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Maintaining readiness for mental rotation interferes with perceptual processes in children but with response selection in adults

Petra Jansen-Osmann *,[1], Martin Heil [1]

Department of Experimental Psychology, Heinrich-Heine-University, 40225 Düsseldorf, Germany

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Abstract

Previous work revealed that mental rotation is not purely inserted into a same-different discrimination task. Instead, response time (RT) is slowed to upright stimuli in blocks containing rotated stimuli compared to RT to the same upright stimuli in pure upright blocks. This interference effect is a result of maintaining readiness for mental rotation. In two experiments we investigated previous evidence that these costs depend upon distinct sub-processes for children and for adults. In Experiment 1, the maintaining costs turned out to be independent of the visual quality of the stimulus for adults but not so for children. Experiment 2 revealed that the maintaining costs were greatly reduced for adults when they performed mental rotation as a go-no-go task, but not so for children. Taken together, both experiments provide evidence that whereas perceptual processes seem to be important for school-age children to maintain readiness for mental rotation, response selection is relevant for adults.

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

* Corresponding author. Tel.: +0211 811 5629.
E-mail addresses: Petra.Jansen-Osmann@uni-duesseldorf.de (P. Jansen-Osmann), Martin.Heil@uni-duesseldorf.de (M. Heil).
[1] Both authors contributed equally to this work.

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1. Introduction

Mental rotation refers to the cognitive process of imagining how an object would look if rotated away from the orientation in which it is actually presented (Shepard & Metzler, 1971). This process is typically studied in a same versus different (i.e., mirror reversed) discrimination task (Cooper & Shepard, 1973) with stimuli presented in different orientations. The overall finding is that reaction time (RT) increases linearly with increasing angular disparity between the stimuli. It is assumed that participants rotate the stimulus back into the upright position before a same-different comparison can be made. 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).

Children are also able to solve this kind of task even before entering school if stimuli are used that are easily identified (Courbois, 2000). Marmor (1975, 1977) was the first to study mental rotation in children in a systematic way. Her aim was to disprove the assumption of Piaget and Inhelder (1971) that children are not able to represent kinetic images until after the age of 7 or 8. She provided evidence that even 4- and 5-year-old children use mental rotation to solve the task with two-dimensional figures. However, 8-year-olds were about twice as fast as 5-year-olds in their speed of mental rotation. The developmental functions of processing speed were investigated in detail by Kail (1988, 1991), Kail, Pellegrino, and Carter (1980). Interestingly, Kail (1988) obtained evidence that the response time decrease with increasing age for different cognitive tasks (visual search, memory search, mental rotation) from primary school age to adolescence was described pretty well by exponential functions with one common rate of change. This pattern of results suggests that some general mechanism (or processing resource) exists that limits performance on cognitive tasks, and that increases in "quantity" with age (see Kail, 1988). Nevertheless, recent evidence (Heil & Jansen-Osmann, in press; Jansen-Osmann & Heil, in press) suggests that the developmental change at least with respect to mental rotation can not fully be accounted for without assuming also qualitative developmental changes.

In a well-controlled series of studies with adults, Ilan and Miller (1994) provided intriguing evidence that maintaining readiness for mental rotation can be dissociated from the process of mental rotation itself. Ilan and Miller (1994) used the framework of Donders (1868/1969) subtraction method to investigate whether or not the mental rotation process is purely inserted into a same/different comparison task. According to Donders (1868/1969), pure insertion means that a mental process can be added or omitted without altering the speed of other processes like stimulus identification or response selection. Donders' assumption was massively criticized for a number of reasons (for a review, see e.g., Sternberg, 1969), based both on introspective reports (e.g., Külpe, 1909) as well as on empirical data (Ulrich, Mattes, & Miller, 1999). Whether pure insertion is satisfied for mental rotation or not was addressed by Ilan and Miller (1994) in detail. The logic of their experiments reads as follows: When the stimulus pair is presented with an angular disparity of, e.g., 90°, then the following processing stages should occur: (1) perceptual processing including stimulus identification, (2) 90° mental rotation, (3) same vs. different judgement including response selection, (4) response preparation and execution. When both stimuli are presented upright, however, no mental rotation is needed, and only steps 1, 3, and 4 are executed. Given the validity of the pure insertion assumption, RT to upright stimuli in a block with stimuli at other orientations (SU-block, i.e., **S**ometimes **U**pright) should not differ from the RT to upright stimuli in a block with upright stimuli only

(AU-block, i.e., **A**lways **U**pright), given that the conditions did not differ with respect to instructions, decisions, responses, as well as stimulus probabilities, a problem smartly solved by Ilan and Miller (1994), as described below.

