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Sex differences in mental rotation and spatial rotation in a virtual environment

Thomas D. Parsons[a], Peter Larson[a], Kris Kratz[a], Marcus Thiebaux[b], Brendon Bluestein[a], J. Galen Buckwalter[c,*], Albert A. Rizzo[d]

[a] *Fuller Graduate School of Psychology, Pasadena, CA, USA*
[b] *Information Sciences Institute, Marina del Rey, CA, USA*
[c] *Southern California Kaiser Permanente Medical Group, 100 S Los Robles, Second Floor, Pasadena, CA, USA*
[d] *Andrus Gerontology Center, University of Southern California, 3715 McClintock Ave, University Park, MC-0175, Los Angeles, CA 90089, USA*

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Abstract

The visuospatial ability referred to as mental rotation has been shown to produce one of the largest and most consistent sex differences, in favor of males, in the cognitive literature. The current study utilizes both a paper-and-pencil version of the mental rotations test (MRT) and a virtual environment for investigating rotational ability among 44 adult subjects. Results replicate sex differences traditionally seen on paper-and-pencil measures, while no sex effects were observed in the virtual environment. These findings are discussed in terms of task demands and motor involvement. Sex differences were also seen in the patterns of correlations between rotation tasks and other neuropsychological measures. Current results suggest men may rely more on left hemisphere processing than women when engaged in rotational tasks.

Keywords: Virtual reality; Cognition; Neuropsychological assessment; Gender differences; Mental rotation task; Neuropsychology

1. Introduction

The ability to mentally rotate an object has been found to produce one of the largest sex differences in the cognitive literature (Linn & Petersen, 1985). In the first studies of mental rotation, Shepard and Metzler (1971) reported a near perfect linear relationship between the reaction time to decide if two drawn objects were the same or different, and the degree of rotational difference between the objects. Using block drawings based on Shepard and Metzler's work, Vandenberg and Kuse (1978) created the mental rotations test (MRT). This test uses line drawings of block stimuli and consists of two 10-item sections in which the subject is required to match two of the four choices to a target figure.

Voyer, Voyer, & Bryden's (1995) meta-analysis of sex differences in spatial abilities, found that the average difference (using Cohen's $d = (M_1 - M_2)/\sigma$) between men and women on the (MRT; Vandenberg & Kuse, 1978), was 0.94 (this represents a very large effect), indicating that men perform nearly one standard deviation above the average performance of women.

A number of explanations have been advanced for the existence of the gender difference in mental rotation. One line of research considers environmental and socio-cultural explanations for sex differences in mental rotation (Sharps, Welton, & Price, 1993). It has been argued that Western cultures perceive spatial tasks as masculine in nature, and that differences in spatial ability might be minimized by engendering the perception that spatial tasks are appropriate for female participants as well as male participants (Lunneborg, 1984; Richardson, 1994; Subrainmanyam & Greenfield, 1994). A second type of explanation for MRT sex differences has emphasized the role of performance factors—task variables that might spuriously inflate the male performance advantage in mental rotation (Goldstein, Haldane, & Mitchell, 1990; Stumpf, 1993). Potential performance factors explored in the literature include task difficulty, previous task exposure, time limits, and weighted scoring systems (Stumpf, 1993; Collins & Kimura, 1997).

Task difficulty is one potential performance factor that has been explored (Bryden, George, & Inch, 1990; Collins & Kimura, 1997). Prinzel and Freeman (1995) found that females demonstrated a speed-accuracy tradeoff as the difficulty of the spatial task increased from 90 to 180°. Increasing the difficulty of the task resulted in a greater gender

* Corresponding author. Tel.: +1-626-564-5535; fax: +1-626-564-3430.
E-mail address: galen.x.buckwalter@kp.org (J.G. Buckwalter).

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difference when conventional scoring procedures were used. Collins and Kimura studied the role of task complexity in mental rotation by designing a two-dimensional rotation task. They found support for the effects of task difficulty as their more difficult two-dimensional rotations produced a male advantage as large as that seen on the MRT. There is, however, no consensus as to the role of task complexity on gender differences in mental rotation. Bryden, George, and Inch manipulated complexity in several ways, and found that while women consistently showed slower rotation performance, rate of mental rotation did not relate to figural complexity.

