Alternative Strategies in Processing 3D Objects Diagrams: Static, Animated and Interactive Presentation of a Mental Rotation Test in an Eye Movements Cued Retrospective Study

Jean-Michel Boucheix and Madeline Chevret

University of Burgundy, LEAD-CNRS, Dijon, France
Jean-Michel.Boucheix@u-bourgogne.fr,
Madeline.Chevret@hotmail.fr

Abstract. Spatial abilities involved in reasoning with diagrams have been assessed using tests supposed to require mental rotation (cube figures of the Vandenberg & Kruse). However, Hegarty (2010) described alternative strategies: Mental rotation is not always used; analytical strategies can be used instead. In this study, we compared three groups of participants in three external formats of presentation of the referent figure in the Vandenberg & Kruse test: static, animated, interactive. During the test, participants were eye tracked. After the test, they were interrogated on their strategies for each item during the viewing of the replay of their own eye movement in a cued retrospective verbal protocol session. Results showed participants used varied strategies, part of them similar to those shown by Hegarty. Presentation format influenced significantly the strategy. Participants with high performance at the test used more mental rotation. Participants with lower performance tended to use more analytical strategies than mental rotation.

Keywords: Mental rotation, Strategy, Presentation formats, Eye movements.

1 Introduction

Designers, learners, are increasingly working with complex 3D diagrams: for example, students in the medical area often use on screen presentations of virtual organs, sometimes in a user controllable modality. Previous research showed that processing successfully complex diagrams is positively correlated with spatial abilities [1, 2]. In previous research on diagrams processing and comprehension, spatial ability is often assessed with mental rotation test. One of the tests commonly used is the Vandenberg and Kruse test [3] inspired by the principle of the cube figures of Schepard & Metzler, fig. 1. People are shown a standard figure on the left and 4 items on the right. Their task is to decide which of the 4 objects on the right has the same shape as the object on the left. For participants, this task is supposed to involve mental rotation processes. In order to compare the configuration of two figures, the subject needs to create an internal representation of the targeted figure, and is supposed to internally simulate the rotation of the figure to bring it to an angle which allows a comparison with the reference object [1, 2].

T. Dwyer et al. (Eds.): Diagrams 2014, LNAI 8578, pp. 139–146, 2014.

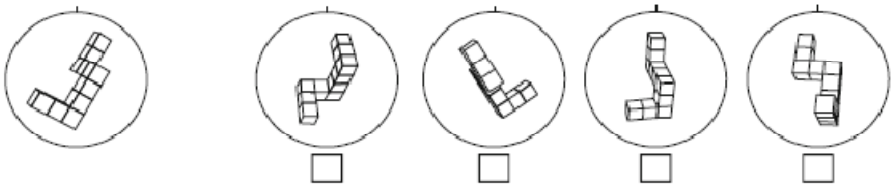

Fig. 1. Example of an item from the Vandenberg and Kruse Mental Rotation test

However, previous research has shown that participants are not always making a mental rotation, but alternative strategies can be used instead [1, 4, 5]. In their study, Hegarty, De Leeuw & Bonura [4], see also Stieff, Hegarty & Dixon [5], used the Vandenberg and Kruse test. Students took a first session of each item of the test. Then gave a think-aloud protocol while solving the items in a second session. Hegarty and colleagues [4, 5] identified several strategies that students used to solve the items. Four main strategies were found. (i) *Mental Rotation* consisted in manipulating or simulating the rotation of the figure. (ii) *Perspective taking* consisted in *"imagining the objects in the problem as stationary, while they moved around the objects to view them from different perspectives"* [5]. Mental rotation and perspective taking are "*imagistic strategies"* [5]. Two others more "analytic" strategies were discovered. (iii) In the "*comparing arm strategy*" participants compared the relative directions of the arms in the standard reference figure to that in each of the four answer choice. (iv) In the "*counting cubes strategy*" participants tried to count the number of cubes in each segment of the reference object and compare that to the other objects in the problem. Participants reported also they used several mixed strategies.

