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EYE MOVEMENTS DURING MENTAL ROTATION OF NONMIRRORED AND MIRRORED THREE-DIMENSIONAL ABSTRACT OBJECTS[1, 2]

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Summary.—Eye movements were recorded while participants ($N = 56$) rotated mirrored and nonmirrored abstract, three-dimensional object pairs into different orientations to assess whether there were oculomotoric differences in fixation switches between mirrored and nonmirrored objects and how an object's plane and depth angle affected visual processing. Compared to other studies, especially depth rotation tasks were responsible for a difference in the sum of fixation switches. This difference seemed to be caused by an increase in incongruent fixation switches, while congruent ones remained stable. Theoretical and practical implications of findings are discussed.

Mental rotation is the cognitive process of rotating an object into different orientations in mental space. In the present study, the oculomotor processing (fixation switches) of nonmirrored and mirrored abstract, three-dimensional Shepard and Metzler objects was investigated, rotated in the picture plane or depth (Just & Carpenter, 1976).

Shepard and Metzler (1971) explored the mental rotation process by presenting pairs of line drawings of three-dimensional objects, each consisting of 10 cubes with three rectangular bends. The task was to decide whether the objects were rotatable (nonmirrored) or not (mirrored). Varying the picture plane and depth angle, and thereby the task complexity, Shepard and Metzler found that objects could be coded in mentally represented images and the rotation process was incremental, that is, reaction time linearly increased with angular disparity, and the objects were transformed similarly to the physical transformation of objects (Wraga, Kosslyn, Thompson, & Alpert, 2003). These results were found on tasks using single cubes with letters on the sides (Just & Carpenter, 1985), drawings of human hands (Cooper & Shepard, 1975), and natural objects (Jolicoeur, 1985, 1988).

Chronometric studies have caused a dispute regarding which factors the rate of rotation (i.e., the slope of increased response time as a function of angle) is dependent on. Eye-movement studies have provided a deeper insight into the micro-structures of ongoing operations during mental rotations (e.g., Just & Carpenter, 1976, 1985; Carpenter & Just, 1978; Irwin

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& Carlson-Radvansky, 1996; Irwin & Brockmole, 2000; De´Sperati, 2003; Hirnstein, Bayer, & Hausmann, 2009). Just and Carpenter (1976) were one of the first to present eye-movement data of three-dimensional Shepard and Metzler tasks. In their study, fixation switches were analysed between simultaneously presented rotation object pairs. Every rotation object was divided into its parts: an open arm, lower arm, and central joint segment. Based on oculomotoric processes, the authors defined three different mental rotation phases: (a) search, (b) transformation and comparison, and (c) confirmation. These results demonstrated that fixation switches increased with angular disparity in all three phases; thus, the majority of fixation switches were observed in the transformation and comparison phase. Just and Carpenter's study (1985) on individuals with high and low spatial ability showed that differences occur primarily in the rotation and confirmation phase, and the group with low spatial ability mentally rotates objects at half the mean speed of the group with high spatial ability. Shiina, Saito, and Suzuki (1997) demonstrated that experts primarily solved Shepard and Metzler tasks with one fixation circle, which was executed from the upper to the lower arms of the two objects, whereas novices varied between several other gaze strategies including multiple fixation circles and more intra-object fixations.

Results on the mirrored Shepard and Metzler tasks have shown an overall mean reaction time of 3.8 sec., nearly 1 sec. longer than for the nonmirrored tasks. In postexperimental interviews, participants indicated they tried to bring into agreement one end of an object with the corresponding end of the other object. Participants made the mirrored/nonmirrored decision after discovering that some parts of the objects were not rotatable into agreement. These verbal reports refer to an analytic strategy, with objects that are segmented to encourage separate rotation of particular object parts (Yuille & Steiger, 1982). Metzler and Shepard (1974) explained longer reaction times as participants' first testing for a direct match between their rotated internal representation and the external stimulus. Whenever they detected a mismatch, they required an additional fixed amount of time to switch to the other response (p. 187). The eye-tracking study of Just and Carpenter (1976) showed that the fixation switches increased within all three task phases, but increased the most within the confirmation phase (on average, 49% of the dwell time). Overall, there was strong evidence that reaction times increased for mirrored objects and with increasing angular degree of rotation (Shepard & Metzler, 1971; Cooper & Shepard, 1973; Cooper, 1975; Jolicoeur, 1985; Milivojevic, Johnson, Hamm, & Corballis, 2003; Núñez-Peña & Aznar-Casanova, 2009).