Biological factors have also been discussed as potential causes for this difference. Biological theories stress the importance of genetics, hormonal influence, brain organization, and maturational factors. Biological explorations of the factors involved in mental rotation include studies of cerebral involvement. Brain imaging studies often suggest mental rotation involves activation of parietal regions (Bonda, Petrides, Frey & Evans, 1995). Alivisatos and Petrides (1997) looked at regional cerebral blood flow with positron emission tomography while young male subjects were performing a mental rotation task. Their findings indicated specific activity within the left inferior parietal region and the right head of the caudate nucleus. Another study utilized time-resolved functional magnetic resonance imaging (fMRI) to investigate brain activity during mental rotation in five female subjects (Richter, Ugurbil, Georgopoulos, & Kim, 1997). Results suggested activation throughout the parietal lobe during the entire period of mental rotation.

When brain imaging studies are done on subjects performing mental rotation tasks, there is some evidence of activation in motor areas of the brain. Cohen et al. (1996) conducted fMRI in 8 subjects and found increased activation in the parietal lobe, but also the middle frontal gyrus and the premotor cortex. Their results suggest that mental rotation engages cortical areas not only involved in direct perception, but brain areas involved in tracking objects in motion and encoding spatial relations. In other words, when their subjects performed a mental rotation task of a non-moving stimulus, they engaged a region of the brain usually associated with processing objects in motion. Kosslyn, Digirolamo, Thompson, & Alpert (1998) monitored cerebral blood flow with positron emission tomography and found the expected increase in parietal region for mental rotation of both blocks and drawings of hands. But they were also able to demonstrate activation of motor areas while subjects mentally rotated the drawings of hands. They suggest this might indicate two different mechanisms used in mental rotation, one that involves areas that prepare motor movements and another that does not.

The distinct hormonal environments of men and women may play a role. For example, cognitive performance differences do not emerge between boys and girls until early adolescence, which is consistent with hormonal theories (Voyer et al., 1995; Maccoby & Jacklin, 1974), although it is possible that gender differences simply increase as a function of biological development. Further support for a constant and uniform biological explanation comes from studies that find similar effect sizes for gender across cultures (Silverman, Phillips, & Silverman, 1996).

The functional organization of the brain may also play a role in gender differences. The timing of hormonal effects on cognitive functioning remains unclear. One possibility may be that prenatal exposure to sex hormones has an organizing effect on the developing brain (Grimshaw, Sitarenios, & Finegan, 1995). It is commonly accepted that the human brain is functionally asymmetrical, with the left hemisphere supporting verbal functions, and the right hemisphere supporting nonverbal functions, including spatial ability (Bryden, 1982; Kolb & Whishaw, 1996). Some studies, however, suggest that women have a greater degree of bilateral processing for spatial tasks (Harris, 1978; McGlone, 1980; Howard, Fenwick, Brown, & Norton, 1992; Turkheimer & Farace, 1992), perhaps using left hemisphere processing to solve both verbal and nonverbal tasks. Men, on the other hand, may have more specialized hemispheric lateralization (Inglis & Lawson, 1982). Mental rotation certainly involves spatial ability, and it has often been shown to be a task dependent on the right hemisphere (Jones & Anunza, 1982; Ditunno & Mann, 1990). The lateralization theories would then suggest that men solve such tasks using mainly right hemisphere processing, whereas women employ a more bilateral approach using the left hemisphere as well. Indeed, it has often been suggested that women's performance deficits on spatial tasks, such at the MRT, may be a result of using a slower verbal strategy to solve spatial problems and encode spatial displays (Vandenberg & Kuse, 1978; Kolb & Whishaw, 1996).

