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Applications of mental rotation figures of the Shepard and Metzler type and description of a mental rotation stimulus library

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Abstract

The 3D cube figures used by Shepard and Metzler [Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, *171*, 701–703] have been applied in a broad range of studies on mental rotation. This note provides a brief background on these figures, their general use in cognitive psychology and their role in studying spatial behavior. In particular, it is pointed out that large sex differences with the 3D mental rotation figures tend to be observed only in particular tasks, such as the Vandenberg and Kuse test [Vandenberg, S. G., & Kuse, A. R. (1978). Mental rotations, a group test of three-dimensional spatial visualization. *Perceptual and Motor Skills*, *47*, 599–604] that involve multiple figures within a single problem. In contrast, pairwise presentation of the same 3D figures yields either small or no significant sex differences. In the context of the very broad range of ongoing research done with 3D figures, and the desirability of uniformity in the stimulus material used, we introduce a library of 16 cube mental rotation figures, each presented in orientations ranging from 0 to 360 degr in 5 degr steps, and with its mirror image, for a total of 2336 figures. This library, freely available to researchers, will help in the creation of mental rotation tasks both for presentation on the computer screen and for pencil and paper applications.

Keywords: Mental rotation; Stimuli; Test; Sex differences; Shepard and Metzler; Vandenberg and Kuse

1. Introduction

This short note contains two separate parts. First, there will be a very brief coverage of the nature and applications of three dimensional cube figure mental rotation figures in psychological research and, second, there will be a description of a library of such figures that will allow researchers to address the entire spectrum of research questions touched upon in the first part.

2. Part I

In Linn and Petersen's (1985) meta-analysis of spatial ability, mental rotation was considered a category that was separate from spatial perception and spatial visualization. The mental rotation of visual objects can be studied with a variety of figures, both two dimensional and three dimensional. Two dimensional stimuli, such as letters or nonsense figures of varying complexity, can only be rotated in the picture plane while three dimensional stimuli can be rotated in depth as well. The vast majority of mental rotation studies with three dimensional stimuli have been based on figures composed of cubes and the seminal study using such figures was published by Shepard and Metzler in Science, in 1971 (Shepard & Metzler, 1971). The figures are presented as two-dimensional visual images that are constructed of 10 cubes and are perceived as three dimensional figures. They are generally referred to as 3D figures even

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though a more correct description would label them as "quasi - 3D" figures because the figures are rendered only in two dimensions (Deregowski, 1979). In the Shepard and Metzler paradigm subjects were presented with a pair of cube stimuli where one figure was rotated with respect to the other, and one of the figures could be identical to or a mirror image of the comparison figure. The task for subjects was to decide, quickly and accurately, whether the two figures were the same or different. Much of the research based on Shepard and Metzler's work asked the question of how subjects rotate figures in their mind's eye and was thus directed at fundamental neurocognitive mechanisms (cf. Kaushall & Parsons, 1981; Shepard & Metzler, 1988; Thomsen et al., 2000; Waszak, Drewing, & Mausfeld, 2005) of spatial perception.

A different application of the Shepard and Metzler figures was introduced by Vandenberg and Kuse (1978). They used the S/M figures to create a pencil and paper test for spatial abilities. One consequence of the availability of a paper and pencil test was the facilitation of studies of individual and group differences, with a focus on the testing of larger groups of subjects. Much of the work done with this or similar tests is correlational in nature, where the research question takes the form "does performance on this test correlate with specific individual characteristics or performances on other tasks"? Examples for this type of research are: is there a relation between mathematical/scientific interests and spatial ability (Casey, Nuttall, & Pezaris, 1997; Geary, Gilger, & Elliott-Miller, 1992; Peters, Lehmann, Takahira, Takeuchi, & Jordan, 2006), does mental rotation performance predict choice of field of surgery and ability in surgeons (Anastakis, Hamstra, & Matsumoto, 2000; Brandt & Davies, 2006; Hedman et al., 2006; Wanzel et al., 2003), or are changes in hormone levels during the menstrual period reflected in mental rotation performance (Hausmann, Slabbekoorn, Van Goozen, Cohen-Kettenis, & Gunturkun, 2000)? However, by far the most common application of the Vandenberg and Kuse test is as prototypical test for sex differences in spatial ability. The sex differences reported initially by Vandenberg and Kuse proved to be reliable and large. Linn and Petersen (1985) summarized the findings of their meta-analysis of sex differences by stating that "We found larger effects at all ages for the Vandenberg and Kuse (1978) version of the Shepard–Metzler mental rotation test than for the other measures of mental rotation "(p. 1487). This conclusion has stood the test of time (Voyer, Voyer, & Bryden, 1995). In much of the research that has followed the original Vandenberg and Kuse paper, it is the sex difference, be it in the context of cultural influences (Quaiser-Pohl & Lehmann, 2002), multicultural comparisons (Peters et al., 2006), or hormonal influences on mental rotation performance (Yang, Hooven, Boynes, Gray, & Pope, 2007), that has received most attention.

