

BASIC RESEARCH STUDIES

Interpretation of three-dimensional structure from two-dimensional endovascular images: Implications for educators in vascular surgery

R. S. Sidhu, MD, MEd, FRCS(C),^{a,b,c} D. Tompa, MAsc,^c R. Jang, BSc,^c E. D. Grober, MD, MEd,^{b,c} K. W. Johnston, MD, FRCS(C),^{a,b} R. K. Reznick, MD, MEd, FRCS(C),^{b,c} and S. J. Hamstra, PhD,^{b,c}
Toronto, Ontario, Canada

Purpose: Endovascular therapy has had a major effect on vascular surgery; surgeons perform tasks in three dimensions (3D) while viewing two-dimensional (2D) displays. This fundamental change in how surgeons perform operations has educational implications related to learning curves and patient safety. We studied the effects of experience, training, and visual-spatial ability on 3D perception of 2D angiographic images of abdominal aortic aneurysms (AAA).

Methods: A novel computer-based method was developed to produce 3D depth maps based on subjects' interpretations of 2D images. Seven experts (certified vascular surgeons) and 20 novices (medical or surgical trainees) were presented with a 2D AAA angiographic image. With software specifically designed for this study, a depth map representing each subject's 3D interpretation of the 2D angiogram was produced. The novices were then randomized into a control group and a treatment group, who received a 5-minute AAA anatomy educational session. All subjects repeated the exercise on a second AAA image. Finally, all novices were given tests of visual-spatial ability, including the Surface Development Test and the Mental Rotations Test. Comparisons between experts and novices were made with depth map comparison, a subject's perception of overall object contour.

Results: The depth maps were significantly different (depth map comparison, $P < .001$) between the expert and both novice groups for the first image. After the educational intervention, the control group and the treatment group exhibited significantly different depth maps (depth map comparison, $P < .001$), with treatment group depth maps more similar to those of the expert group. There were no significant correlations between the visual-spatial tests and the novice depth map comparison with the expert group.

Conclusions: This is the first study to examine perception of endovascular images in an educational context. Perception of overall surface contour of 3D structures from 2D angiographic images is affected by experience and training. With application of methods of vision science to an important problem in surgery, this research represents a first step in understanding the nature of visual perceptual processes involved in execution of an increasingly common clinical task. These results have implications for understanding and studying the endovascular learning curve. (*J Vasc Surg* 2004;39:1305-11.)

Clinical Relevance. This research represents a unique collaboration in an effort to understand and solve one of the greatest problems facing surgical educators and surgeons. This research uses applied tools in vision science to understand the perceptual constraints involved in minimally invasive surgery. Specifically, we examined the mental three-dimensional maps experts use when viewing two-dimensional displays. Furthermore, we compared experts with novices in an effort to assist surgical trainees.

Minimal access techniques have dramatically influenced every surgical specialty.¹ With advances in angiographic technology the development of minimally invasive methods has had a major effect on the practice of vascular surgery.²

From Division of Vascular Surgery,^a Department of Surgery,^b Wilson Centre for Research in Education,^c Faculty of Medicine, University of Toronto.

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Reprint requests: Ravindar S. Sidhu, MD, Toronto General Hospital, Centre for Research in Education/Surgery, 1 Eaton S, Rm 1-565, 200 Elizabeth St, Toronto, Ont M5G 2C4, Canada (e-mail: raviparv@hotmail.com). 0741-5214/\$30.00

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Fig 1. Example settings of the gauge figure at multiple points on a geometric image.

pital stay, and time off from work.¹ Despite these benefits, significant challenges have been noted.^{1,3-6} The equipment and technology required for minimal access surgery is expensive; the assessment of safety, efficacy, and effectiveness of minimal access surgery procedures compared with conventional procedures is in its infancy; and, most important, educational issues have proved to be a significant hurdle to the widespread dispersion of minimal access surgery techniques.