1.1 Strategies and Presentation Format of the 3D Objects

In the present study we followed the line of research initiated by Hegarty and colleagues [1, 2, 4, 5, 6]. The goal was to examine the possible effect of different external presentation formats of the standard reference figure of the Vandenberg test on the strategies used for solving the problem items. Three different presentation formats of each item of the test were designed and proposed to three different groups of participants. In the first format, the left figure was the standard static presentation, fig. 1. In the animated format, the 3D left figure rotated dynamically (and slowly) on itself showing all the different sides of the figure. In the interactive animated format, the participant could rotate the figure on itself, to view all the sides of the object in a user controllable modality. In all formats, the four figures on the right side remained static. The size of the figures was the same in all formats. One main expectation (H1) was that different external formats could elicit varied strategies. Some of them may be different from those found in previous research [4, 5]. Three complementary hypotheses were proposed. (i) (Hc2), the effect of the formats on strategies could be different depending of the participant's performance level at the Vandenberg and Kruse test. (ii) (Hc3) whatever the condition, strategies used at the Vandenberg test

could vary according to performance level at this test (high *vs*. low), but also according to the performance level at another different spatial ability test which measures the spatial orientation abilities, a competence found dissociated from mental rotation [6]. Kozhevnikov & Hegarty [6] showed participants with higher spatial ability level used often the *"comparing arm strategy"* than participants with lower ability level. (iii) (Hc4), animated and interactive figures might "facilitate" mental imagery and improve the performance at the Vandenberg test. However, recent results from Keehner, Hegarty, Cohen, Khooshabeh & Montello [7] showed clearly that *"what's matter is what you see, not whether you interact"* with the diagram.

2 Method

2.1 Participants, Experimental Design and Materials

Fifty eight students participated in the study (*M*age = 20.6 years, 46 females). They were randomly assigned to three groups (4 males in each group) in each format: Static presentation *vs.* Animated, *vs.* user-controlled animated presentation of the left reference figure of the Vandenberg & Kruse test. A computer screen version of the 19 items of the test (plus training items) was designed from the French adapted version. Participant's task is to decide which 2 of the 4 objects on the right have the same shape as the object on the left. Eye movements of participants were recorded during the test (Tobii 120 hz). Responses and reaction times to each item were recorded. A think-aloud verbal protocol second session was undertaken after the end of the test. A microphone connected to the computer recorded the verbal explanation given by each participant about its strategy for each item. Finally the spatial orientation test (Kozhevnikov & Hegarty [6]) was used. This test measures the ability to imagine different perspectives or orientations in space (by drawing arrows). Response accuracy is measured with the size of the angular deviation from the right perspective.

2.2 Procedure

After having completed the training items of the Vandenberg test, each participant eyes were calibrated for eye tracking recording. Then each participant individually undertook the test itself (one item at once). For control matter of the time across the formats, the presentation time of each item was fixed; here 30 sec. per item was given. Participants were told to take their decision as fast as possible. After the test, each participant was shown the replay (slow speed) of his (her) own eye movements. Participants were told to rely on the replay of eye movements, for each item, to think-aloud and explain in detail their own procedure used during the test to find the right figures (25-35 min./subject). This *cued retrospective verbal protocol procedure* based on the traces of dynamic eye movements could strengthen the reliability of the participant's explanation. Finally, each participant completed the spatial orientation test.

2.3 Coding and Analyses Criteria for Dependant Variables

The following variables were analyzed (i) the verbal explanations about strategies (two independent raters), (ii) the performances (means, *SD,* medians) at the Vandenberg test (each correct response was awarded 1 point), (iii) and reaction time (per item). Eye movements were also analyzed as well as the performances at the spatial orientation test. This paper will be focused on the presentation of the results about (i) the strategies at the mental rotation test; (ii) their relation with presentation formats and (iii) with the performance levels at the Vandenberg test and at the spatial orientation test.

