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Abstract

Older participants are slower than younger individuals in rotating objects in their minds. One possible explanation for this effect of age in mental rotation (MR) relies on the different strategies used to perform the task. The present study aimed at exploring whether this account could explain the age-associated slowing in MR with unfamiliar objects. Younger and older participants were assessed with two MR tasks with three- (Exp.1) and two-dimensional objects (Exp.2). In both experiments, these objects were characterised by different complexity levels (simple integrated objects vs. complex multi-part objects). In processing simple objects, the performance of the two age groups was comparable. However, systematic differences were observed between the mental rotation rates of younger and older adults while processing complex objects. Younger participants were faster in processing complex than simple objects, whereas older participants were slower in rotating complex as compared to simple objects. These results revealed that different mental rotation strategies were selected by the two age groups when rotating complex objects. A simplified representation of the objects was generated and transformed by younger participants in their mind's eyes, while a piecemeal transformation strategy was adopted by older participants.

Key words:

mental rotation, strategy selection, aging, unfamiliar objects

Introduction

Mental rotation (MR) refers to the ability to represent and rotate an image in one's mind. It constitutes one important process in the general class of mental transformations as well as a critical component of spatial intelligence. In a classic MR task, introduced by Shepard and Metzler (1971), participants are asked to compare pairs of objects to determine whether they are identical or not. On different trials, these objects are presented with different angular disparities and participants have to mentally rotate one of the objects in order to accurately execute this parity judgement. Typically, response times (RTs) increase linearly with increasing angular disparity (Shepard & Metzler, 1971). Following the presentation of the objects, at least three cognitive sub-processes can be identified in a MR task (Heil, 2002; Stoffels, 1996): an early phase of stimuli identification/encoding, the proper MR process and a late phase of decision-making/response selection. The slope derived from the linear RT function of angular disparity is assumed to reflect the central phase of MR, representing how quickly the mental representation of the object can be rotated in the mind's eyes (MR rate). The intercept derived from the RT function of angular disparity is assumed to reflect the early phase of stimuli encoding/ identification and/or the later phase of decision-making (Cooper & Shepard, 1973; Just & Carpenter, 1976, 1985).

The linear increase in RTs across angular disparities has been observed in both younger and older individuals (Band & Kok, 2000; Borella, Meneghetti, Ronconi, & De Beni, 2014). However, several studies reported systematic differences between age groups indicating an age-associated delay in MR (e.g., Hertzog & Rypma, 1991; Puglisi & Morrell, 1986). More specifically, a larger intercept characterised the performance of older participants indicating an age-associated slowing in either the initial stage of stimuli encoding/ identification or the final decision-making processes (Dror & Kosslyn, 1994).

Furthermore, several studies observed steeper slopes in older compared to younger participants, suggesting the presence of an age-associated slowing of the MR rate (Cerella, Poon & Fozard, 1981; Gaylord & Marsh, 1975). These differences between the estimated slopes of younger and older individuals in MR were present in tasks with unfamiliar objects (Gaylord & Marsh, 1975; Hertzog & Rypma, 1991; Puglisi & Morrell, 1986). However, the evidence is less consistent in MR tasks using familiar objects. Some studies confirmed steeper slopes in older compared to younger participants (Cerella et al., 1981), while others failed to observe an age-related difference in the MR slopes (Jacewicz & Hartley, 1979). Hence, although there is some evidence suggesting systematic slowing of MR rates with age, it is not clear whether this reflects a direct consequence of age on this specific spatial processing or whether it could be accounted for by other variables. For example, the age-associated decline in working memory capacity (Brockmole & Logie, 2013) can help to explain the slower MR rates observed in older participants. In addition, older individuals are found more likely to prioritize accuracy at the expense of response speed, especially when coping with larger rotation angles and therefore produce steeper slopes (Hertzog, Vernon, & Rypma, 1993).

Alternatively, changes in the speed of MR rates can depend on the specific strategy used to perform the MR task, as suggested by recent evidence in younger individuals (Khooshabeh, Hegarty & Shipley, 2013; Zhao & Della Sala, 2018). Two commonly used strategies have been identified to be involved in MR of objects: holistic and piecemeal transformation. The holistic strategy (e.g., Cooper & Podgorny, 1976) refers to a dynamic imagery process in which the object is transformed in one's mind as a whole, akin to its actual physical rotation. By contrast, the piecemeal transformation (e.g., Folk & Luce, 1987) is based on an analytical process that transforms the object feature-by-feature (or piece-by-piece). The typical linear increase pattern seen in RTs with increasing angular disparity could be achieved by using either a holistic or a piecemeal transformation (Cooper 1975; Cooper & Podgorny, 1976). As stimulus complexity increases, more time is needed to transform the features/segments constituting the stimulus and to manipulate their spatial relationship when participants adopt a piecemeal strategy as compared to a holistic one. Thus, a piecemeal transformation strategy results in steeper slopes when the MR task involves complex objects (Folk & Luce, 1987; Yuille & Steiger, 1982), while no effect of stimulus complexity on the estimated slopes is observed during holistic processing because the internal representation of the object is maintained and manipulated as a whole regardless of its complexity (Cooper & Podgorny, 1976).