Another possibility is that hormones have an activating effect on cognitive functioning in adulthood (Janowsky, Oviatt, & Orwoll, 1994). Van Goozen et al. (1994, 1995) report that exposure to androgens in adulthood dramatically affects both verbal and spatial ability in adults undergoing sex-reassignment surgery. Research suggests that adult estrogen levels may also relate to mental rotation and spatial ability in both men and women (Silverman et al., 1995; Silverman & Phillips, 1993; Hampson, 1990).

1.1. *Virtual reality (VR) assessment*

Understanding the extent to which biological and performance factors underlie sex difference in mental rotation has proven to be a difficult task. However, emerging technologies, such as computer generated virtual reality (VR), may assist researchers in getting more reliable, valid, and precise information about cognitive processes involved in mental rotation.

Virtual reality has been defined as an advanced computer interface that allows humans to become immersed within a computer-generated simulated environment (Rizzo et al., 1998). Potential VR use in assessment and rehabilitation of human cognitive processes is becoming recognized as technology advances (Pugnetti et al., 1995; Rose, 1996). Since VR allows for precise presentation and control of dynamic perceptual stimuli (visual, auditory, ambulatory, and haptic conditions), it can be used as a virtual world test situation that combines the control and rigor of laboratory measures with the ecological validity of real life situations. Additionally, a range of behavioral responses can be accurately recorded in the perceptual environmental context that complex stimuli are presented. VR may be uniquely suited for assessment of spatial functioning, allowing for presentation of three-dimensional (3D) objects in a consistent and precise manner, which subjects can then manipulate depending on a range of task demands (Rizzo et al., 1998; Astur, Ortiz, & Sutherland, 1998).

We developed a new measure of virtual reality spatial rotation (VRSR) designed using stimuli from the MRT. The combination of greater control and description of stimuli along with more precise measurement of responses should allow for more accurate characterization of cognitive processes involved in spatial rotation and new insights into sex-based performance differences, strengths, and weaknesses.

Although the VRSR was designed using stimuli from the MRT, an important distinction should be made between brain processing of MRT stimuli and brain processing of VRSR stimuli. When processing MRT or VRSR stimuli, motor processes (explicit or implicit) may be assigned to the role of outputs from higher-level information processing. Hence, the motor system may be viewed as a simple output device for cognition. Further, visuomotor anticipation may be understood as the functional motivation for mental rotation. Correspondingly, mental rotation in both the paper and pencil MRT as well as the VRSR makes use of motor planning and anticipation.

The main difference here being that the MRT mental rotation does not make use of the cortical and subcortical mechanisms responsible for the execution of movement. Nevertheless, this does not mean that mental rotation in both the MRT and VRSR do not share some of the motor system's neural substrate. PET has been used to study mental rotation of hands, found activation of supplementary motor cortex and the superior premotor areas, as well as motor-related parietal regions (Parsons et al., 1995). Further, fMRI has been used to show changes in cortical activity during mental rotation, found activation in premotor area 6, areas 7a and 7b, and area 8 (Cohen et al., 1996). Hence, motor areas are being used for both the paper and pencil MRT and the VRSR. As a result, the paper and pencil MRT, as well as the VRSR are internal mental tasks.

Based on the literature, we expect sex differences on both the MRT and VRSR. Given sex differences in hemispheric specialization (Howard et al., 1992), we conducted an exploratory analysis of relations between rotation tasks (MRT and VRSR) and other neuropsychological measures. We expect to see men's scores on rotation tasks correlate with right hemisphere or spatial tasks, while women's rotation scores are expected to reflect a more bilateral approach showing significantly stronger associations with verbal tasks as well. Additionally, no sex differences are expected in correlations between rotational tasks and a measure of executive functioning.

2. Method

2.1. Participants

60 subjects (26 males and 34 females) between the ages of 18 and 41 were initially recruited from undergraduate and graduate schools as well as a technological institute. Subjects were assigned to a group that received the VRSR test or a control group based on convenience. This strategy did not produce equivalent groups on MRT performance. To assure equivalence on this crucial factor subjects were matched based on sex and baseline MRT performance. This produced 22 pairs of subjects with initial MRT scores within 2 points of each other (20 male subjects and 24 female subjects), an age range from 18 to 41 ($M = 27.9$; S.D. = 5.4), and education levels ranging from 12 to 25 years ($M = 17.45$; S.D. = 2.8). Of 44 subjects matched, 75% were Caucasian, 11% were Asian, 7% Hispanic, 5% African–American, and 2% were Filipino. Experimental subject and matched controls' equivalency information is provided in Table 1. Sex comparisons are listed in Table 2.