3 Results

Varied strategies were found, and the number of times they occur counted. Some strategies were similar to those described by Stieff & al., [5], others were specifically related to the different presentation formats of the standard reference figure.

3.1 Strategies and Presentation Formats

Three "types" of strategies have been distinguished. The First type called "global" strategy was composed of five strategies some of them based on the use of mental rotation of the object: (i) *Mental rotation*. Subjects manipulate and imagine the rotation of the figure as exemplified by the following eye movements' cued retrospective protocol: *"I turned it* (the figure)*, I looked if it corresponded when I turned it in my head"*. (ii) *Looking at the middle* of the figure and turning around it, which seems similar to the "*perspective taking"* strategy. The following protocol is an example: *"*(here) *I look at all the figure, I look around at the overall shape and I compare (to the other figures)"*. (iii) *Mental Completion of the rotation* from the animation. This strategy is taken only by participants' in the animated format. The subjects used the initiation of the rotation of the figure as "a priming" for completing mentally themselves the rotation of the figure. This is exemplified by the following protocols: "*When it* (the figure*) turns, I look if it falls similarly and then I incline it in my head"*; *"I wait until it is running and I anticipate the rotation"* (iv). *Matching*. In the animated condition, participants looked at the external rotation of the left figure and compared each of the position (shape) of the object with the figures on the right. Two examples of participant's protocols using this strategy are as follow: *"I waited and when I saw that the figure arrived at the same position (shape) as another, I selected it"; "I waited until it turns in the same figure"*. (v). *User-control of the rotation*. In the interactive animated format, participants initiated and controlled the rotation of the figure step by step. This strategy was used for aligning the shape of the standard figure on the shape (position) of the figures on the right. The following protocol excerpts are examples: *"*(here) *I try to put it (the figure) in the same position"*; *"I try to place it to see all"*. Secondly, two more "analytical" strategies were found. (i) "*Comparing arm axes*". This strategy was similar to Hegarty & al. [1, 5]. Participants compared the direction of the cubes arms of the left figure to the

directions of the arms of the figure on the right. Here is an example of a protocol: *"I looked more at the orientation ends, I looked at the ends and I tried to see where it was going; here, I focused on the bottom part to see and compare to the top part whether it went over to the right or left most"*. (ii). *"Counting cubes"*. This strategy is also similar to the strategy found by Hegarty [1, 5]. Participants counted the number of cubes of the standard figure and compared it with the cubes of the other figures as exemplified in the following protocol: *"I counted the cubes, I looked at the layouts and I counted"*. Finally, a third strategy type is the use of *Mixed strategies.* In the mixed strategy type, participants used at least an analytical and a global strategy. The number of time each strategy was reported to be used by each subject was counted for each of the 19 items of the test. The data are presented in Table 1.

Table 1. Mean number of times (and SD) each type of strategies was used across conditions

Strategy/ Format	Mental Rotation	Looking Middle	Complet. Rotation	Match	Control rotation	Comp. Arms	Count Cubes	*Mixed*
Static	14.65 (5.16)	3.65 (4.40)	0 (0)	0 (0)	0 (0)	9.60 (6.83)	4.20 (5.97)	*9.70 (6.83)*
Animated	0.79 (1.93)	1.53 (2.96)	0.47 (1.42)	8.90 (5.54)	0 (0)	9.31 (5.42)	7.00 (6.93)	*5.68 (4.70)*
Interactive	6.15 (5.56)	1.68 (3.05)	0 (0)	0 (0)	13.05 (5.69)	10.00 (6.29)	2.05 (2.77)	*3.37 (4.24)*

One way ANOVAs comparing the single individual strategies by condition were performed. For static format, the analysis showed significant differences between strategies in favor of mental rotation, F (3, 57) = 16.1, $p < .001$, $\eta^2 = .45$. For the animated format, significant differences were found between strategies in favor of matching and comparing arms, F (5, 90) = 14.80, $p < .001$, $\eta^2 = .45$. For the interactive format also differences were observed in favor of the control of rotation and comparing arms (F (12, 330) = 23.80, $p < .0001$, $\eta^2 = .46$). This result supports H1. A mean of 3.50 (SD = 0.97) strategies per subject was used. A complementary ANOVA on the number of mixed strategies showed the differences between formats was significant (F (2, 55) = 6.86; $p = .002$ $\eta^2 = .20$).