Choi et al⁷ reviewed trends in abdominal aortic aneurysm (AAA) repair by trainees at Washington University in St Louis, Mo. In 1995 a typical vascular surgery trainee performed 4% of AAA repairs with an endovascular approach, compared with 75% in 2000. The adoption of this new technology has significant educational implications; surgeons and trainees are learning the procedures together, and are faced with having to quickly acquire new perceptual and psychomotor skills. Compared with conventional open surgery, the skills required, techniques performed, and equipment used are radically different. Taken together, these factors are responsible for the well-described “learning curve.”⁸

The issues of learning curves, three-dimensional (3D) perception, and emergence of minimal access surgery are particularly important and timely with respect to AAA repair. A two-dimensional (2D) representation of a 3D structure as the sole visual input in performance of an operation is a major departure from traditional “open” vascular surgery. In endovascular surgery, findings on a 2D display place limits on accurate judgment of depth while manipulating instruments, catheters, and guide wires, and on recovery of information about the 3D structure of complex tissue. Eliminating direct visualization and interaction with tissues in the “real” 3D surgical environment has fundamentally altered the art of surgery.

There have been few studies concerning visual perception in minimal access surgery.^{3,6,9,10} Most of these studies focused on laparoscopic surgery, and emphasize the lack of research into visual perceptual factors in minimal access surgery. No studies have looked at visual perception issues in endovascular surgery. In recent pilot work¹¹ we developed a measurement tool for an individual’s judgment of 3D structure from depiction in 2D, based on the basic vision science work of Koenderink et al.^{12,13} With this tool it is possible to develop 3D profiles of an object (depth maps) based on a subject’s interpretation of relevant 2D cues. Hence a method now exists to enable measurement of how much depth an individual sees in each part of a given 2D clinical image.

The current study is the first application of this technology to surgical images in an educational context. The following research questions were addressed: Do vascular surgeons and novice trainees differ in their perception of 3D from 2D clinically relevant images? Does an educational intervention affect novice performance? Does innate visual-spatial ability predict novice performance?

METHODS

The study was conducted in the Visual Perception Laboratory, Toronto General Hospital, University of Toronto, Canada. Ethics approval was obtained from the institutional ethics review committee. Experts (certified vascular surgeons) and novices in vascular surgery (first-year, second-year, or third-year postgraduate trainees in surgery or trainees in nonsurgical disciplines) were invited to participate in the study. Novices were excluded if they had been previously assessed with any of the visual-spatial tests or if they had participated in more than five open AAA repairs.

Assessment instruments

Assessment of 3D structure: Surface attitude measurement. Each subject was presented with a 2D depiction of a 3D structure on a computer monitor. Judgments of local surface attitude were made at multiple points on the image. To capture these judgments of surface attitude, each subject used a computer mouse to orient a special depth gauge figure.

This gauge figure consists of two concentric rings with an axle running perpendicular through the center of the rings (Appendix, online only). To generate a subject’s 3D interpretation of the 2D image, the gauge figure was presented at multiple preselected points on the image. For each point, the subject’s task was to orient the gauge figure in such a manner that the rings appeared tangential or “painted on” the perceived surface of the 3D structure of the object at that point; hence the axle was perpendicular to the perceived surface of the 3D structure of the object at that point.

Once the subject was satisfied with the local surface attitude setting, it was recorded with a mouse click. The gauge figure was then removed, and the subject was presented with another gauge figure in a new random location



Fig 2. Anteroposterior angiographic images of an abdominal aortic aneurysm used in phase I (*left*) and phase III (*right*).

on the display. This was repeated until a map of the entire display was obtained (Fig 1).

Assessment of visual-spatial ability: Test details. The Surface Development Test requires mental visualization of how a 2D piece of paper can be folded to form a particular 3D object. The Mental Rotations Test requires mental rotation of 2D depictions of 3D objects. These tests involve higher level visual-spatial abilities that may be similar to those required to successfully interpret endovascular images.

Experimental procedure

Orientation. All subjects were given an introduction to the basics of angiography, AAAs, and the surface attitude gauge figure tool.

Phase I (first image, 30 minutes). All subjects, both novices and experts, were asked to assess surface attitude at 80 points of an anteroposterior angiographic image of an AAA (Fig 2), and depth maps for each subject were generated. The 80 points were selected to include the infrarenal neck and proximal portion of the AAA on the angiogram, a segment with significant change in contour.