2.2. Virtual reality system

The VRSR system uses an ImmersaDesk drafting-table format virtual prototyping device. The Pyramid Systems

Table 1
Descriptive statistics ($n = 22$)

Variable	Mean and S.D.	
Age	29.09	5.56
Education	18.19	3.06
MRT	25.63	7.79

Note: MRT— mental rotation test.

Table 2
Gender comparisons

Variable	Male mean and S.D.		Female mean and S.D.		*t*-score	*d*
MRT	29.1	6.61	22.66	7.69	−2.11* (0.04)	0.90
VRSR Dur	50.93	12.73	49.96	12.12	−0.18 (NS)	0.05
VRSR Eff	16.66	3.51	17.35	5.02	0.37 (NS)	−0.11
Block Design	41.30	8.43	41.50	7.11	0.06 (NS)	−0.03
JLO 33.31	7.03	34.71	10.05	0.37	−0.16	

Note: MRT—mental rotation test; VRSR—virtual reality spatial rotation; Dur—duration score (sum of 20 items); Eff—efficiency score; ( )—*P*-level; (∗)—reached 0.05 significance level; NS—nonsignificant. JLO—judgment of line orientation. For JLO and Block Design a high indicates better performance.

ImmersaDesk employs stereo glasses and magnetic head and hand tracking. This rear-projection system offers a semi-immersive VR and features a 4×5-foot rear-projected screen positioned at a 45° angle. The screen's size and position give a wide-angle view and the ability to look down as well as forward.

The VRSR assessment and training system was designed to present a target stimulus (TS) that consists of a specific configuration of 3D blocks within a virtual environment. The stimuli appear as "hologram-like" three-dimensional objects floating above the projection screen. After presentation of TS, the participant is presented with the same set of blocks (working stimuli (WS)) that needs to be rotated to the orientation of the target and then superimposed within it. The participant manipulates the WS by grasping and moving a sphere shaped "cyberprop" which contains a tracking device. The motion of the sphere is imparted upon the WS. Upon successful superimposition of the WS and TS a "correct" feedback tone is presented and the next trial begins. The new WS appears attached to the sphere (user's hand), and a new TS appears. In this mode of interaction, users do not need to press any buttons or select objects. The WS simply appears attached to the sphere for users to manipulate.

We calculated the following stimuli information. Stimulus orientation is represented by a single linear rotation around a 3D vector and is specified as a group of four values: three defining a 3D vector of unit length, and an angle in degrees. Magnitude is defined as angular difference between two orientations. The TS can be aligned to WS by a single minimal rotation around some fixed 3D vector. The degrees required to do this are found in the rotational task magnitude, ranging from 0 to 360°. If rotational axis is nearly parallel to viewer's line of sight, rotations of the object will not reveal new faces to viewer and task is equivalent to a 2D rotational task. As the axis is moved to become parallel to view-plane, the task requires a fully 3D understanding of object appearance. This is calculated as the sine of the angle between rotational axis and line of sight, and so varies from 0 to 1.

We assessed rotational ability by recording the amount of time to complete rotation as well as efficiency of the solution. The most efficient execution of a rotational task follows the shortest angular path from stimulus to target, about a fixed axis. Samples are taken at regular intervals (every 0.1 s) during task execution, defining an angular path as the subject searches for a solution. Summing angular differences between sequential samples gives the angular length of that path, and calculating the ratio of the shortest possible path to this summed length gives the efficiency of the task execution. This value varies from 0 (poor) to 1 (ideal).