While Linn and Petersen provided an extensive discussion of the work done by Shepard and Metzler and others who worked with the "pairwise" presentation paradigm, they did not note the fact that sex differences were not commented upon in these earlier studies. In seeking reasons for the discrepancy between the "pairwise" presentation paradigm and the presentation used in the Vandenberg and Kuse test, a partial explanation can be found in the experimental designs that are favored in studies that examine basic mechanisms as opposed to individual and group differences. In most of the studies by Shepard and Metzler and their successors, small numbers of subjects were given large numbers of trials. Due to interindividual differences in performance and the small number of subjects, it would have been more difficult to detect sex differences under these conditions and this may account for part of the discrepancy. However, even when larger numbers of subjects are tested, the sex differences on the "pairwise" (henceforth referred to as "S/M") presentation tend to be either nonsignificant or notably weaker than for the "V/K" presentation (Butler et al., 2006; Peters, 2005; Voyer et al., 2006). One possible explanation for the weaker effects for sex with the S/M presentations lies in the individual problems used in this and the Vandenberg and Kuse test. In the V/K presentation, subjects are shown a target figure derived from the Shepard and Metzler figures, and four comparison figures that are arranged to the right of the test figure. Two of these figures are rotated versions of the test figure and two are not. Thus, in performing mental rotations with the comparison figures, subjects have to identify which comparison figures match the target figure and which do not.

The most salient differences between the S/M presentation and the V/K test are as follows. In the pairwise presentation, eye movement travel is limited to travel between the two figures. In contrast, solution of the V/K problems requires more extensive eye movement travel between the five figures because the solution of each of the V/K problems (Vandenberg & Kuse, 1978) is based on multiple comparisons rather than only one. At the very least, the target figure has to be compared with each of the comparison figures and subjects have to ascertain that they do not make false positive choices or false negative choices for each of the four figures, and in each case the eye travel trajectory is farther than is the case for the pairwise S/M presentations. To the extent that for each comparison some processed version of comparison figure has to be kept in memory so that it can be compared to the target figure, the memory load for such comparisons must be appreciably higher for the V/K problems than for the S/M presentation. In particular, while the S/M presentation allows the subject to concentrate on two figures only, with no requirement to inhibit interference from a previous stimulus pair, the V/K presentation requires rapid switching between stimulus pairs that have to be "assembled" from the range of choices available, with active inhibition of interference from other stimulus pairs that are in play for the duration of dealing with a given problem.

There also is the factor of time in the solution of mental rotation problems. Traditionally, in the Shepard and Metzler paradigms, the reaction time is noted whenever a decision is made. Thus, subjects perform a given number of problems and this does not change as a function of the speed of solution for each individual problem. In contrast, for the V/K problems, there is a specific span of time provided for the entire test that is generally insufficient to solve all problems. As a result, if more time is spent on a given problem, this affects the time available for the remaining problems and the time pressure is acute. In short, there are several differences in the designs involving S/M presentations and the V/K test, all of which can contribute to the differences in the magnitude of sex effects observed for the two paradigms. It may well be that there is an additional factor in the observation of solid sex differences with the V/K but not with the S/M stimulus presentations, and this may not reside in the stimuli themselves but in the way in which the two sexes look at the stimuli. If it is the case that females are more likely to examine given stimuli in thorough detail, they may extract more information from the mental rotation stimuli than is necessary to make a quick and accurate "same/different" decision. In the case of the pairwise S/M presentation, this would not be as much of a problem because there is not so much detail to be looked at. In contrast, the much richer visual presentation of the V/K presentation invites dwelling on detail to a much greater extent. This controversial speculation (controversial because it does not emphasize the role of mental rotation ability as such) is influenced by the observation that females tend to take in more information for some stimulus presentations than males (Silverman, Choi, & Peters, 2007). This tendency might be advantageous in some situations, as in the Silverman spatial memory task (Silverman & Eals, 1992), but not in others, as in the V/K task. Manipulation of the visual detail but not of the basic rotation requirements of the mental rotation stimuli might address this possibility.