Phase II (treatment phase, 5 minutes). Novices were randomized to two groups: a control group and a treatment group. Subjects in the treatment group were given a 5-minute teaching session (educational intervention), which included a review of multiple angiograms and 3D computed tomographic reconstructions of anatomic changes in AAAs. This intervention was designed to simu-

late a typical educational session that might be given to a novice resident during a rotation in vascular surgery.

Phase III (second image, 30 minutes). All subjects, both novices and experts, were asked to repeat the surface attitude exercise at 78 points on a new anteroposterior angiographic AAA image (Fig 2). The 78 points were again selected to include the infrarenal neck and proximal portion of the AAA on the angiogram.

Phase IV (visual-spatial testing, 20 minutes). All novice subjects were administered tests of visual-spatial ability (Surface Development Test, Mental Rotations Test). Expert subjects were not given the Mental Rotations Test or Surface Development Test; this group was assumed to be “expert,” regardless of innate visual-spatial ability.

Data analysis

Generation of depth map. During the surface attitude task the subject adjusted the gauge figure for each point on the image, to produce an estimate of slant and tilt, which represent the angular deviation from a flat fronto-parallel plane. These estimates are combined across the entire surface to create a measure of the subject’s perception of 3D structure. This produces the subject’s perceptual 3D depth map. Details of depth map generation are given in the Appendix (online only).

Outcome measures. Visualization of 3D structure on the angiographic images was measured in three ways: depth map comparison, surface perception error, and novice depth map comparison with the expert group.

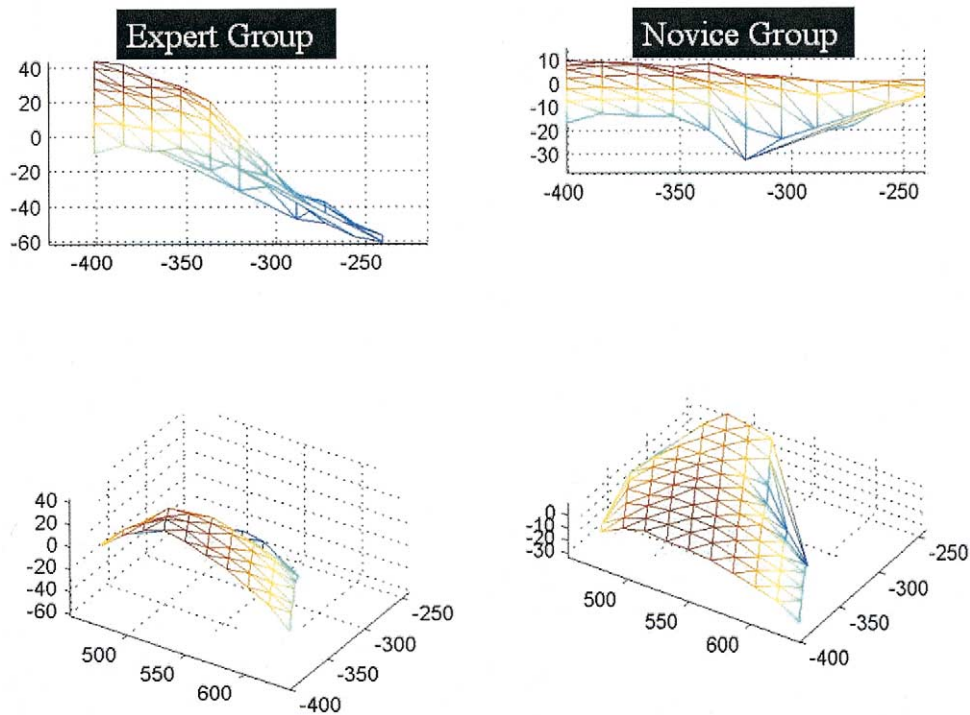


Fig 3. Example depth maps generated by a member of the expert group (*left*) and a member of the novice group (*right*) in phase I.