2.3. Procedures

The University of Southern California's Institutional Review Board approved the study. Experimental sessions took place over a 2 h period. After informed consent was obtained, basic demographic information, computer experience and usage, and spatial activities history (Newcombe et al., 1983) were recorded. Next, a baseline measure of mental rotation ability was assessed using a redrawn version (Peters et al., 1995) of the mental rotation test (MRT-A) of Vandenberg and Kuse (1978). Subjects then completed a neuropsychological battery administered under standard conditions. Following completion of the neuropsychological battery, subjects completed the motion history questionnaire (Kennedy & McCauley, 1984) and simulator sickness questionnaire (Kennedy, Lande, Berbaum, & Lilienthal, 1993), which includes a pre-VR exposure symptom checklist.

After baseline assessment 22 subjects of the 44 subjects received tests in a virtual environment that included a training component that is part of a separate study. These 22 subjects participated in a VRSR task that assessed, and in a procedure being analyzed in a separate study, trained mental rotation abilities. For the current study the 22 subjects who took the VRSR first completed five non-rotational practice trials. Then each subject's VRSR baseline performance was assessed over 20 trials using a VR version of the items from the pencil and paper MRT. The 20 stimulus items were designed to closely approximate the Vandenberg and Kuse (1978) MRT items.

This paper focuses on the gender effects seen at the baseline assessment only. Thus our measures of duration and efficiency reflect the average of the initial 20 trials. We therefore have a total of 22 participants with both baseline VR and paper and pencil assessment.

2.4. Testing instruments

The neuropsychological battery included a diverse collection of instruments. Mental rotation ability was assessed using the MRT (Vandenberg & Kuse, 1978; Peters et al., 1995). This test used line drawings of block stimuli and consisted of two 10-item sections in which the subject was required to match two of the four choices to a target figure. Incorrect choices were mirror images of the target or alternative block configurations. Standard administration provided for a five-minute time limit on each 10-item section. With two points given for each correct response, scores ranged from 0 to 40. The alternate form of the MRT uses the same drawings but reorders their presentation and switches position of the target stimuli.

Visuoconstruction abilities were measured by the Block Design subtest of the WAIS-R (Wechsler, 1981). The Trail-Making Tests B was used to evaluate executive control processes and attention (Army Individual Test Battery, 1944). The Judgment of Line Orientation was used to evaluate visuoperceptual skills (Benton, Varney, & Hamsher, 1978). The California Verbal Learning Test was employed to assess verbal learning and memory (Delis, Kramer, Kaplan, & Ober, 1983). These tests are all commonly used for neuropsychological assessment of these cognitive processes and as such have widely used normative information available. Finally, surveys of simulator sickness and motion sickness history were administered (Kennedy & McCauley, 1984; Kennedy et al., 1993). These questionnaires were included to gather data on the possible co-variant of motion sickness or "cyber-sickness", a factor that research suggests effects women more than men (Kennedy, Lanham, Massey, & Drexler, 1995; Stern & Koch, 1996).

2.5. Data analysis

This study is cross-sectional in nature. *T*-tests were used to investigate whether sex differences occurred on the VRSR in relation to performance on time and efficiency factors. We hypothesized that men and women would show different patterns of correlations between both MRT and VRSR, and the other neuropsychological measures. Correlational matrices were used to test this hypothesis.

3. Results

As predicted, sex performance differences on the MRT were found to significantly favor males ($t(42) = -3.27$; $P = 0.002$).

For the VRSR, however, no differences were observed between males and females on duration ($t(20) = -0.18$; $P = 0.86$), or efficiency ($t(20) = 0.37$; $P = 0.72$). Female subjects did not perform significantly worse than males on other visuospatial measures in the testing battery, whether or not motor components or dimensionality differences were present. Sex differences did not reach significance on a *T*-test comparing performance on the block design ($P = 0.21$), while a nonstatistical trend emerged with the judgment of line orientation (JLO; $P = 0.10$). Results from all sex comparisons are listed in Table 2.

