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Acta Psychologica 122 (2006) 280–287

acta psychologica

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Violation of pure insertion during mental rotation is independent of stimulus type, task, and subjects' age

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Received 3 August 2005; received in revised form 5 December 2005; accepted 6 December 2005
Available online 24 January 2006

Abstract

The experiment validated and extended the finding of Ilan and Miller (1994) [A violation of pure insertion: mental rotation and choice reaction time. *Journal of Experimental Psychology: Human Perception and Psychophysics* 20, 520–536] that the mental rotation process is not purely inserted into a mirror-normal discrimination task. In contrast to their work we used other experimental stimuli (drawings of animals instead of characters), a different task (same/different comparison) and investigated this effect under a developmental perspective. Adults and children between the age of 8 and 10 took significantly longer to respond to upright drawings of animals in conditions containing rotated stimuli than in conditions containing only upright stimuli, indicating a violation of pure insertion. In general, we found evidence that the violation of pure insertion during a mental rotation task itself can be generalised across stimulus type, task, and subject populations. However, for children this effect was independent of the format of the stimuli, while for adults the effect was larger for mirror-imaged than for identical objects. This suggests that the violation of pure insertion might occur at different processing stages as a function of age.

PsycINFO classification: 2340

Keywords: Mental rotation; Pure insertion; Children; Adults; Spatial processing

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doi:10.1016/j.actpsy.2005.12.006

1. Introduction

The cognitive process of imagining the representation of an object turning around is called mental rotation (Shepard & Metzler, 1971) and constitutes an important aspect of the general class of spatial transformations as well as a critical ingredient in spatial intelligence. Thanks to the many fields dealing with mental rotation, a bulk of evidence has accumulated suggesting, e.g., that mental rotation is implemented in the parietal cortex (e.g., Jordan, Heinze, Lutz, Kanowski, & Jäncke, 2001) and works in a continuous, analog way (e.g., Heil, Bajric, Rösler, & Hennighausen, 1997).

The mental rotation process is typically studied in the mirror-normal discrimination task (Cooper & Shepard, 1973) with stimuli presented in different orientations. Participants are required to decide whether e.g., an alphanumeric character is presented in its normal form or as a mirror image. The overall finding is an approximately linear increase of reaction time with increasing angular departure from the upright. It is assumed that participants rotate a stimulus back into the upright position before a mirror-normal judgement can be made. The processing stages involved in a mental rotation task at least include stimulus identification, mental rotation, parity judgement, response selection and motor processes (see, e.g., Heil, 2002), with the duration of the mental rotation process being a function of stimulus orientation. If the stimulus is upright, no mental rotation should be involved at all. The mental rotation process is needed when subjects have to decide on the parity of visual stimuli from different viewpoints (e.g., Vanrie, Beatse, Wagemans, Sunaert, & Van Hecke, 2002) but not necessarily when viewing three-dimensional objects from different viewpoints (e.g., Gauthier et al., 2002; Willems & Wagemans, 2001).

The question arises whether mental rotation fulfils the requirements of "pure insertion" in that kind of task. Donders (1868/1969) assumed pure insertion, which means that a mental process can be added or omitted without altering the speed of other processes like stimulus identification or response selection. He concluded that if the validity of the pure insertion assumption is given, then the subtraction method can be used to measure the speed of mental processes. If two tasks requiring the same composition of identical subprocesses differ only in that one task requires an additional mental process, then the difference in reaction time (RT) of the two tasks would measure the duration of the extra mental process.

Donders's assumption was massively criticized for a number of reasons (for a review, see e.g., Ilan & Miller, 1994; Sternberg, 1969), based both on introspective reports (e.g., Külpe, 1909) as well as on empirical data (Ulrich, Mattes, & Miller, 1999). The assumption of pure insertion, however, might be correct for some mental processes in some tasks but not for other processes or for the same processes in other tasks. It is, therefore, an empirical question whether pure insertion is satisfied for mental rotation or not.

This question was addressed by Ilan and Miller (1994) in detail. In their first experiment, participants had to solve a mirror-normal discrimination task with normal versus mirror image characters in two different experimental conditions: In the SU-condition (sometimes upright), the stimuli were presented sometimes upright and sometimes rotated in different orientations. In the AU-condition (always upright) the stimuli were presented always upright. The results clearly revealed that subjects took substantially longer to respond to upright characters in conditions containing rotated stimuli (SU) than in conditions containing only upright stimuli (AU). Furthermore, the authors showed that this "rotational uncertainty" effect was not caused by the need to determine stimulus orientation, was independent of the visual quality of the stimulus, and only appeared in a choice reaction time task but not in a go-no-go task.