Depth map comparison (overall object contour). Depth map comparison is a subject's perception of overall object contour. Depth map comparison is calculated as a pairwise comparison with the Spearman rank correlation. It compares all depth values for one subject's depth map with another's depth map. Depth map comparison for all pairwise comparisons of one group can be averaged to obtain a depth map comparison mean for that group; this value represents the similarity in perceived shape among members of that group. In addition, depth map comparison was used to compare groups by averaging the pairwise comparisons between members of different groups; this value represents the similarity in perceived shape between different groups. See the Appendix (online only) for details.

Surface perception error. Surface perception error is a measure of the degree to which a subject perceives a coherent surface. With use of the gauge figure settings, an estimate of the subject's 3D surface structure is calculated. Surface perception error is based on the residual error from the best-fitting surface by method of least squares. It is defined as the root mean squared deviation of the fitted surface with respect to the calculated depth of the individual gauge figure settings. A high surface perception error value indicates more error in coherent surface perception. The lower the value the more the perceived 3D structure represents a coherent surface.

Novice depth map comparison with expert group. Accuracy of 3D shape perception is defined as the degree to which each novice is similar to the expert group, specifi-

cally, the mean of the depth map comparison values of each novice with each member of the expert group. This measure was used to assess the correlation between visual-spatial ability and perceived 3D structure.

RESULTS

Participants. Seven experts and 20 novices participated in the study. All members of the expert group were certified vascular surgeons. Of the 20 novices, 17 were junior surgical trainees (postgraduate year 1, 2, or 3), two were internal medicine trainees, and one was an anesthesiology trainee. Ten novice subjects were randomized to the control group, and 10 subjects were randomized to the treatment group. All recruited subjects completed the study. No subjects were excluded; all novices had participated in fewer than five open AAA repairs.

Experts versus novices in phase I. There was a significant difference in perception of overall object contour (depth map comparison) between the novice group and the expert group. The relationship between the novice and expert groups (mean depth map comparison between groups, 0.840 ± 0.109) was significantly different ($t_{[329]}, 4.39; P < .001$) compared with the perception of overall shape contour within the novice group (mean depth map comparison within novice group, 0.883 ± 0.070). That is, the novices' depth maps correlated highly with one another, but poorly (statistically significant) with those of the expert group.