Assessment of the prediction that the men's scores on rotation tasks would correlate more highly with spatial tasks, while women's scores would show stronger correlations with measures of verbal learning and verbal memory is presented in Table 3. Men's MRT scores showed significant correlations with three of four neuropsychological measures. They positively correlated with block design ($r = 0.77$, $P = 0.001$), CVLT at trial 5 ($r = 0.68$, $P = 0.001$), and CVLT long delay ($r = 0.62$, $P = 0.003$). Women's initial MRT scores positively correlated with block design ($r = 0.59$, $P = 0.002$), but no significant relationship was found with the CVLT scores or Trails B. Assessment of the significance of differences between male and female correlation coefficients between MRT1 and the above neuropsychological measures revealed significance only for MRT1 and CVLT at trial 5 ($P = 0.0542$).

Next, we looked at the relationship between VRSR and selected neuropsychological measures. All correlation coefficients between VRSR measures of Duration and Efficiency and selected neuropsychological measures appear in Tables 4 and 5, where they are listed by sex. Assessment of the significance of differences between male and female correlation coefficients between Duration 1 and the above neuropsychological measures revealed significance only for between duration 1 and CVLT long delay ($P = 0.0004$). Assessment of the significance of differences between male and female correlation coefficients between efficiency 1 and the above neuropsychological measures revealed significance only for between efficiency 1 and CVLT Long Delay ($P = 0.0035$). See Table 3 for all correlation coefficients listed by sex.

Finally, in light of our concern that any changes noted on VR measures may be related to side effects associated with

Table 3
Correlation coefficients between mrt and other selected neuropsychological measures listed by gender

Variable	Male MRT ($n = 10$)	Female MRT (n=12)	Significance of difference
CVLT AT5	0.80*, $P = 0.006$	0.25, NS	$P = 0.05$
CVLT LD	0.62*, $P = 0.05$	0.32, NS	$P = 0.33$
TRAILS B	−0.43, NS	0.25, NS	$P = 0.08$
Block design	0.87*, $P = 0.001$	0.70*, $P = 0.02$	$P = 0.18$

Note: MRT—mental rotations test; CVLT AT5—california verbal learning test at trial 5; CVLT LD—california verbal learning test long delay; (*)—reached 0.05 significance level; NS—nonsignificant. For all tests other than trails B a high score indicates better performance.

Table 4
Correlation coefficients between duration and other selected neuropsychological measures listed by gender

Variable	Men's Dur	Women's Dur	Sig. of diff.
CVLT AT5	−0.76*, $P = 0.01$	−0.61*, $P = 0.04$	$P = 0.3838$
CVLT LD	−0.78*, $P = 0.008$	0.22, NS	$P = 0.0004$
TRAILS B	0.69*, $P = 0.02$	0.22, NS	$P = 0.0629$
Block design	−0.86*, $P = 0.001$	−0.65*, $P = 0.02$	$P = 0.1202$
MRT1	−0.66*, $P = 0.04$	−0.42, NS	$P = 0.2965$

Note: (*)—reached 0.05 significance level; DUR—duration; CVLT AT5—California verbal learning test at trial 5; CVLT LD—California verbal learning test long delay; MRT—mental rotations test; NS—nonsignificant: Sig. of diff.—significance of the difference between correlation coefficients. For all tests other than Trails B a high score indicates better performance.

Table 5
Correlation coefficients between efficiency and other selected neuropsychological measures listed by gender

Variable	Men's Eff.	Women's Eff.	Sig. of diff.
CVLT AT5	0.54, $P = 0.10$	0.54, $P = 0.09$	$P = 1.0000$
CVLT LD	0.60, $P = 0.07$	−0.31, NS	$P = 0.0035$
TRAILS B	−0.43, NS	−0.35, NS	$P = 0.7737$
Blocks	0.79*, $P = 0.007$	0.70, $P = 0.01$	$P = 0.5351$
MRT1	0.60, $P = 0.06$	0.27, NS	$P = 0.2093$

Note: (*)—reached 0.05 significance level; EFF—efficiency; CVLT AT5—California verbal learning test at trial 5; CVLT LD—California verbal learning test long delay; MRT—mental rotations test; NS—nonsignificant. Sig. of diff.—significance of the difference between correlation coefficients. For all tests other than Trails B a high score indicates better performance.

