] (%, ± SD)	25.37 (± 15.40)	42.09 (± 17.32)	4.68	$P < 0.01$
Response time in milliseconds (± SD)	8,059.3 (± 1,101)	6,752.6 (± 825)	5.95	$P < 0.01$
Level of confidence on the scale 0–10 (± SD)	4.90 (± 1.96)	6.48 (± 1.56)	3.96	$P < 0.01$

[a] Hit rate = Percentage of structures identified correctly out of 36 possible.

(SPSS Inc., Chicago, IL). The following statistical analyses were carried out: (a) descriptive (mean and standard deviation) analysis of variables; and (b) Student's *t*-test for independent samples in order to determine whether there were significant differences between experimental conditions that affected the outcome measures. Finally, multivariate analyses of variance (MANOVA) were run to examine the main effects and possible interaction effects. The level of significance was $P < 0.05$.

RESULTS

The sociodemographic characteristics and visual-spatial ability for both experimental conditions (conventional and volumetric) are shown in Table 1. No significant differences were found between groups in age ($t_{(78)} = 0.27$, $P < 0.05$) or visual-spatial ability ($t_{(78)} = 1.79$, $P < 0.05$).

The hit rate, response time, and degree of confidence in identifying and locating subcortical structures in conventional and volumetric conditions are depicted in Table 2. Both experimental groups showed significant differences in these variables. The 3D condition provided a greater number of correct answers and a higher level of confidence in comparison with the 2D condition. Moreover, the response time was significantly lower in 3D vs. 2D. Finally, satisfaction with the 3D condition was high (Mean = 4.20 ± 0.43, range: 0–5).

MANOVA was run to study the effect of the previous level of competence (novice vs. expert), image type (morphological vs. functional), and difficulty of the brain structures (easy vs. difficult) on the hit rate. Table 3 shows the means and standard deviations (in parentheses) for both conditions (2D and 3D) according to the previous level of training, image type, and difficulty.

There were significant differences between groups. As expected, participants with more specific training in neuroanatomy ($F_{(1,78)} = 55.23$, $P < 0.01$) had a higher hit rate than participants with less education. In relation to the images, simple ($F_{(1,78)} = 16.59$, $P < 0.01$) and morphological ($F_{(1,78)} = 16.59$, $P < 0.01$) images had a higher hit rate than complex and morphological images, respectively. Difficulty was the only variable that showed a significant interaction with the experimental conditions of visualization ($F_{(1,78)} = 7.84$, $P < 0.05$). The 3D condition yielded a lower decrease in the hit rate in comparison with the conventional 2D visualization when the images were difficult (Fig. 3).

DISCUSSION

This study has demonstrated that volumetric visualization improves the identification and location of subcortical brain structures in both morphological and functional images. The 3D experimental condition showed not only more accuracy but also less response time. Moreover, participants in the 3D condition were more confident in their responses in comparison to the 2D control condition. Together, these results support the efficiency and usefulness of 3D volumetric visualization for neuroimaging interpretation.

Other studies support the benefits of 3D visualization in the location and identification of anatomical structures (Grauke and Richardson, 2010; Chariker et al., 2011), but

Table 3.

Competence, Image Modality, and Difficulty in Identifying Brain Structures Expressed by Hit Rates for Participants in Both Cross-Sectional (2D) and Volumetric (3D) Experimental Conditions

Experimental conditions	Competence		Modality		Difficulty	
	Novices	Experts	Morphological	Functional	Easy	Difficult
2D–Cross-sectional (± SD)	13.36 (± 11.10)	37.38 (± 15.81)	39.68 (± 8.04)	17.59 (± 11.71)	48.76 (± 9.08)	18.99 (± 14.22)
3D–Volumetric (± SD)	32.76 (± 14.15)	49.42 (± 10.22)	57.15 (± 11.04)	38.15 (± 13.07)	54.42 (± 18.15)	36.75 (± 16.08)

Hit rate = Percentage of structures identified correctly out of 36 possible.

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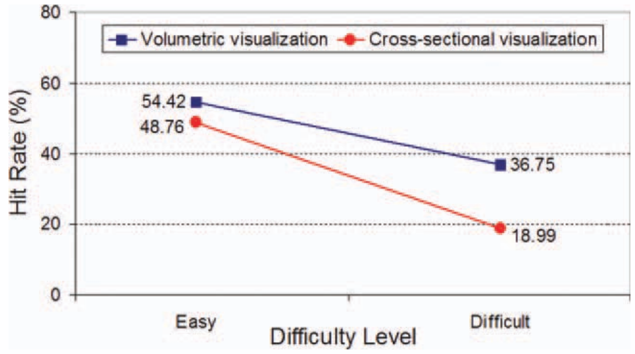

Figure 3.

Effect of interaction between visualization condition and difficulty of the structure.

only some of them describe the importance of 3D visualization for brain structures (Estévez et al., 2010).

Specifically, Perandini et al. (2010) found that 3D visualization helps individuals to identify and locate brain structures quickly, which is consistent with the present study. In fact, 3D visualization creates a more accurate representation of the structures and map of the relationships between them, which at the same time reduces the demand on cognitive resources for mental reconstruction from conventional 2D images (Pillay, 1994). Therefore, according to Gould et al. (2008), it is not surprising that the 3D condition is associated with greater confidence in responses and high satisfaction. In short, the present study's results support the notion that 3D volumetric visualization of brain structures is more valuable in terms of accuracy, time, and demand of cognitive resources in comparison with conventional 2D models.

It is worth noting that even experts showed a low percentage of correct answers, but several reasons could be behind this. Half of the target structures had already been categorized by an independent committee of experts as "difficult to identify". Furthermore, the participants were not very familiar with the experimental task and the experts showed substantial variability between individuals in terms of years of experience. In any case, these results have important implications for neuroimaging education, as they are essentially based on the interpretation of structures considered difficult to identify (e.g., hippocampus and amygdala), which is often a challenge in neuroimaging interpretation (Gouws, et al., 2009).

The present study therefore confirms the benefits of 3D visualization, particularly in the interpretation of complex images, and the use of this modality is promising for the fields of neuroanatomy education and professional practice. This proposal has been defended by recent trends in neuroanatomy education (Gould et al., 2008; Crossingham et al., 2009; Drake et al., 2009; Gómez et al., 2010) and the gradual increase in research based on this type of 3D technique with neurological and neuropsychiatric patients (Abou-Saleh, 2006; Phillips, 2007; Eldaief and Dougherty, 2008; Silén et al., 2008; MacQueen, 2010). However, empirical evidence regarding its benefits has been limited so far.

Some limitations of the study should be described. First, only healthy images were used in order to reduce the puzzling effect of pathological conditions. The analysis of these effects was not an objective of the present study, but future research should test the performance of volumetric vs. cross-sectional visualization with pathological images. Although the participants were not assigned randomly, groups were well-matched by such factors as age, visual-spatial abilities, gender, and previous competence in neuroanatomy to avoid the effect of common confounding variables.

In short, these results support evidence in favor of using volumetric visualization systems for locating subcortical structures, particularly with images considered difficult to identify. This is currently one of the most important goals in improving neuroanatomy education and the learning of subcortical structures, and remains clinically relevant for both students and professionals working in the field of neuroscience.

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