Strategy selection in MR tasks is directly inferred from the differences between MR slopes observed with objects of different complexities. In the literature, object complexity has been manipulated by changing either the number of the components of an integrated object (Cooper, 1975; Cooper & Podgorny, 1976) or the number of the perceptually distinct pieces that make up multi-part objects. Typically, objects characterised by an increased number of components or pieces are considered as more complex stimuli (Podgnory & Shepard, 1983).

Notably, the strategy used during a MR task may be not only determined by the complexity of the visual stimuli, but also by the way in which these stimuli are mentally represented. In several behavioural experiments, a shallower MR slope was observed for complex as compared to simple stimuli (Yuille & Steiger, 1982; Zhao & Della Sala, 2018), suggesting that the rotation of complex stimuli was faster as compared to simple ones. Such shallower slopes were interpreted as participants' having the ability to generate a partial image of complex stimuli in their minds' eyes to complete the MR tasks (Yuille & Steiger, 1982). Alternatively, Liesefeld and Zimmer (2013) found that redundant information (not relevant for the rotation) could be automatically detected and discarded or ignored by participants, so that only the orientation-dependent information was maintained for further mental processing.

The performance of older individuals in MR tasks, as revealed by a recent study, benefits from specific training that encourages them to use the strategy based on concrete object manipulation and imagery (Meneghetti et al., 2018). In other words, older individuals can learn a specific rotation strategy which results in both short- and long-term improvements in their MR abilities when specifically trained to do so. Here we ask whether the differences in rotation strategy selection can explain the age differences observed in MR rates. Few studies to date have explicitly manipulated the effect of stimulus complexity with the aim of investigating the rotation strategies employed by younger and older individuals. Dror and colleagues (2005) assessed the performance of younger and older participants in a MR experiment with two-dimensional (2D) drawings of *familiar* objects (e.g., a helicopter or a house) with different levels of complexity. Stimulus complexity was quantified by calculating the compactness of the drawing (see e.g., Podgorny & Shepard, 1983). Simpler stimuli had a higher compactness value while more complex stimuli had a lower compactness value. Younger participants used a holistic strategy in processing simple objects but swapped to a piecemeal transformation in processing complex ones, showing a steeper slope. However, older participants processed both simple and complex objects in a similar manner. The authors interpreted this lack of complexity effect in older participants as evidence that they maintained a holistic strategy while processing both simple and complex objects, because this strategy poses less demands on cognitive resources, including their ability to memorize and mentally manipulate the objects.

Aims and Hypotheses

While Dror et al. (2005) provide initial evidence for systematic differences in strategy selection between younger and older individuals with *familiar* objects, it is worth noting that holistic processing is more likely to be adopted when the stimuli are familiar or over-learned (Bethell-Fox & Roger, 1988). It remains to be established whether analogous strategy differences between age groups would be observed with *unfamiliar* objects. The present study was aimed at investigating whether age-related slowing in MR rates could be accounted for in terms of the difference in strategies that younger and older people may use to solve MR tasks with *unfamiliar objects* with different levels of complexity.

Participants were asked to rotate simple and complex unfamiliar objects (arm-like cubes in Exp.1 and polygons in Exp.2). Stimulus complexity was manipulated by increasing the number of segments that constituted the objects (‘simple’ integrated objects vs. ‘complex’ multi-part objects). In addition, the vividness of visual imagery was assessed and controlled for. This is because this ability has been found to affect strategy selection in MR tasks (Logie, Pernet, Bunocore, & Della Sala, 2011; Zeman et al., 2010; Zhao & Della Sala, 2018). Thus, only normal-to-good imagers were selected from each age group to ensure that any difference in performance across participants was due to their age rather than any discrepancy in their visual imagery abilities.

In line with existing literature, we will infer the rotation strategy used by participants from the stimulus complexity effect observed on the MR slopes of each age group. According to Cooper’s (1975) complexity effect hypothesis (see also Cooper & Podgorny, 1976), the presence of a complexity effect with steeper MR slopes for more complex as compared to simpler objects will reveal a piecemeal transformation strategy. On the other hand, a complexity effect with shallower RT slopes for the more complex than the simpler objects will suggest a partial transformation whereby participants store and transform in their mind only a partial image of the object (Yuille & Steiger, 1982; Zhao & Della Sala, 2018).