Table 6
Gender comparisons on simulator sickness questionnaire at time 1 and time 2.

	Time 1		Time 2	
	Mean	S.D.	Mean	S.D.
Men				
Exp	2.60	2.71	1.40	1.89
Ctr	2.33	2.64	2.67	4.00
Women				
Exp	4.25	3.65	3.08	2.81
Ctr	5.08	3.70	4.75	3.01

Note: Exp—experimental group; Ctr—control group.

immersive environments, we used data from the simulator sickness questionnaire collected prior to and after administration of tests protocols for both groups. Given that we found no significant changes on any of our VR or MR tasks, there is no rationale for controlling for side effects on performance. However, we report exploratory analysis of changes in side effects for both groups. An ANOVA comparing all female with male subjects demonstrated that females report significantly more side effects than males ($F(1, 39) = 5.54$; $P < 0.02$.) Still, there was no three-way interaction between sex, group, and occasion ($F(1, 39) = 0.17$; $P < 0.67$). Table 6 lists means and standard deviations for side effects data by sex, occasion, and group.

4. Discussion

The findings from this utilization of VE for evaluating sex differences on a spatial task are intriguing. As predicted, sex differences on a paper-and-pencil version of MRT were replicated. However, sex differences predicted on the VRSR measures of Efficiency and Duration were not found. We also hypothesized that men's scores on rotation tasks would correlate more highly with spatial measures, while women's scores would reflect a more bilateral approach, strong associations with both verbal and spatial measures. Surprisingly, significant correlations did emerge, but in the opposite direction from those predicted. Women's rotation scores correlated mainly with spatial measures, while men's rotation scores correlated with both spatial and verbal measures.

Although a male/female performance difference was found on the MRT, replicating the literature, no support was found for VRSR sex differences on Duration, or Efficiency. VRSR protocol items are placed to approximate the position of 20 MRT drawings. While these stimuli produced a robust sex difference when presented as 2D drawings, their 3D presentation, requiring motor manipulation, failed to elicit a sex effect. The explanation for absent sex differences in the VE condition may rest with cognitive domains changed or added when the test was transposed into a VE.

The confirmation of a gender difference on the MRT and the lack of a difference on the VRSR suggest that there are either differences in how males and females approach the two tasks or differences in the cognitive demands of the two tasks. The potential differences in cognitive demands that the two tests place on subjects are numerous and likely not of a single origin. We limit our discussion to the differences in stimulus complexity and its relation to the effects of either dissimilar ways in which males and females approach the two tasks or the effects of increased dimensional complexity and concomitant increases in working memory requirements. From our theoretical perspective, moving from MRT to VRSR results in an increase in the complexity of a stimulus (from 2D to 3D) and results in an increase in the cognitive load (working memory) of the task. We consider our data on a perceptual continuum with stimuli and tasks increasing in complexity to match "spatial conditions." As a result, working memory load seems to increase steadily with stimulus complexity, due to task demands. Therefore we asserts that the relation between stimulus complexity and task demand reflects a functional relationship between stimulus complexity and the load of working memory for these stimuli. We argue that stimulus complexity provides a parsimonious theoretical framework for understanding the differences between these tasks with full realization that interpretations are variegated by one's working heuristics.

First, stimulus complexity might be a key to sex differences and may be a key factor leading to male advantage in mental rotation (Linn & Petersen, 1985; Collins & Kimura, 1997; McWilliams, Hamilton, & Muncer, 1997). Stimulus complexity may result in sex difference related to dissimilar strategies employed by males and females when attempting to solve a spatial visualization task. Linn and Petersen (1985) suggest that the slower performance of women on the MRT may reflect a tendency to double check answers by rotating them more than once. They also point out that when using a "part-by-part" rotational strategy, women may be more inclined to rotate additional parts of the block objects before deciding on an answer, thus utilizing a less efficient strategy. If either of these suggestions were in fact the case, the VRSR might eliminate their effect. When an item has been correctly superimposed in the VRSR, a subject receives an immediate "correct" feedback tone and the next item appears. There is no opportunity or need for double-checking an answer, which could slow down performance. Second, when the cyberprop is moved in the VRSR condition, the whole working object responds, enabling a "gestalt" approach. There is no need for subjects to employ a "part-by-part" rotational strategy, again eliminating the use of a less efficient approach to solving the problem.