3.2 Performances at the Test and Presentation Formats

Results for scores and reaction times at the Vandenberg test are presented in Table 2.

Table 2. Mean scores (and SD) and time at the French version of Vandenberg & Kruse test

Format	Static	Animated	Interactive
Scores (out of 38)	18.45 (8.90)	17.21 (8.69)	16.26 (6.03)
Time (in second per item)	19.97 (5.07)	17.91 (3.88)	24.42 (2.39)

The analysis of performances and times results (ANCOVA with time as covariate factor, groups as between subject factor and performance as the dependant factor) indicated that there was no effect of the presentation formats on performances (F (2, 54) = 1.89, p = .16, η^2 = .06). A significant effect of reaction times on the scores was found (F (1, 54) = 5.72, p = .02, η^2 = .10). For results on times, a one factor ANOVA (formats as the between subject factor and reaction times as the dependant variable) revealed a significant effect of formats (F (2, 55) = 13.44, p< .0001, η^2 = .33). Regarding the scores at the spatial orientation test, a one factor ANOVA (with formats of the Vandenberg test as the between factor and the mean size of the angular deviation from the right perspective at orientation test as the dependant variable) showed there was no effect of presentation formats (F (2, 55) = 0.75, *ns*.; M*Static*, 32° (SD = 18.10), M*Animated*, 40.3° (SD = 23.3°); M*Intercative*, 35.23° (SD = 22.01).

3.3 Strategies and Spatial Ability Performances

To explore the relations between the strategies and performances at the Vandenberg test, the distribution of scores at this test was split into high and low performances groups (median for each presentation format) Table 3. Further, in order to examine the relations between strategies used in the Vandenberg "mental rotation" test and performances at spatial orientation test the same technique was undertaken, Table 4.

Table 3. Mean number of times (SD) each type of strategy was used for high and low spatial groups at the Vandenberg test

Strat/Gr		Rot	Look M	Compl	Match	Contr	Arms	Count	Mixed
Stat.	H	15.6 (4.87)	3.08 (3.05)	0 (0)	0 (0)	0 (0)	9.33 (6.64)	2.33 (3.34)	9.25 (6.82)
	L	13.25 (5.6)	4.50 (6.05)	0 (0)	0 (0)	0 (0)	10.0 (7.56)	7.0 (8.01)	10.37 (7.27)
Anim.	H	1.00 (1.91)	0.28 (0.75)	0.57 (1.5)	9.86 (5.58)	0 (0)	9.14 (4.81)	7.14 (9.2)	5.0 (4.86)
	L	0.66 (2.01)	2.25 (3.54)	0.42 (1.44)	8.33 (5.69)	0 (0)	9.42 (5.69)	6.92 (5.71)	6.08 (4.78)
Intera	*H*	*8.37 (4.8)*	*1.50 (3.46)*	*0 (0)*	*0 (0)*	*13.00 (6.3)*	*5.37 (4.17)*	*0.75 (1.38)*	*3.12 (3.39)*
	L	*4.54 (5.73)*	*1.81 (2.89)*	*0 (0)*	*0 (0)*	*13.09 (5.52)*	*13.36 (5.44)*	*3.00 (3.19)*	*3.54 (4.92)*

For the Vandenberg test, a repeated measures ANOVA was conducted on the number of times strategies were used, with spatial group's levels at the test as the between subjects factor and the strategy types (the seven singles) as the within factor. As expected (H3c), the interaction between group's levels and strategies was significant F (6, 336) = 2.45, p = .025, η^2 = .05. High level performers used more Mental rotations (F (1,56) = 5.60, p = .021); and less analytical strategies (comparing

arms axes, counting cubes) (F (1,56) = 7. 04, p = .01) than lower level performers. A similar analysis was conducted with spatial group's level at the orientation test, table 4. The interaction between group's levels and strategy types was not significant (F (6,336) = 0.43, *ns*). Consistent with previous research by Hegarty & al., [1, 2, 4, 5, 6, 7], this result tends to confirm that the orientation test measures a specific competence which is different from mental rotation. The correlation between the two tests, was significant (r (df 58*) =-.53, p < .05)*, this relation was not very high.