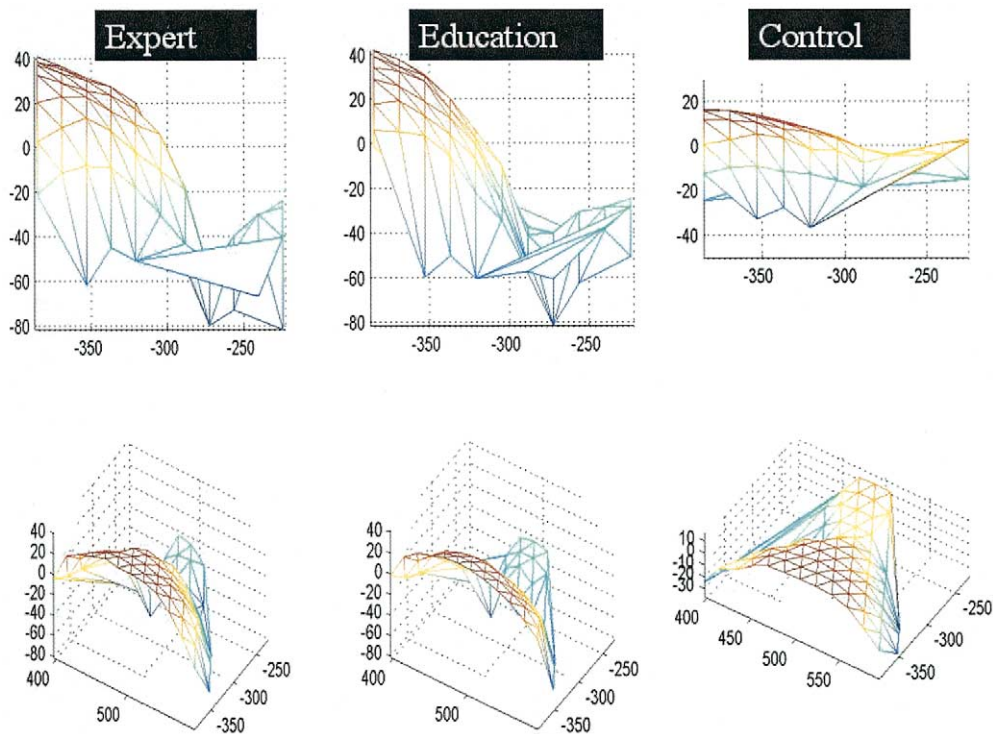


Fig 4. Example depth maps generated by a member of the expert group (*left*), a member of the treatment group (*center*), and a member of the control group (*right*) in phase III.

The experts had more elaborate perceived 3D structure compared with the relatively flat perception of the novices. Representative depth maps generated from a typical expert and a typical novice for phase I are presented in Fig 3. These depth maps highlight the statistically significant differences in overall contour of the perceived 3D structure of the AAA.

There was no significant difference in mean surface perception error values for the novice group (3.34 ± 1.33) and the expert group (3.04 ± 1.22 ; $t_{[25]}$, 0.524; $P = .61$).

Effect of educational intervention. After the educational intervention there was a significant difference in perception of overall object contour between the treatment and control groups; the treatment group was more similar to the expert group. The mean depth map comparison between-group value representing the treatment group–expert group relationship (0.939 ± 0.038) was significantly higher ($t_{[138]}$, 4.96; $P < .001$) than the mean depth map comparison between-group value representing the control group–expert group relationship (0.891 ± 0.072). In phase III the expert and treatment groups both had more elaborate perceived 3D structure compared with the relatively flat perception of the novices in the control group. Example depth maps generated for an expert, a treatment group novice, and a control group novice for phase III are shown in Fig 4. These depth maps highlight the statistically significant differences between groups in overall contour of the perceived 3D structure of the AAA.

The mean surface perception error values for the control group (4.62 ± 2.66) and the treatment group (5.13 ± 1.31) were not significantly different ($t_{[18]}$, 0.541; $P = .595$) in phase III.

Visual-spatial ability and perceived 3D structure. There were no significant correlations between how similar novice perception was to that of the expert group (novice depth map comparison with expert group) in phase I, and either the Mental Rotations Test ($r = 0.05$; $P = .84$) or the Surface Development Test ($r = 0.108$; $P = .65$).

DISCUSSION

Differences between experts and novices. Despite a paucity of literature, it is widely accepted in medicine that the interpretation of a clinically relevant 2D image relies as much or more on training and experience as it does on the actual physical cues present on the image. The results of the current study support this contention.

With respect to object contour, experts differed significantly from novices in perception of the 3D structure of an AAA when presented with an angiographic image. Such images are relatively simple (2D gray-scale x-ray films), yet experts consistently “perceived” more elaborate 3D structure than novices did. To our knowledge, this is the first study to quantify and capture these perceptual differences related to experience, exposure, and training.

These findings have important implications for further research in this area. Perception of surgical images can now

be quantified. With further technical refinements, perceptual measurements may eventually be made during routine clinical activity on a variety of relevant images. Also, by demonstrating that this tool enables measurement of perceptual differences existing between subjects with different levels of training or experience, there is evidence for its construct validity.

We found no significant differences in surface perception error scores between experts and novices, which suggests that both groups perceived a coherent surface to the same extent, albeit the contour of the perceived surface was different between the experts and novices. There were enough visual cues on the image that novices were able to perceive a coherent 3D structure. However, it seems they were unable to “perceive” as much depth or contour as experts viewing the same image. Because members of the novice group had all participated in fewer than five open AAA repairs, meaningful analysis of perception on the basis of experience in that group was not possible.

The focus of this study was on expert-novice differences. As education researchers, we were primarily interested in what experts perceive, what novices perceive, and how novices can be made to become more like experts. By virtue of their experience and training, we assumed the experts have a better visual-spatial “construct” of AAAs than novices do. Given that the measurement variables are all relative (depth map comparisons), mathematical comparison with the actual object is not possible. With future research we hope to address this issue.