An additional possible explanation of a gender difference on the MRT and the lack of a difference on the VRSR may be that there are differences in the cognitive demands of the two tasks. The VRSR adds the appearance of real 3D to stimuli. The cognitive process subjects undergo in the VRSR does not require creation of 3D cognitive representations from 2D drawings—a process hypothesized to inflate sex difference in paper-and-pencil tests of mental rotation (McWilliams et al., 1997; Voyer et al., 1995). This raises the issue of "stimulus complexity" and the presumed difference between the paper and pencil MR task and the VRSR. Accordingly, is the subject performing the VRSR task required to rotate the object in his or her "mind's eye"; does he or she manipulates the test stimuli (working stimuli) hologram so that it matches the target stimulus? If this were the case, the VRSR would not be a measure requiring mental rotation. Further, as sex differences were observed in the paper and pencil measures, and no sex difference was observed in the VRSR, it may appear that the modification did not account for the imagery demands inherent in the paper and pencil version.

However, from our theoretical formulation, we tend to assign motor processes, explicit or implicit, to the role of outputs from higher-level information processing. Hence, we believe that the motor system is a simple output device for cognition. Further, we believe that visuomotor anticipation is the functional motivation for mental rotation. By this we mean that mental rotation in both the paper and pencil MR as well as the VRSR makes use of motor planning and anticipation. The main difference here being that the MR mental rotation does not make use of the cortical and subcortical mechanisms responsible for the execution of movement. Nevertheless, this does not mean that mental rotation in both the MR and VRSR do not share some of the motor system's neural substrate. Motor areas are used for both the paper and pencil MR task and the VRSR (Cohen et al., 1996; Parsons et al., 1995). As a result, the argument that the paper and pencil MR task is an internal mental task, while the VRSR is a wholly different external task does not seem to hold.

In summary, our prediction that men's scores on rotational tasks (MRT and VRSR) would correlate more highly with the spatial tasks; while women's rotational performance would show stronger correlations with measures of verbal learning and verbal memory, was not supported. Further, we did not predict the observed sex differences in correlations between rotational tasks and a measure of executive functioning. These findings are not consistent with the putative understanding of functional asymmetry summarized above (Kolb & Whishaw, 1996; Turkheimer & Farace, 1992; Inglis & Lawson, 1982).

In an attempt to explain current results, that seemingly suggest more bilateral processing in men than women on the rotational tasks, we draw upon studies that question traditional assumptions of hemisphere involvement in mental rotation (Voyer & Bryden, 1990). Further, there are studies that tested only male subjects, and found more left hemisphere involvement in mental rotation (Fischer & Pellegrino, 1988). These studies suggest rotation tasks, such as MRT require generation of a mental representation—mediated by left hemisphere. Another possibility is that the MRT requires a great deal of analysis as one encodes geometric properties of a shape and deduces relations between its parts. Such demands are beyond simple perception of spatial information and may make specific demands upon the left hemisphere.

Future studies should include a larger pool of subjects to make factor analysis a possibility for statistical investigation. Determining which factors load differently for men and women may assist in revealing variables that underlie performance effects. We have suggested stimulus complexity, including visual working memory, and task demands, are as variables that changed in the transposing of MRT to VE. One or a combination of these factors may account for the lack of sex differences in VRSR. Future VE research has the potential to address questions raised in the current study.

Further, future studies should also involve combining VR with an eye-tracking device, so stimuli can be precisely presented to either left or right visual fields. Such control will make it possible to clarify hemispheric involvement in tasks such as the VRSR, and further understand sex differences that may arise.

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