Study Design

The aim of the present study was an analysis of the fixation switches during the rotation process of simultaneously presented Shepard and Metzler object pairs (Just & Carpenter, 1976).[3] As in Just and Carpenter (1976), it was considered that fixation switches are of crucial importance because they give an insight into active processing of information within the visual-spatial working memory regarding keeping and processing information (Hyun & Luck, 2007). Of interest was the effect of a picture plane rotation and depth rotation in nonmirrored compared to mirrored object pairs, and how this is related to fixation switches; specifically, whether there is a difference in the sum of fixation switches (Just & Carpenter, 1976). Hypothesis 1 was that the fixation switches would increase in mirrored picture plane and depth rotation tasks. The second question is which type of fixation switches would dominate the rotation process—those between the same object areas (congruent fixation switches) or between different object areas (incongruent fixation switches, see Fig. 1). Hypothesis 2 was that the incongruent fixation switches would increase in mirrored picture plane and depth rotation tasks. The third question of interest was whether there were differences between congruent fixation switches in the upper and lower object areas. Yuille and Steiger (1982) considered that the lower object area plays a crucial role in mental rotation. Thus (Hypothesis 3) a difference in fixation switches was expected between nonmirrored and mirrored picture plane and depth rotation tasks.

Method

Participants

Fifty-six students participated, of whom 33 (59%) were women and 23 men (41%). The mean age was 25 yr. (*SD* = 4.5, range = 13–45). All reported normal or corrected-to-normal vision (glasses: 25%, contact lenses: 17.9%).

Stimulus Material

The stimulus material comprised 16 mental rotation tasks. Within each task, two simultaneously presented three-dimensional objects were shown, each consisting of 10 line drawings of cubes with three rectangular bends, originally used by Shepard and Metzler (1971). All rotation object pairs to be rotated were presented on a white background. Half of the right-hand objects were replaced by the mirror image of the left-hand object. Within the eight nonmirrored object pairs, four object pairs were not rotatable congruently through a picture plane rotation (45–180°), the other four through a plane and depth rotation (45–45° to 180–180°). This classification was also made within the mirrored objects.

To analyze the fixation switches, the three-dimensional objects were constructed and numbered from the 10 line drawings of cubes. Single fixa-

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[3] We were not interested in proving Just and Carpenter's model (1976) of rotation phases.

tions were manually paired, counted, and noted as related to the appropriate cube. All objects had a consistent numbering sequence to ensure that a single fixation referred either to the same segments (for nonmirrored pairs) or to isomorphic pairs of segments (for mirrored pairs). In a further analysis, the two rotation bodies were divided into upper and lower segments. The upper part corresponded to Segments 1 to 5 of an object, the lower part Segments 6 to 10. The segmentation into three parts, also used by Just and Carpenter (1976), was not used because the geometry naturally permits division into two right-angle bends (cf. Hall & Friedman, 1994). The overall number of fixation switches was the sum of congruent and incongruent changes of gaze fixation. Incongruent fixation switches were a change in fixation from the upper-segment area (Segments 1 to 5) of one object to the lower-segment area (Segments 6 to 10) of the other object, or vice versa. Congruent fixation switches were similarly defined as changes between gaze fixation on the upper segment area from one rotation object to the upper segment area of the other rotation object or between the lower segment area from one rotation object to the lower segment area of the other rotation object (see Fig. 1).

Apparatus

The table-mounted eye-tracking device from LC Technologies, Inc., consisted of a Pentium IV computer with a NVIDIA GeForce 4 MX 4000

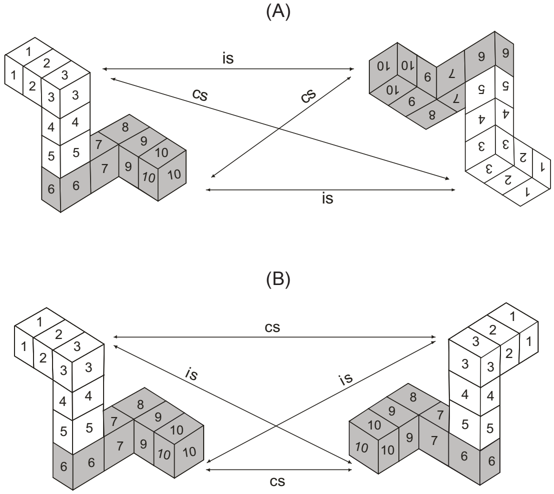

Fig. 1. Mental rotation tasks. Segmentation and types of fixation switches within a nonmirrored (180°) rotation task (A) and a mirrored (180°) rotation task (B); Upper-segment area (Segments 1 to 5); Lower-segment area (Segments 6 to 10); Incongruent fixation switches (is); Congruent fixation switches (cs).