Table 4. Mean number of times (SD) each type of strategy was used at the Vandenberg test for high and low performance groups at the Hegarty's spatial orientation test

Strat/Gr		Rot	Look M	Comp l	Match	Contr	Arms	Count	Mixed
Stat.	H	13.8 (6.52)	2.7 (2.98)	0 (0)	0 (0)	0 (0)	11.9 (6.8)	2.2 (3.76)	10.2 (7.71)
	L	15.5 (3.47)	4.6 (5.48)	0 (0)	0 (0)	0 (0)	7.3 (6.36)	6.2 (7.22)	9.2 (6.21)
Anim.	H	0.70 (1.63)	1.00 (1.94)	0.40 (1.26)	9.70 (6.25)	0 (0)	10.40 (5.5)	7.30 (8.42)	6.10 (5.91)
	L	0.89 (2.31)	2.11 (3.85)	0.55 (1.66)	8.0 (4.84)	0 (0)	8.11 (5.39)	6.67 (5.13)	5.22 (3.15)
Interact	*H*	*5.40 (5.6)*	*2.90 (3.87)*	*0 (0)*	*0 (0)*	*12.50 (6.83)*	*8.50 (5.19*	*1.60 (1.83)*	*2.40 (2.54)*
	L	*7.00 (5.72)*	*0.33 (0.5)*	*0 (0)*	*0 (0)*	*13.67 (4.41)*	*11.66 (7.28)*	*2.55 (3.6)*	*4.44 (5.54)*

4 Conclusion and Further Analyses

The goal of this study was to compare the effect, on the use of strategies, of the conditions of presentation of the standard figure in the Vandenberg test: static, animated and user controllable formats. Participants were interrogated on their strategies during the viewing of a replay of their eye movements. Results showed participants used varied strategies, part of them similar to those shown by Hegarty and others new. An animation favors matching; an interactive presentation favors the control of rotation. Participants with high performance at the test used more mental rotation and less analytical strategies than participants with lower performance.

References

1. Hegarty, M.: Components of spatial intelligence. In: Ross, B.H. (ed.) Psychology of Learning and Motivations, vol. 52, pp. 265–297. Elsevier, Amsterdam (2010)
2. Hegarty, M., Waller, D.: A dissociation between mental rotation and perspective-taking spatial abilities. Intelligence 32, 175–191 (2004)
3. Vandenberg, S.G., Kruse, A.R.: Mental rotations, a group of three dimensional spatial visualization. Perceptual and Motor Skills 47, 599–604 (1978)
4. Hegarty, M., De Leeuw, K., Bonura, B.: What do spatial ability test really measure. In: Proceedings of the 49th Meeting, Psychonomic Society, Chicago, IL (2008)

5. Stieff, M., Hegarty, M., Dixon, B.: Alternative strategies for spatial reasoning with diagrams. In: Goel, A.K., Jamnik, M., Narayanan, N.H. (eds.) Diagrams 2010. LNCS (LNAI), vol. 6170, pp. 115–127. Springer, Heidelberg (2010)
6. Koshevnikov, M., Hegarty, M.: A dissociation between object manipulation and perspective taking spatial abilities. Memory & Cognition 29, 745–756 (2001)
7. Keehner, M., Hegarty, M., Cohen, C., Khooshabeh, P., Montello, D.: Spatial reasoning with external visualizations: What matters is what you see, nor whether you interact. Cognitive Science 32, 1099–1132 (2008)