Using characters as stimuli, Ilan and Miller (1994) clearly revealed that subjects took substantially longer to respond to upright characters in blocks containing rotated stimuli (SU) than in blocks containing only upright stimuli (AU), thus violating the pure insertion assumption. The additive factor method developed by Sternberg (1969) was used to discover the source of the pure insertion violation. The authors showed that this ''rotational uncertainty'' effect (a) was not caused by the need to determine stimulus orientation, (b) was independent of the visual quality of the stimulus, (c) was more pronounced for ''mirror'' responses than for ''normal'' responses, (d) only appeared in a forced-choice reaction task but not in a go-no-go task, and (e) did not depend upon the complexity of response preparation. Thus, it appears that for adults, perceptual processes as well as response preparation operates at approximately the same speed in AU and SU blocks while response selection is the primary site for the rotational uncertainty effect. Moreover, Ilan and Miller (1994) obtained evidence that the rotational uncertainty effect was hardly modified by the angular deviation occurring on the previous trial in the SU block. Thus, even when the analysis was restricted to upright stimuli that followed upright stimuli in the previous trial, the violation still occurred (see, e.g., Los, 1996).

To sum up, the interference is not caused by the process of mental rotation itself. The interference was obtained with upright stimuli, and no mental rotation is required on these trials. Therefore, Ilan and Miller (1994) concluded that (a) the crucial process is maintaining readiness for mental rotation which (b) interferes with response selection.

Jansen-Osmann and Heil (2006) recently investigated whether the results of Ilan and Miller (1994) can be generalised across the specific experimental details realised. In contrast to the work of Ilan and Miller (1994), we used different experimental stimuli (pairs of drawings of animals instead of single characters), a different task (a same/different comparison between two stimuli instead of a mirror/normal discrimination) and investigated the rotational uncertainty effect under a developmental perspective. We found evidence that, in general, the rotational uncertainty effect can be generalised across stimulus type, task, and subject populations. Adults as well as children between the age of 8 and 10 took significantly longer to respond to upright drawings of animals in blocks containing rotated stimuli than in blocks containing only upright stimuli. Most crucially, however, whereas this effect depended on the response type (same versus different) for adults, the rotational uncertainty effect was independent of the response type for children. The adults' larger effect for different than for same responses was in line with the results of Ilan and Miller (1994), and constituted converging evidence that maintaining readiness for mental rotation interferes with response selection. Response selection is assumed to be easier for ''same'' responses than for ''different'' responses (Cooper & Shepard, 1973). This conclusion was validated by the finding of Ilan and Miller (1994) that the rotational uncertainty effect disappeared in a go-no-go task, i.e., a task where response selection is substantially reduced in difficulty.

We (Jansen-Osmann & Heil, 2006) took our finding of an equal-sized rotational uncertainty effect for ''same'' versus ''different'' responses for children aged 8–10 years as preliminary evidence for a *qualitative difference* between adults and school-aged children. We hypothesised that the rotational uncertainty effect might not originate from interference of maintaining readiness for mental rotation with response selection for children as it can be assumed for adults, but instead might possibly originate from interference of maintaining readiness for mental rotation with the perceptual process of stimulus identification. To test this hypothesis explicitly, two experiments are presented: In the first experiment we investigated the role of perceptual processes, while in the second one we concentrated on the response selection stage.

If the rotational uncertainty effect found by Ilan and Miller (1994) for adults and by Jansen-Osmann and Heil (2006) for children and adults depends on the response selection stage for adults but on perceptual processes for children, clear predictions follow from the Sternberg (1969) additive factor method when manipulating the perceptual quality of the stimuli: If the addition of mental rotation slows perceptual processing for children, then the rotational uncertainty effect should be larger when visual quality is poor. For adults, however, Ilan and Miller (1994) successfully demonstrated that the rotational uncertainty effect did not depend upon the perceptual quality of the stimuli, a finding that should be replicated. Additionally, the interaction between response type and age group reported by Jansen-Osmann and Heil (2006) and described above should also be replicated, providing evidence that response selection is crucial for the rotational uncertainty effect of adults but not so for children.