Ilan and Miller (1994) argue that in a mirror-normal discrimination task, the process of response selection is altered when mental rotation is added thus violating the assumption of pure insertion.[1] This conclusion, in fact, suggests a level of generalisation that is not fully justified by the experiments reported. It is the goal of our study to evaluate the generalisability of Ilan and Miller's (1994) finding with respect to: (a) stimulus type, (b) type of task, and (c) subjects' age.

Given the fact that (upright) alphanumeric characters are massively over-learned, an alternative interpretation for the findings of Ilan and Miller (1994) is at least possible, suggesting that subjects use some kind of "short-cut" in order to identify characters' parity in the AU-condition. If this is true, the whole composition of sub-processes might differ between SU- and AU-conditions, and the conclusion of Ilan and Miller (1994) would have to be modified substantially. To learn more about whether the violation of pure insertion observed by Ilan and Miller (1994) can be generalised, the goal of the present study was to extend their results in three different aspects: (1) we used other experimental stimuli than characters, i.e., animal pictures which are not overlearned; (2) we used a same/different comparison task instead of the single-stimulus mirror-normal task realised by Ilan and Miller (1994). This task should demand fewer memory processes; and (3) we tested children in addition to adults in order to figure out whether the violation of pure insertion during mental rotation is already present for elementary school children.

Under a developmental perspective, empirical evidence suggests that children are able to solve mental rotation tasks even before entering school if sufficiently simple stimuli are used which are easily identified by young children (Courbois, 2000). Moreover, the speed of mental rotation increases during childhood (Kail, 1991). The finding of a violation of pure insertion during mental rotation also for children would constitute additional evidence that the findings of Ilan and Miller (1994) are not restricted to massively overlearned stimuli.

To summarize, it is our goal to investigate the generalisability of the violation of pure insertion in a mental rotation task observed by Ilan and Miller (1994) under a developmental perspective with stimuli other than characters and a task that differs from the one used in the original study. We chose simple drawings of animals (Rossion & Pourtois, 2004) given that these stimuli are sufficiently simple to be mentally rotated by children aged 8–10 years (Wiedenbauer & Jansen-Osmann, in press), and at the same time, are not massively over-learned as characters are (at least for adults).

If mental rotation indeed is purely inserted into the sequence of processes required for the same-different comparison, then no difference in RT should be found between upright stimuli in conditions containing only upright stimuli and conditions also containing rotated stimuli. If, however, pure insertion is violated during mental rotation as suggested

[1] Ilan and Miller (1994) incorporated their experiments into the framework of Donders's subtraction method, and therefore, we followed this line of reasoning. Alternatively, it is easily possible to use the idea of switching costs as a framework (see, e.g., Rogers & Monsell, 1995) for describing the findings reported by Ilan and Miller (1994) as well as those in the present paper. The RT difference between pure and mixed blocks, then, is denoted as "mixing costs", which, with respect to the normal and mirror versions, turned out to be asymmetrical. A comprehensive review of mixing costs with special emphasis on different views of their origin is given by Los (1996).

by Ilan and Miller (1994), then RT to upright drawings should be faster in conditions containing only upright stimuli. A crucial technical problem, i.e., to control for stimulus probability, was already solved smartly by Ilan and Miller (1994), and we followed this solution. The 12 drawings used were divided into 3 sets of 4 drawings. One set always appeared upright in both conditions of trials, and these stimuli resulted in the crucial RTs. A second set appeared upright in the AU condition but at a 90° rotation in the SU one. A third set of 4 drawings also appeared upright in the AU condition but at a 180° rotation in the SU one. Because all stimuli appeared equally often in both conditions, this arrangement equated stimulus probability. Which drawing was used in which set was counterbalanced across subjects.

2. Methods

2.1. Subjects

Forty-eight children between the age of 8 and 10 (24 males, 24 females) and 48 adults (24 males, 24 females) participated in this study.[2] The mean age of the children was 9.04 years and that of the adults 24.73. Children were recruited through advertisements in local newspapers.

2.2. Apparatus and stimuli

The experiment was run on a PC with a 17″ monitor located approximately 60 cm in front of the subjects. The experimental stimuli consisted of coloured drawings of 12 different animals (camel, crocodile, dog, donkey, elephant, grizzly, lion, pig, rhino, sheep, turtle, and zebra, respectively, from Rossion & Pourtois, 2004). Each drawing was used, when presented upright, in one version facing to the left and one facing to the right.

Two drawings of the same animal were presented together. The left drawing was presented always upright facing either to the left or to the right. The right drawing was either facing to the same side or was a mirror image of the left. Furthermore, the right drawing was rotated 0°, 90° or 180° clockwise in the SU condition but was always upright in the AU one. Subjects responded "same" by pressing the left mouse button with their index finger and "different" by pressing the right mouse button with their middle finger.