graphics card. The object pairs were displayed on a 17-in. computer monitor (View Sonic VG700b) with a display refresh rate of 75 Hz. Eye movements were recorded with a frequency of 2 × 60 Hz with two binocular cameras which were positioned beneath the computer display. The software of the Eyegaze Analysis System from LC Technologies, Inc., was NYAN, which allowed registering, recording, and analysis of fixation. The fixation was defined as the point between two saccades at which eyes were relatively stationary and information input and rotation of the objects occur (Irwin & Carlson-Radvansky, 1996; Irwin & Brockmole, 2000). Two observation monitors allowed watching the right and left eyes (through input from the left and right binocular cameras beneath the computer display) during the process of eye-tracking to correct for the sitting posture of participants when necessary. The distance to the display was about 60 cm.

Procedure

The pupil-center corneal reflection method was used to calibrate individual participants' eye-movement patterns which took an average of about 3 min. After successful calibration, participants were presented two training tasks. In the first training task, the right-hand object was rotatable into congruence with the left-hand object. In the second training task, the right-hand object was not rotatable into congruence, because the objects were mirror images of each other. Participants were instructed to comment verbally on every rotation task: if the two objects could be rotated into congruence (Give the answer "Yes"), or if the two objects were mirror images of each other (Give the answer "No"). After presentation of the training tasks, participants' questions were answered. Subsequent to the training, participants were presented with the 16 main tasks. The experimenter noted each answer and, using the left mouse button, presented the next rotation task. There was no time limitation (cf. Shepard & Metzler, 1971).

Statistical Analyses

Hypothesis 1 was investigated with a two-way, between-groups analysis of variance (ANOVA) to examine the effect of mirrored versus nonmirrored rotation tasks as well as picture plane versus depth rotation as independent variables, with the dependent variable being sum of fixation switches. Hypothesis 2 was investigated with a two-way, between-groups multivariate analysis of variance (MANOVA) with the independent variables of mirrored versus nonmirrored and picture plane versus depth rotation, and the dependent variables of congruent versus incongruent fixation switches. Hypothesis 3 was investigated with a two-way, between-groups MANOVA with the independent variables of mirrored versus nonmirrored and picture plane versus depth rotation, and the dependent variables of congruent fixation switches in the upper object area versus congruent fixation switches in the lower object area.

RESULTS

Hypothesis 1

The interaction effect between mirrored versus nonmirrored rotation tasks and picture plane versus depth rotations was statistically significant ($F_{1,220} = 10{,}40$, $p = .001$; $\eta^2 = 0.01$, power = .23). Means in Table 1 show that depth rotation tasks were responsible for the increase. There was no statistically significant main effect for mirrored versus nonmirrored rotation tasks ($F_{1,220} = 2.64$, $p = .11$) and picture plane versus depth rotations ($F_{1,220} = 1.74$, $p = .19$). For within-task and between-tasks comparisons, using *t* tests, see Table 2.

TABLE 1

MEANS FOR FIXATION SWITCHES PER TASK FOR NONMIRRORED AND MIRRORED PICTURE PLANE AND DEPTH ROTATION TASKS

Switch	Nonmirrored Plane		Nonmirrored Depth		Mirrored Plane		Mirrored Depth	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Sum	47.91	20.56	42.04	23.76	42.98	22.54	56.98	25.12
Congruent	25.73	12.11	21.07	12.20	20.00	11.32	27.89	14.07
Incongruent	22.18	11.12	20.96	14.91	22.98	13.05	29.09	12.57
Upper area	12.52	7.96	6.84	5.29	11.13	7.75	10.11	6.65
Lower area	13.21	5.99	14.23	8.39	8.88	5.84	17.80	9.63

Hypothesis 2

In the next step, congruent and incongruent fixation switches were differentiated within the sum of fixation switches (Table 1). The interaction effects between mirrored versus nonmirrored rotation tasks for congruent fixation switches ($F_{1,220} = 14.20$, $p < .0005$; $\eta^2 = 0.01$, power = .24) and incongruent fixation switches ($F_{1,220} = 4.45$, $p = .04$; $\eta^2 = 0.004$, power = .10) were statistically significant. The main effect for nonmirrored versus mirrored rotation tasks was not statistically significant for congruent fixation switches ($F_{1,220} = .11$, $p = .74$) but was statistically significant for incongruent fixation switches ($F_{1,220} = 6.62$, $p = .01$; $\eta^2 = 0.01$, power = .17). The main effect for picture plane versus depth rotation was not statistically significant for congruent ($F_{1,220} = .94$, $p = .33$) or incongruent fixation switches ($F_{1,220} = 1.99$, $p = .16$). For within-task and between-task comparisons, using *t* tests, see Table 2.