The entire discussion of sex differences in relation to the different forms of stimulus presentation is, in principle, not necessary because of the historically different applications of the S/M and V/K presentations. However, in the context of the study of sex differences, the present discussion is necessary for two reasons. First, the general statement that mental rotation tasks are the tasks of choice when large sex differences in spatial performance are to be demonstrated needs to be qualified. Not all mental rotation tasks are equally suitable for this purpose and the S/M presentation paradigm is weak at best in terms of demonstrating sex differences. Second, in recent work with mental rotation and sex differences in brain activation patterns, the S/M presentation figures are preferred over figures that do not employ pairwise presentation (Jordan, Heinze, Lutz, Kanowski, & Jancke, 2001; Jordan, Wuestenberg, Heinze, Peters, & Jaencke, 2002; Thomsen et al., 2000; Voyer et al., 2006). Obviously, this is not because this form of mental rotation task is most useful in determining sex-related activation differences in mental rotation. Instead, the temporal restrictions especially for fMRI procedures work best with tasks that are quick and discrete rather than ongoing.

It is obvious from the preceding discussion that the study of mental rotation abilities, as based on the original Shepard and Metzler stimuli, has many facets and continues at a high level of intensity. In experimental psychology, this is one of the few cases where a comparatively similar set of stimuli is used across a wide variety of work. However, standardized stimuli are not used and it seemed appropriate to provide a library of mental rotation stimuli that is sufficiently large to meet the needs of a broad community of archers. Such a library is described below.

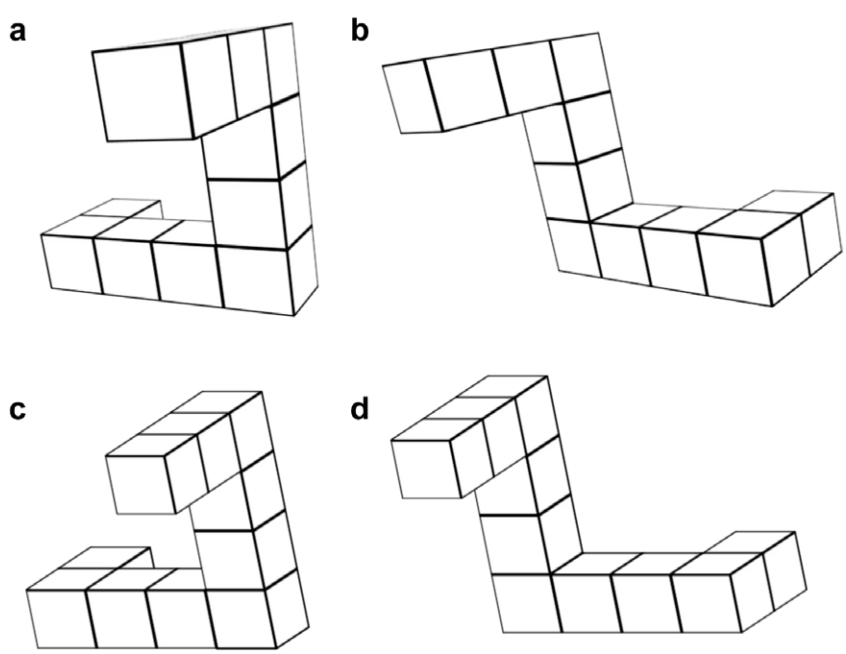

Fig. 1. The first pair shows a figure and its mirror image, drawn in perspective. The second pair shows the same figures, drawn orthogonally.