2. Experiment 1

2.1. Methods

2.1.1. Subjects

Forty eight children between the age of 8–10 (24 males, 24 females) and 48 adults (24 males, 24 females; age range 19–41 years) participated in this study. The mean age of the children was 8.66 years and that of the adults 29.22 years. Children were recruited through advertisements in local newspapers.

2.1.2. Apparatus and stimuli

The experiment was run on a PC with a 17'' monitor located approximately 60 cm in front of the subjects. As in the study of Jansen-Osmann and Heil (2006), 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, with 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 block 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.

A crucial technical problem, i.e., to control for stimulus, decision and response probabilities, was already solved by Ilan and Miller (1994), and we followed this solution. The 12 different drawings used in our study were divided into three sets of four drawings. One set always appeared upright in both conditions of trials, and these stimuli resulted in the crucial RTs to be compared. A second set of four drawings appeared upright in the AU condition but at a 90° rotation in the SU one. A third set of four 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 as well as response probability. Which drawing was used in which set was counterbalanced across subjects.

The experimental manipulation of visual quality was added such that half of the stimuli (randomly intermixed) were visually degraded by superimposing random patterns of coloured dots over them. This is a method used by Ilan and Miller (1994) and known as effective in increasing perceptual recognition time (e.g., Hansen & Sanders, 1988).

2.1.3. 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 blocks of 192 trials, the order of which was counterbalanced across subjects, an AU- and a SU-block, each one preceded by 48 corresponding practice trials. In the AU-block, all drawings of animals were presented upright, in the SU-block some animals were upright but others were rotated at 90° or 180°. Before each block, participants were given instructions on the nature of the task.

Each trial began with a blank screen lasting 500 ms. Thereafter, the pair of drawings appeared and remained on until the subject responded. Following a correct response, a "+", following an incorrect response, a "−", appeared in the centre of the screen for 500 ms. After 1500 ms the next trial began. After every 48 trials, a break of self-determined length was introduced. Each combination of facing of the left drawing (left–right), format of the right one (normal-mirror imaged), animal (12) and visual quality (intact-degraded) occurred twice resulting in 192 experimental trials for each experimental block.

2.1.4. Experimental design

The factor age group (children vs. adults) was varied between subjects. The factors block type (AU vs. SU), perceptual quality (intact vs. degraded), response type (same vs. different) and angular disparity in the SU-condition (0°, 90°, 180°) were varied within subjects. The order of presentation between the AU and SU block and the gender of the participants were balanced. Reaction time and error rates served as dependent variables. Analyses of variance were calculated, and the significance levels were corrected according to the method of Huynh and Feldt (1976) to compensate for non-sphericity of the data.

2.2. Results and discussion

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 (6.4% on average). RTs in the SU block (see Fig. 1) served as a manipulation check to validate that subjects indeed were using mental rotation to solve the task.

2.2.1. RT in the SU block

The main-effects of the factors age group, $F(1,94) = 72.74$, $MS_e = 1387434$, perceptual quality, $F(1,94) = 130.24$, $MS_e = 19620$, response type, $F(1,94) = 33.70$, $MS_e = 58844$, and angular disparity, $F(2, 188) = 109.98$, $MS_e = 206289$, all $p < .01$, were significant. RTs in the SU block increased with increasing angular disparity indicating a speed of men-

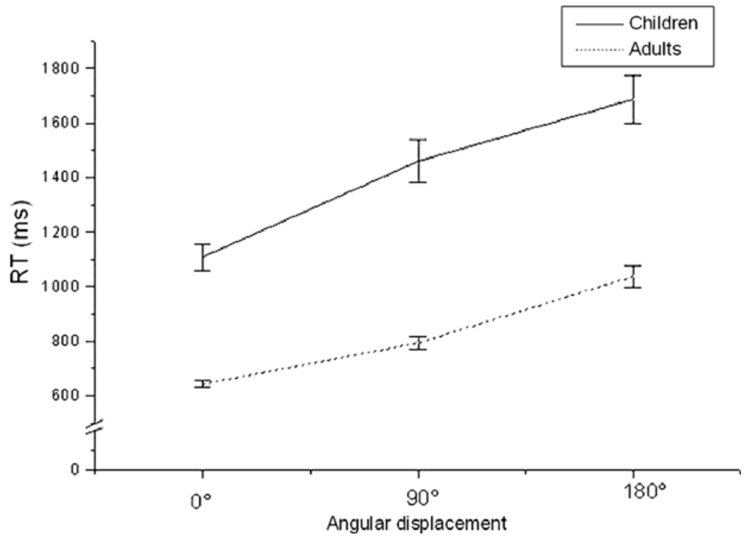

Fig. 1. Mean RT (in ms) as a function of angular disparity and age group in the SU-block in Experiment 1 (error bars indicate standard errors).

tal rotation of about 370°/s. Adults responded substantially faster than children (824 ms vs. 1416 ms). RTs to same stimuli were faster than RTs to different stimuli (1079 ms vs. 1162 ms), and, additionally, RTs to intact stimuli (1073 ms) were faster than RTs to degraded stimuli (1168 ms), validating our experimental manipulation of perceptual quality.