There has been concern regarding how to best teach and disseminate minimal access surgery procedures while maintaining patient safety during the “learning curve.”^{5,7,14-16} To further understand this learning curve, the implications and limitations of operating in 3D while viewing in 2D must be studied. The results of the current study provide a foundation for this important research, that is, development of a valid, quantitative method to measure 3D perception of 2D images in a surgical context.

Effect of educational intervention. After a simple educational intervention that simulated a real-life clinical exercise, the treatment group differed significantly from the control group with respect to object contour in the 3D perception of an AAA when presented with an angiographic image. Furthermore, the perception of the treatment group was more similar to that of the expert group.

Significant effect was achieved with the teaching session. However, the novices did not become experts after a brief training intervention. Possible reasons for the great improvement in novice performance after the training session include the unique nature of the session, with emphasis on morphologic features and structure; lack of sensitivity with the perception measurement instrument; and a relatively small contribution of visual-perception to the construct of expertise. Further research is necessary to clarify the relevant contributions of these issues to the findings of this study.

To our knowledge, this is the first study to describe the effect of an educational intervention by quantifying a

change in the 3D perception of clinical images. This offers further evidence that appropriate training can affect clinically relevant 3D perception. These results should prompt clinicians to consider modifying instructional content. Traditionally, knowledge imparted by surgeons and textbooks is relative to diagnosis, epidemiology, treatment, and decision-making. There is little or no “geometric” information about structure or anatomy of tissues; however, this may be important, given the relevance of this information in this era of minimal access surgery and the current findings that perception can be altered by instruction. The effect of such teaching may then become the subject of further research.

Visual-spatial ability and perception of angiographic images. Visual-spatial ability did not correlate with novice performance in this study. These results are contrary to those of Wanzel et al,^{17,18} who demonstrated that visual-spatial ability correlated with the surgical performance of trainees during a spatially complex procedure. Of interest, Wanzel and colleagues also found that a training intervention eliminates novice differences in performance related to visual-spatial ability, which suggests that, although important, innate visual-spatial ability is outweighed by factors such as training and experience. We speculate that in the current study it is likely that these factors were much more important than innate visual-spatial ability in the context of interpretation of angiographic images.

Limitations of the study. This study was conducted in a controlled environment. In reality, interpretation of surgical images and performance of operations take place in a wide variety of environments, with differing levels of noise, light, and equipment quality. The decision to perform the study in a controlled environment, and hence sacrifice face validity, was made in an effort to ensure that differences in results could be attributed to experimental factors.

Perception of 2D images in a minimally invasive environment occurs in real time with motion of tissues and instruments (dynamic imaging). Given that there was little research in this field, as an initial approach we decided to address perception of static images only. Although further research is required to assess dynamic perception, we believe the principles established with the current research will remain the same.

Perceptual issues in the context of the endovascular learning curve. As with traditional surgery, endovascular surgery requires a multitude of skills that must be attained to become a competent surgeon. Perceptual issues may explain only a portion of the learning curve. For example, in addition to viewing 2D displays there are numerous other learning issues that merit further attention. For example, surgeons are also using long, awkward devices; they are viewing anatomy from a different perspective; some of the techniques used in traditional surgery cannot be performed because they require manual manipulation or retraction; and patient anatomy is altered by the method of obtaining access (eg, anatomic distortion during implantation of large endovascular stent grafts). The effect of these factors must

also be assessed. The results of this study must be taken in context of the entire problem of educating surgeons. Although perception is one of the most obvious factors, its relative contribution to acquisition of surgical skill and the performance of surgery remains speculative.

This is the first study to examine perception of surgically relevant endovascular images. By application of methods of vision science to an important problem in surgery, this research represents a first step in understanding the nature of visual perceptual processes involved in the execution of an increasingly common clinical task.

CONCLUSIONS

Expert surgeons and novice trainees differ significantly with respect to 3D perception of 2D angiographic images.

Novice perception of 3D from 2D images becomes more similar to that of experts after a short educational intervention.

Innate visual-spatial ability does not correlate with accuracy of perceived 3D structure of angiographic images among novices.

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