2.3. Procedure

Individual test sessions lasted about 60 min and took place in a laboratory at the Heinrich-Heine-University of Duesseldorf. Subjects were told to respond as quickly and as accurately as possible. Each session consisted of two conditions, the order of which was counterbalanced across subjects, an AU- and a-SU condition, each one preceded by 48 corresponding practice trials. In the AU-condition all drawings of animals were presented upright, in the SU-condition some animals were upright but others were rotated at 90° or 180°. Before each condition, participants were given instructions on the nature of the task

[2] All analyses were run with "gender" included as a between-subject effect. Gender, however, resulted in no reliable main effect or interaction term at all.

required and they were told that stimuli would appear always upright (in the AU-condition) or sometimes upright (in the SU-condition).

Trials were presented in blocks of 48 trials each. The procedure was partially self-paced in that the subjects initiated each block by pressing a key. Each trial began with a 500 ms lasting blank screen. Thereafter, the pair of drawings appeared and remained on until the subject responded. Following a correct response a "+" appeared and following an incorrect response a "−" appeared in the centre of the screen for 500 ms. After 1500 ms the next trial began. Each combination of facing of the left drawing (left-right), format of the right one (same-mirror reversed), and animal (12) occurred three times resulting in 144 experimental trials for each experimental condition.

3. Results

Only trials with correct responses were used for RT analyses. Prior to analyses, RT data were trimmed. RTs more than 2 SDs above or below the mean per condition and per subject were excluded. RTs in the SU condition (see Table 1) served as a manipulation check to validate that subjects indeed were using mental rotation to solve the task. We found main effects of age group, angle of orientation, and format, and three two-way interactions between the factors angle of orientation and format, angle of orientation and age group and angle of orientation and order of presentation.

RTs in the SU condition increased with increasing angular disparity, $F(2,184) = 831.38$, $p < .01$, indicating a speed of mental rotation of about 447°/s. Adults responded faster than children (885 versus 1193 ms, $F(1,92) = 178.25$, $p < .01$). RT to normal stimuli (997 ms) were faster than RT to mirror pairs (1089 ms, $F(1,92) = 96.19$, $p < .01$). Moreover, we found three two-way interactions involving the factor stimulus orientation: with factor format, $F(2,184) = 9.67$, $p < .01$, indicating the well-known pattern of larger mirror-normal differences for upright than for upsight-down stimuli. With factor order of presentation, $F(2,184) = 4.59$, $p < .05$, indicating somewhat slower rotation rates when SU was performed second (417 versus 483°/s), and finally, with factor age group, $F(2,184) = 6.87$, $p < .01$, indicating an age effect of about 290 ms for both upright and upsight-down stimuli that was increased to about 380 ms when the angular disparity was 90°.

The comparison of main interest, however, was the effect on upright stimuli of the condition in which they appeared (see Table 1). Responses to these stimuli were 38 ms faster in the AU than in the SU condition ($F(1,92) = 30.62$, $p < .01$), see Fig. 1. Moreover, in addition to main effects of age ($F(1,92) = 204.19$, $p < .01$) and format ($F(1,92) = 138.32$, $p < .01$), we obtained a two-way interaction of condition and format ($F(1,92) = 8.12$,

Table 1
Mean RT (and SE in parentheses) as a function of AU-SU-condition, stimulus orientation, format, and age group, respectively

Age group	Format	AU (0°)	SU (0°)	SU (90°)	SU (180°)
Children	Same	892.34 (16.87)	926.27 (19.07)	1159.57 (22.02)	1345.36 (21.56)
	Different	999.61 (18.66)	1034.53 (17.43)	1277.72 (21.43)	1417.29 (22.71)
Adults	Same	635.96 (12.61)	653.34 (13.35)	819.34 (16.95)	1076.31 (21.83)
	Different	664.21 (15.66)	730.40 (14.90)	916.80 (19.9)	1114.27 (24.21)

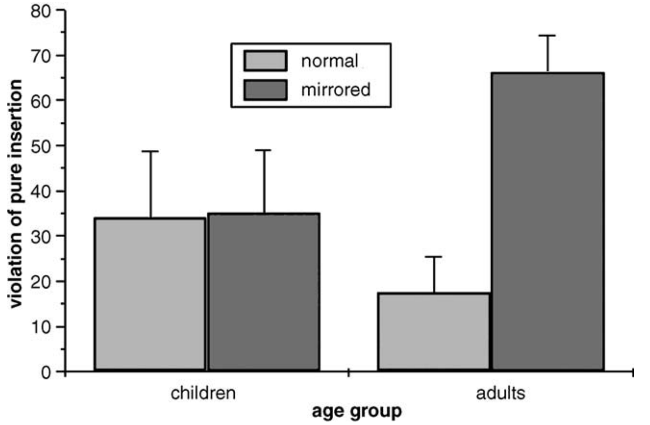

Fig. 1. Mean effect (in ms) of condition as a function of format and age group (error bars indicate SE). Shown is the amount of violation of pure insertion, i.e. the differences in RT for upright stimuli embedded in rotated stimuli minus RT of the same upright stimuli embedded in all upright stimuli only.