Moreover, we found two two-way interactions involving the factors age group and angular disparity, $F(2, 188) = 5.75$, $MS_e = 206\,289$, and age group and perceptual quality, $F(1,94) = 50.62$, $MS_e = 19\,620$, both $p < .01$: First of all, the RT difference between the 180° and 0° condition turned out to be larger for the children than for the adults (578 ms vs. 393 ms), see Fig. 1. Second, the effect of perceptual quality was larger for children than for adults (153 ms vs. 35 ms).

2.2.2. *The rotational uncertainty effect*

Error rates again were low, and as the only reliable effects we obtained effects of age group, $F(1,94) = 8.28$, $MS_e = .003$, response type, $F(1,94) = 27.7$, $MS_e = .002$, both $p < .01$ and an unsystematic three-way interaction between the factors block type, response type and perceptual quality, $F(1,94) = 4.01$, $MS_e = .002$, $p < .05$, which is not relevant in this context. Children made more errors than adults (1.4% vs. 0.6%), all participants made more errors with different than with same responses (1.5% vs. 0.5%).

The comparison of main interest, however, was the RT effect on upright stimuli of the block type in which they appeared. We found main effects of age group, $F(1,94) = 113.49$, $MS_e = 1411\,493$, perceptual quality, $F(1,94) = 194.16$, $MS_e = 9034$, response type, $F(1,94) = 43.45$, $MS_e = 53\,580$, and block type, $F(1,94) = 46.99$, $MS_e = 9034$, all $p < .01$. Responses were faster for adults (603 ms) than for children (1041 ms), in the AU (770 ms) than in the SU block (875 ms), for same (785 ms) than for different responses (860 ms) and faster for intact (790 ms) than for degraded stimuli (855 ms), validating the experimental manipulation of perceptual quality.

Moreover, in addition to the main effects we found two two-way interactions between the factors age group and response type, $F(1,94) = 4.68$, $MS_e = 53\,580$, $p < .05$, and between age group and perceptual quality, $F(1,94) = 49.71$, $MS_e = 9034$, $p < .01$. The

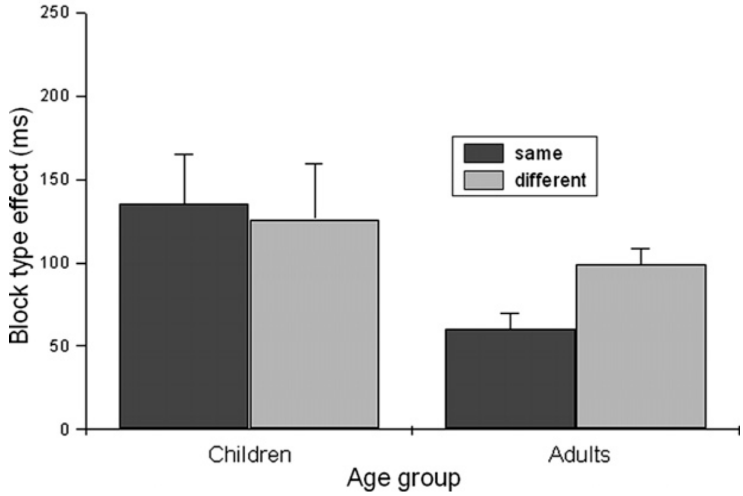

Fig. 2. Mean effect (in ms) of block type as a function of response type and age group (error bars indicate standard errors) in Experiment 1. Shown is the amount of violation of pure insertion, i.e., the differences in RT for upright stimuli embedded in block with rotated stimuli minus RT of the same upright stimuli embedded in blocks with upright stimuli only.

difference in the RT between same and different responses was larger for children (99 ms) than for adults (50 ms). Furthermore, the RT-difference between degraded and intact stimuli was also larger for children (97 ms) than for adults (32 ms).