3. Part II

The stimulus library. Researchers who work with the Vandenberg and Kuse test tend to use either the original version of the test, much deteriorated because it is available only in various degrees of visual degradation, or a redrawn version that was provided by Peters et al. (1995). In contrast, researchers working with the S/M paradigm tend to create their own stimuli. To the extent that similar types of stimuli are used in both paradigms, and because both paradigms continue to be widely used, we decided to provide an extensive library of individual stimuli that can be used to create V/K and S/M tasks of any kind. This library contains 16 different figures. Each, consistent with Shepard and Metzler's approach, is composed of 10 cubes. In drawing the figures, we have tilted them by 15 degr from the vertical axis. This is done so that when rotated versions are given, the number of cryptic images that would arise if a branch were entirely occluded by a column of cubes in a face-on presentation are minimized. Each figure is rendered in 5 degr steps of rotation from the basic orientation, from 0 to 360 degr. The same is done for a mirror image of each of these figures. Thus, the basic number of figures in the library is $73 \times 16 \times 2$, for a total of 2336 images. Images are available for all three cardinal axes of rotation, and thus a total of 3×2336 images are available. A comment needs to be made about the axes of rotation. Conventionally, when two-dimensional coordinates are given, the vertical axis is designated as the Y axis (ordinate) and the horizontal axis is designated at the X axis (the abscissa). However, and this is also a matter of convention (Watt, 2000), when a third axis is added, the vertical axis is designated as the Z axis. The axis that is in the horizontal plane is designated as the X axis and the axis that provides the depth dimension is designated as the Y axis. Thus, in the stimulus library, when it is stated that one of the sets of stimuli is rotated around the Z axis, this means that the stimuli are rotated in 5 degr steps around the vertical axis (imagine a skater spinning around the vertical axis). Rotation around the X axis denotes rotation around the horizontal axis (imagine a log spinning in the water) and rotation around the Y axis denotes rotation around the axis in depth (imagine a propeller rotating around the drift shaft as viewed by the pilot of a single engined plane).

In creating the images, the question arose as to whether perspective or orthogonal drawings should be used. There is no clear reason to favor one over the other. The perspective drawings have the advantage that convergence and relative size cues add to the illusion of depth. However, as Fig. 1a and b illustrate, perspective drawings can produce rather different looking mirror images because of the way the graphics software creates these images. In orthogonal drawings the illusion of depth created by the inherent structure of the figure is quite powerful even though there is no convergence of parallel lines Fig. 1c and d. Moreover, the mirror figures that are created with the orthogonal approach look very similar to each other. For these reasons

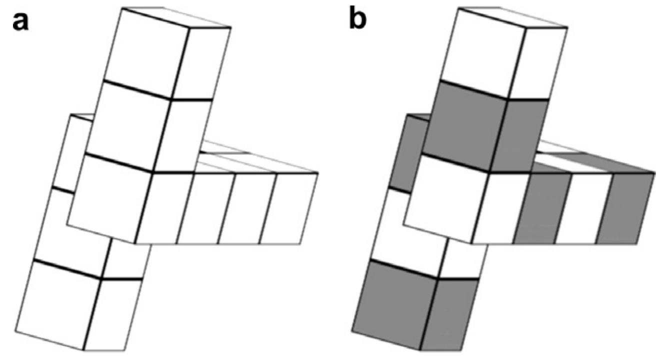

Fig. 2. This pair shows an orthogonally drawn figure with and without alternation of white and gray cube surfaces.

we have opted to draw the stimuli with the orthogonal method.

A second issue is whether the figures should be drawn in plain white as a wire frame figure, or with alternating black and white cubes (Fig. 2). The latter method offers the advantage of providing a clearer picture in cases where the rotation leads to a "crowding" of cubes, and alternating black and white cubes allow a better distinction between cubes. This is why some researchers have opted to use black and white alternating cubes (cf. Jordan et al., 2002). To the extent that black and white alternating cubes are different from the cubes used in the original research, the stimulus library provides both types.

Finally, there is the issue of the background. The stimuli have been used against a dark background and a light background. For computer presentation this makes little difference. However, if the stimuli are used to compose paper and pencil tests, a dark background is impractical because of the unnecessary use of toner. The stimulus library provides both versions, with stimuli presented on a white or a gray background.

Thus, the series of 2336 stimuli that are provided in the stimulus library are available in the three cardinal axes of rotation, and for each of these three axis rotations the stimuli are available as wireframe stimuli or as stimuli constructed with alternating black and white blocks.

The entire set of stimuli is available on a dark or a light background and in either a jpg or bmp format. The jpg format offers the advantage of compression but jpg images do deteriorate with repeated saving while bmp images do not.

It is our intent to make the stimulus library freely available to all interested researchers.[2]

[2] In the short term, the stimulus library will be available for researchers on DVD. Please allow for the cost of the blank DVD, mailing cost, and a nominal charge for writing the DVD. Either one of the authors can be contacted. (mpeters@uoguelph.ca, battista.christian@gmail.com). For the longer term, and in order to ensure continued access to the resource, we endeavour to make the stimulus library accessible through the website for the psychology department at the University of Guelph, and through the facilities of the library of the University of Guelph.

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