Hypothesis 3

In a further step, we differentiated between upper and lower object parts within congruent fixation switches (see Fig. 1). Concerning Hypoth-

TABLE 2

Within- (Nonmirrored and Mirrored) and Between- (Plane and Depth) Tasks Comparisons With Independent-samples *t* Tests

Switch	Comparison		*t*	*df*	*p*	η^2
Sum	np	nd	1.40	110	.17	.02
	mp	md	−3.10	110	.002	.08
	np	mp	1.21	110	.23	.01
	nd	md	−3.24	110	.002	.09
Congruent	np	nd	2.03	110	.05	.04
	mp	md	−3.27	110	.001	.09
	np	mp	2.59	110	.011	.06
	nd	md	−2.74	110	.007	.06
Incongruent	np	nd	.50	110	.63	.002
	mp	md	−2.5	110	.01	.05
	np	mp	−.35	110	.73	.001
	nd	md	−3.12	110	.002	.08
Upper area	np	nd	4.44	110	.001	.15
	mp	md	.75	110	.46	.01
	np	mp	.94	110	.35	.01
	nd	md	−2.88	110	.005	.07
Lower area	np	nd	−.74	110	.46	.004
	mp	md	−5.94	110	.001	.24
	np	mp	3.88	110	.001	.12
	nd	md	−2.09	110	.04	.04

Note.—np = nonmirrored picture plane; nd = nonmirrored depth; mp = mirrored picture plane; md = mirrored depth.

esis 3, there was an interaction effect for the upper area ($F_{1,220} = 6.22$, $p = .01$; $\eta^2 = .01$, power = .27) and lower area ($F_{1,220} = 15.03$, $p < .0005$; $\eta^2 = .02$, power = .27). Main effects for nonmirrored versus mirrored rotation tasks and congruent fixation switches upper area ($F_{1,220} = 1.01$, $p = .32$) and lower area ($F_{1,220} = .14$, $p = .71$) were not statistically significant. Main effects for picture plane versus depth rotation and congruent fixation switches upper area ($F_{1,220} = 12.83$, $p = .0005$; $\eta^2 = .02$, power = .84) and lower area ($F_{1,220} = 23.76$, $p < .0005$; $\eta^2 = .02$, power = .84) were statistically significant. For within-task and between-task comparisons, using *t* tests, see Table 2.

Discussion

In the present study, differences in fixation switches were investigated in nonmirrored and mirrored three-dimensional Shepard and Metzler rotation tasks, in which objects had to be rotated in picture plane or depth. Results confirmed findings from Just and Carpenter (1976, 1985) that the sum of fixation switches is higher for mirrored objects in comparison to nonmirrored objects. However, this effect is only found for depth rotations. One possible reason is that the phases of search, rotation, and confirmation in depth rotation tasks have to be run through several times when corresponding parts cannot be brought into conformity (Just & Carpenter, 1976; Shiina, *et al.*, 1997). Fixation switches can be seen as a refresh rate within the visuospatial working memory, necessary to keep up the fading object representation within the working memory in simultaneous object rotations (Hyun & Luck, 2007). The constant refresh is logically more difficult for a mirrored depth rotation. The subdivision of the sum of fixation switches into congruent and incongruent fixation switches showed tendencies toward a dominance of congruent fixation switches for nonmirrored picture plane tasks and mirrored depth tasks, while incongruent fixation switches increased only in mirrored depth tasks. The results of Just and Carpenter (1985) indicated that one possible reason for errors in nonmirrored rotation tasks is the incorrect combination of noncorresponding object parts in the search phase. In the present study, this was only observed in depth rotation tasks. In picture plane rotation tasks, the sum of fixations in mirrored and nonmirrored tasks did not differ significantly, which could be explained by the higher fixation switches in the phases of search and confirmation (Just & Carpenter, 1976) or because of different rotation strategies (cf. Kanamori & Yagi, 2002) in which incongruent fixation switches are crucial for the solution process. With respect to congruent fixation switches, it is assumed that primarily the lower segment area has great relevance for successfully solving an abstract three-dimensional rotation task (Just & Carpenter, 1976; Yuille & Steiger, 1982). The findings confirmed previous results from reaction time studies, as higher congruent fixation switches were found between lower segment areas, particularly in mirrored depth rotation tasks. Further investigations are necessary to clarify the role of mirrored three-dimensional objects for visual cognition. The oculomotoric processing of mirrored objects can give a clearer picture of how nonmirrored objects are mentally represented and manipulated.

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