In addition to the interactions mentioned above, we obtained two three-way interactions of block type, age group and perceptual quality, $F(1,94) = 20.60$, $MS_e = 14375$, $p < .01$ and of block type, age group and response type, $F(1,94) = 4.10$, $MS_e = 9899$, $p < .05$, that constitute the theoretically most relevant results of Experiment 1. First of all, the size of the rotational uncertainty effect as a function of age group did depend upon the format of the stimuli, replicating the results of Jansen-Osmann and Heil (2006), see Fig. 2. Whereas the rotational uncertainty effect for children did not depend upon the format (and, thus, the difficulty of the response selection stage, see Cooper & Shepard, 1973; Ilan & Miller, 1994), for adults the rotational uncertainty effect was found to be larger for different (99 ms) compared to same responses (60 ms), see Fig. 2. Moreover, for intact stimuli, we replicated the results of Jansen-Osmann and Heil (2006), i.e., a rotational uncertainty effect of equal size for children (83 ms) and for adults (82). When the visual quality was degraded, however, the rotational uncertainty effect increased substantially for children (178 ms) but did not change at all for adults (77 ms), see Fig. 3.

With this experiment we tested the hypothesis that the violation of pure insertion might originate in perceptual processes for children but not for adults. Our results are straightforward: Children and adults indeed mentally rotated the stimuli, as was validated in the SU block. Furthermore, we replicated the rotational uncertainty effect for children and adults in a same/different comparison task (Jansen-Osmann & Heil, 2006). Both children and adults needed more time to respond to upright stimuli embedded in blocks with stimuli at other orientations compared to the same upright stimuli embedded in blocks with upright stimuli only. Moreover, with intact stimuli we replicated the pattern of results obtained by Jansen-Osmann and Heil (2006) that the rotational uncertainty effect depended upon response selection for adults but not so for children because the interaction with response type was present for adults but again absent for children. Most importantly, however, the rotational uncertainty effect for children was substantially larger than

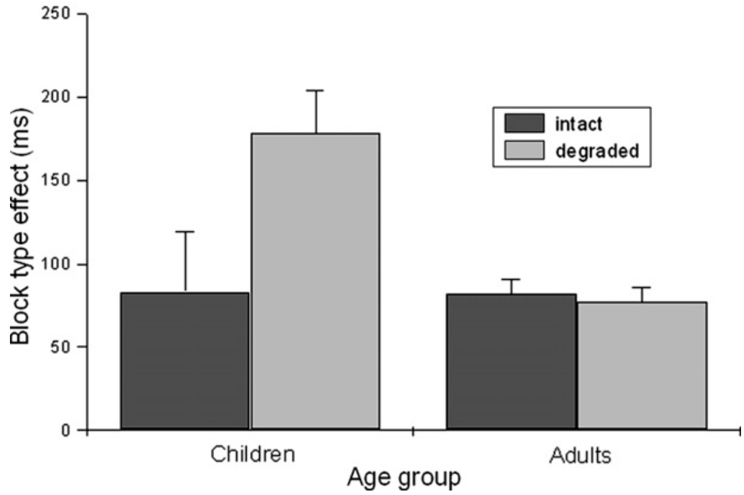

Fig. 3. Mean effect (in ms) of block type as a function of perceptual quality and age group (error bars indicate standard errors) in Experiment 1. Shown is the amount of violation of pure insertion, i.e., the differences in RT for upright stimuli embedded in blocks with rotated stimuli minus RT of the same upright stimuli embedded in blocks with upright stimuli only.

for adults only in the condition with degraded stimuli. With intact stimuli, there was no difference in the rotational uncertainty effect between children and adults. Thus, while the interference is independent of perceptual processes for adults, this pattern constitutes strong evidence for the assumption that the interference depends upon perceptual processing for children.

If the rotational uncertainty effect indeed depends on the response selection stage for adults but not so for children, this effect should be reduced or eliminated in an easier response selection task like a go-no-go task for adults only. We expected that only small or no difference in reaction time should be found between upright stimuli in blocks containing only upright stimuli and in blocks also containing rotated stimuli for adults in a go-no-go task. If, however, the violation of pure insertion during mental rotation does not depend on the response selection processing stage for children, then reaction time to upright drawings should be faster in blocks containing only upright stimuli for children. Therefore, the rotational uncertainty effect, of equivalent size for children and adults in a choice task, should be substantially larger for children than for adults in a go-no-go task.