$p < .01$) as well as a three-way interaction of condition, format and age ($F(1,92) = 7.46$, $p < .01$): For adults, the effect of AU- versus SU-condition was more pronounced for mirrored than for normal pairs of drawings (17 versus 66 ms) whereas the effect did not depend on the format for children (34 versus 35 ms, respectively). Tested individually, all four AU- versus SU-condition effects differed reliably from zero (t-values: 2.19, 8.23, 2.28, 2.50, respectively, all $p < .05$).

Additionally, the two-way interaction of format by age group turned out to be reliable ($F(1,92) = 16.34$, $p < .01$) indicating a smaller difference between normal and mirror reversed drawings for adults (645 versus 697 ms) than for the children (909 versus 1017 ms). Finally, we obtained a two-way interaction of condition and order of presentation ($F(1,92) = 5.63$, $p < .05$), indicating a larger effect of condition when the SU block was done first (22 versus 55 ms).

Error rates were rather low, and as the only reliable effect we obtained an interaction of age group by condition. Whereas error rate for adults did not depend on block type (1.7% versus 1.2%), children made slightly more errors in the SU condition compared to the AU one (7.6% versus 5.0%).

4. Discussion

We tested the assumption of pure insertion of the mental rotation process into a same/different comparison task by comparing RTs to upright stimuli embedded in upright stimuli only, with RT to the same upright stimuli embedded in with stimuli at other orientations, containing the same instructions, the same decisions, the same responses, as well as the same stimulus probability. Moreover, the RTs in the SU condition as a function of character orientation successfully served as a manipulation check that subjects indeed mentally rotated the stimuli when they were non-upright.

The results are pretty straightforward: the violation of pure insertion during mental rotation obtained by Ilan and Miller (1994) with alphanumeric characters as stimuli, with a single-stimulus mirror-normal discrimination task, and with adults as subjects can indeed be generalised more widely. The violation was obtained also with drawings of animals as stimuli, with a same/different comparison task, and not only with adults but also with children aged 8–10 years as subjects. Therefore, the conclusion reached by Ilan and Miller (1994), that the mental rotation process is not purely inserted into a mirror-normal discrimination task, is not restricted to the massively over-learned stimuli used in their study. Moreover, the conclusion is also not restricted to a single-stimulus mental rotation task requiring the comparison with a memory representation of the normal stimulus but is also found with a two-stimulus task where the comparison is made with the visually presented normal form. Thus, a reduction of memory demands did not change the pattern of results.

As expected, children needed more time to complete the mental rotation task than adults, and their speed of mental rotation was also slower. But a new result is that children in their early school years also show a violation of pure insertion in the mental rotation task. In contrast to the adults, however, this effect did not depend upon the format of the stimuli. A possible explanation for this observation rests on the conclusions that were reached by Ilan and Miller (1994). The authors suggested that the process of response selection is altered when mental rotation is added. This conclusion was based, inter alia, on the observation that the AU- versus SU-condition effect was larger for mirror image than for normal versions, an observation replicated in our study with the adults. According to Ilan and Miller (1994), this is due to the fact that response selection is more difficult for mirror stimuli because the "default value" for the response is "normal". According to our data, the idea of a "normal (or "same") is the default response" does hold even more so for the children given that the format effect was about three times larger for the children than for the adults. Nevertheless, the size of the violation effect (see Fig. 1) did not depend on the drawings format for the children while it did so for the adults. This might suggest that the violation of pure insertion despite being present for both adults and children might be caused by an alteration of distinct processing stages as a function of age. One might speculate that whereas the violation is located in the response selection stage for adults, it might be located at the stage of stimulus identification for children. More data are needed to test this hypothesis explicitly.

Acknowledgements

This study was supported by the German Research Foundation. We thank Conny Delbos, Leonie Lange, Monika Renvert and the students of the cognitive psychology course for their help during data acquisition. We gratefully appreciate the helpful comments of Jeff Miller, Bruno Rossion, and Johan Wagemans on an earlier version of this manuscript.

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