3. Experiment 2

3.1. Methods

3.1.1. Subjects

Forty eight children between the age of 8–10 years (24 males, 24 females) and 48 adults (24 males, 24 females, age range 19–36 years) participated in this study. The mean age of the children was 8.29 years and that of the adults 23.99 years. Children were recruited through advertisements in local newspapers.

3.1.2. Apparatus, stimuli and procedure

Apparatus, stimuli and procedure were the same as described in the condition of intact visual stimuli of Experiment 1, with one exception: Half of the subjects of each age group were told to respond "same" by pressing the left mouse button with their index finger and not to respond at all when they saw two animals facing different directions. The remaining subjects had to respond to different stimuli and to withhold any response to the same stimuli. Each trial began with a blank screen lasting 500 ms. Thereafter, the pair of drawings appeared and remained on until the subject responded or until 3.500 ms were over.

3.1.3. Experimental design

The factors age group (children vs. adults) and response mapping ("go" for same vs. "go" for different stimuli) were varied between subjects. The factors block type (AU vs. SU) and angle of orientation in the SU-condition (0°, 90°, 180°) were varied within subjects. The order of presentation between the AU and SU block and the gender of the participants were balanced. Reaction times and error rates served as dependent variables. Analyses of variance were calculated, and the significance levels were corrected according to the method of Huynh and Feldt (1976) to compensate for non-sphericity of the data.

3.2. Results and discussion

3.2.1. RT in the SU block

RTs in the SU block (see Fig. 4) again served as a manipulation check to validate that subjects indeed were using mental rotation to solve the task. Three main effects of the factors age group, $F(1,94) = 101.28$, $MS_e = 104461$, response mapping, $F(1,94) = 9.05$, $MS_e = 104461$, and angle of orientation, $F(2, 188) = 437.38$, $MS_e = 11716$, all $p < .01$, were found. RTs in the SU block increased with increasing angular disparity indicating a speed of mental rotation of about 390.62°/s. Adults responded faster than children (794 ms vs. 1177 ms). RT to same stimuli (928 ms) was faster than RT to different pairs (1043 ms). Moreover, we found one two-way interaction involving the factors age group and angle of orientation, $F(2, 188) = 4.40$, $MS_e = 11716$, $p < .05$, indicating that the reaction time difference between the 180° and 0° condition is larger for children than for adults (504 ms vs. 416 ms, $F(1,94) = 5.00$, $MS_e = 18448$, $p < .05$).

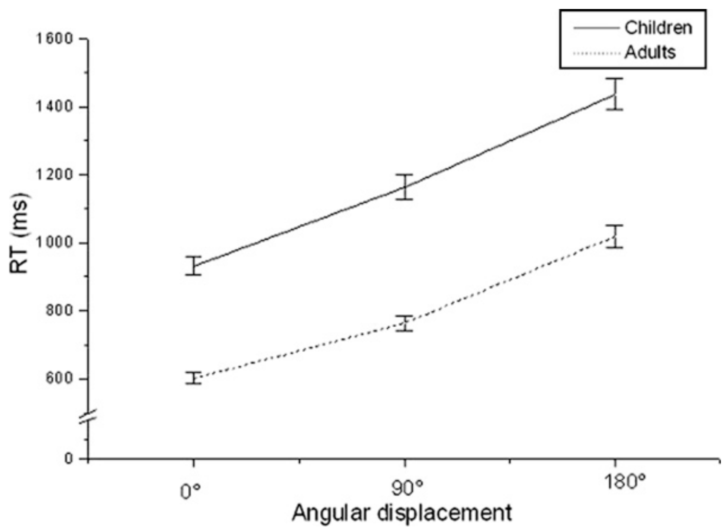

Fig. 4. Mean RT (in ms) as a function of angular disparity and age group in the SU-block in Experiment 2 (error bars indicate standard errors).

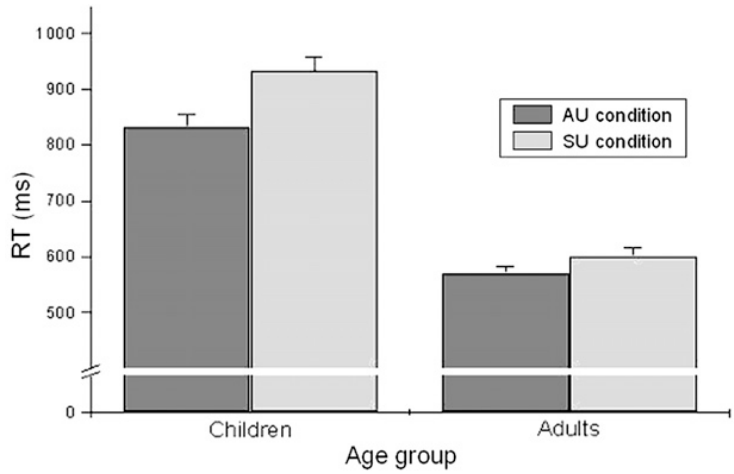

Fig. 5. Mean RT (in ms) for upright stimuli as a function of condition and age group (error bars indicate standard errors) in Experiment 2.

3.2.2. The rotational uncertainty effect

Error rates were very low, and as the only reliable effects we obtained main effects of age group, $F(1,94) = 12.13$, $MS_e = .001$, for misses and $F(1,94) = 17.83$, $MS_e = .001$, both $p < .01$ for false alarms. Children made more errors compared to adults (0.8% vs. 0.0% misses, and 3.0% vs. 0.8% false alarms).

The comparison of main interest, however, was the effect on upright stimuli of the block type in which they appeared. Responses to these stimuli were 65 ms faster in the AU than in the SU block, $F(1,94) = 37.06$, $MS_e = .5541$. Moreover, in addition to the main effect of age group, $F(1,94) = 131.61$, $MS_e = 33295$, we obtained a two-way interaction of block type and age group, $F(1,94) = 10.62$, $MS_e = 5541$, all $p < .01$, see Fig. 5: For children, the effect of AU- vs. SU-block was three times larger than for adults (99 ms vs. 29 ms). Tested individually, both rotational uncertainty effects differed reliably from zero (t values: 2.46 for adults, 5.65 for children, both $p < .05$).

3.2.3. Statistical comparison of the RUE across both experiments

A direct comparison between RT in a two-alternative forced-choice task versus a go-no-go task is problematic because of either an unequal number of stimuli or an unequal number of responses. Moreover, error rates usually differ because of different speed-accuracy trade-offs in these two tasks. Nevertheless, we compared the RUE, i.e., the block type effect, between the two experiments, i.e., the visual intact choice task condition of Experiment 1 and the go-no-go task of Experiment 2. The two-way interaction between age group and experiment turned out to be reliable ($F(1, 188) = 4.51$, $MS_e = 70597$, $p < .05$). The rotational uncertainty effect for children did not differ between the two experiments (83 ms vs. 99 ms). However, the reduction in response selection difficulty from a choice- to a go-no-go-task reduced the rotational uncertainty effect for adults from 82 ms to 29 ms ($F(1,94) = 4.98$, $MS_e = 72132$, $p < .05$).

To sum up, Experiment 2 further tested the assumption that the violation of pure insertion in a mental rotation task found for adults as well as for children might depend upon different processing stages. We used a go-no-go task by comparing RTs to upright stimuli embedded in blocks with upright stimuli only, with RTs to the same upright stimuli embedded in blocks with stimuli at other orientations. Both block types contained the same instructions, the same decisions, the same responses, as well as the same stimulus probabilities. Moreover, the RTs in the SU block as a function of angular displacement successfully served as a manipulation check that subjects indeed mentally rotated the stimuli when they were non-upright.

The results are pretty straightforward again: The rotational uncertainty effect was also evident in a go-no-go task, but with one crucial difference: The violation of pure insertion that turned out to be of equal size for children and adults in a choice reaction task (intact perceptual quality of Experiment 1) was found to be three times larger for children than for adults in a go-no-go task. This finding is pretty much in line with the idea of Jansen-Osmann and Heil (2006) that while maintaining readiness for mental rotation interferes with a more central process related to response selection for adults (see Ilan & Miller, 1994; Ruthruff, Miller, & Lachmann, 1995), it might be more perceptually based for children. If this hypothesis is true, then reducing the difficulty of the response selection process by introducing a simpler go-no-go response mapping (Ilan & Miller, 1994) instead of a two-alternative forced-choice decision should reduce the interference due to the rotational uncertainty effect for the adults but not for the children, exactly what was found. The violation effect for children did not differ between the intact perceptual condition of Experiment 1 that realized a choice task and Experiment 2 that realized a go-no-go task with simpler response selection. Decreasing the response selection difficulty, however, reduced the violation effect for adults, thus substantiating the idea that maintaining readiness for mental rotation interferes with more central process related to response selection for adults only.

With adults, Ilan and Miller (1994) found that the rotational uncertainty effect was reduced to a non-significant 24 ms with a sample-size of 20 subjects. In our Experiment 2 with 48 adults, the 29 ms effect observed still was reliable. Nevertheless, given the differences in power, we do regard our results as a successful replication of the Ilan and Miller (1994) findings.

4. General discussion

In both experiments we found that RTs to upright stimuli were significantly longer when they were embedded in a block of rotated stimuli than when they appeared only with other upright stimuli. This so-called rotational uncertainty effect (Ilan & Miller, 1994) held true for children as well as for adults, thus replicating our first study (Jansen-Osmann & Heil, 2006), for same as well as for different responses, in a go-no-go task as well as in a two-alternative forced-choice task, and for intact as well as for visually degraded stimuli, thus it appears to be a robust phenomenon. Nevertheless, and much more interesting, the size of the rotational uncertainty effect varied in a systematic way that was pretty much in line with the idea originally postulated by Jansen-Osmann and Heil (2006), that the interference effect is localized more centrally involving response selection (substantiating the conclusion of Ilan & Miller, 1994) for adults whereas it involves perceptual processes for children.

This conclusion is based on the following results:

1. The rotational uncertainty effect for intact stimuli in a choice task is of equal size for children and adults.
2. The rotational uncertainty effect for degraded stimuli in a choice task is substantially larger for children than for adults.

3. The rotational uncertainty effect in a choice task depends upon the response type for adults, but is independent of response type for children.
4. The rotational uncertainty effect in a go-no-go task is substantially reduced for adults but not so for children.

Thus, although response type produced a significant effect on RT for both children and adults, the effects of response type and rotational uncertainty were additive for children but interacted for adults such that a smaller effect of uncertainty was found for the simpler "same" response. Additionally, while with intact stimuli and a choice task children and adults showed a rotational uncertainty effect of the same size, using a simpler response mapping in a go-no-go task resulted in a reduction of the rotational uncertainty effect for adults but not so for children. In contrast, although visual quality produced a significant effect on RT for both children and adults, the effects of visual quality and rotational uncertainty were additive for adults but interacted for children such that a smaller effect of uncertainty was found for the simpler intact stimuli. Taken together, the pattern of results obtained in the present study is in line with the conclusion of Ilan and Miller (1994) that the rotational uncertainty effect for adults results from interference with more "central" response selection processes and the hypothesis of Jansen-Osmann and Heil (2006) that the rotational uncertainty effect for children results from interference with perceptual processes. This is an intriguing observation, and further research will be needed to specify the exact nature of this kind of double dissociation.

In accordance with the conclusions derived by Ilan and Miller (1994), it has to be pointed out that maintaining readiness for mental rotation instead of mental rotation itself is interfering with response selection for adults but with perceptual stimulus identification for children. First of all, this conclusion is based on logical grounds. The comparison of interest is based on trials with upright stimuli where no mental rotation itself is required at all. Even more convincing, however, is the empirical basis for this conclusion. If the interference would have been caused by mental rotation itself, then with factor "angular disparity" we should have observed the same pattern of additive and interactive effects we observed with factor AU versus SU block type. But this was not the case. For example, angular disparity and visual quality turned out to be additive for adults as well as for children whereas block type and visual quality were additive for adults but interacted for children. In fact, for all the interactions with block type we found, the corresponding interactions with angular disparity were absent and vice versa. Thus, it is not the cognitive process of mentally rotating a stimulus that double dissociates between children and adults, but it is the sheer maintenance of readiness to mentally rotate a stimulus.

Further research will be needed to evaluate whether this pattern of results holds only true for mental rotation itself, or whether maintaining readiness for other cognitive processes might result in similar patterns of dissociations. If so, then we might suggest general changes in executive control across childhood development (see, e.g., Cepeda, Kramer, & Gonzalez de Sather, 2001). Otherwise, and here at the latest we turn speculative, one might suggest that while adults maintain readiness for mental rotation, they correctly prepare response selection processes because these turned out to be crucial for mental rotation (Band & Miller, 1997; Ruthruff et al., 1995), and thus, the adult pattern of interference might have resulted. Children, however, (as well as some cognitive psychologists in the past) might have been fooled by the apparent similarity of mental rotation with perceptual processes, and thus prepared perceptual processes incorrectly while maintaining readiness for mental rotation.

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