We predicted that younger participants would be flexible in manipulating their visual representations for complex stimuli, and more efficient in rotating those by showing a shallower slope in their RTs as compared to simple stimuli. On the other hand, if older participants select the same strategy to rotate both simple and complex objects as previously observed for familiar stimuli (Dror et al., 2005), no stimulus complexity effect would be observed in the present study during the MR of unfamiliar objects. However, processing unfamiliar objects poses additional cognitive demands as compared to familiar ones because participants cannot rely on the objects' stored visual representations. Thus, older participants might have selective difficulties in representing the whole image of complex unfamiliar objects and might adopt different strategies to rotate simple and complex unfamiliar objects. The results of the current study add to our understanding of the extensively documented age-related slowing in MR tasks.

Experiment 1

In this experiment, we aimed to explore whether strategy selection differs in younger and older adults in MR tasks with three-dimensional objects by examining the complexity effect in each age group.

Method

Participants

Twenty-four younger and twenty-four older participants were recruited for this experiment. One younger and three older participants were excluded due to their overall low accuracy (< 50%). Younger participants were all students recruited from the University of Edinburgh and all older participants were educated at university level and volunteered to participate. All participants were right-handed, with no history of neurological disorders. They all had normal or corrected-to-normal vision by self-report.

Both younger and older participants were given the Vividness of Visual Imagery Questionnaire (VVIQ-2; Marks, 1999), a standardized questionnaire assessing general visual imagery use and experience (Pearson, Deepros, Wallace-Hadrill, Heyes, & Holmes, 2013) and a questionnaire previously used to detect individual differences in strategy selection in MR tasks (Zhao & Della Sala, 2018). Four younger and two older participants were poor imagers[1] (VVIQ score < 100) and were excluded from the study. Therefore, nineteen younger (VVIQ score ranged from 105 to 146, mean = 121.3; 19 to 24 years old, M = 22.4; 10 females) and

[1]In our previous study, poor imagers were defined as those scoring 100 or less on the VVIQ. Therefore, we used this cut-off score to exclude poor imagers in the present experiment.

nineteen older (VVIQ score ranged from 105 to 159, mean = 130.8; 65 to 84 years old, M = 74.3; 10 females) participants contributed data to this study.

Stimuli

Two types of stimuli (Standard and non-Standard) with different complexity levels were used in the present experiment in line with our previous work (Zhao & Della Sala, 2018). Simple stimuli (Standard; see top row in Fig.1) were the typical integrated objects used in Shepard and Metzler (1971) while complex ones (non-Standard; see bottom row in Fig.1) consisted of three separate segments. Both Standard and non-Standard stimuli consisted of ten cubes. The Standard stimuli (top row in Fig.1) were the typical 3D cube objects often used in MR experiments (Shepard & Metzler, 1971). The non-Standard stimuli[2], depicted on the bottom row of Fig.1, were devised by decomposing the arms of the Standard stimuli and moving them away from the main body part. Compared to Standard stimuli, the less compact non-Standard stimuli are harder to rotate holistically (Podgorny & Shepard, 1983)

On each trial a pair of objects was presented with different angular disparity ranging between 0° and 160° with 40° increments (angular disparity: 0°, 40°, 80°, 120°, 160°). Stimuli could be rotated along two axes, picture plane or in depth. On half of the trials, the two objects were identical whereas on the remaining half one object was paired with its mirror image (version: identical or mirror). In each block, there were 20 types of trials (5 angular disparity

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[2] The design of the non-Standard stimuli was different from that of our previous study (Zhao & Della Sala, 2018). In our previous study, the non-Standard objects were designed by withdrawing two cubes from the Standard stimulus, so that a similar configuration characterized both Standard and non-Standard stimuli. However, participants might have mentally filled the missing cube spontaneously on non-Standard trials. In this case stimuli could be considered as volumetric primitives. Therefore, we used a different stimuli design to prevent this possibility.

× 2 stimulus version × 2 rotated axis) each repeated 10 times. Two blocks of 200 randomly presented trials were presented separately for Standard and non-Standard stimuli. The sequence of these two blocks was counterbalanced across participants in each ageing group.

-----Insert Figure 1 about here-----

Procedure

Participants sat in front of a computer with their index fingers positioned on the keys "F" and "J" of a standard qwerty keyboard (used to respond to the stimuli). All keys were masked except for the two task relevant keys which were marked by the letters "S" and "D", indicating "same" and "different" respectively. For half of the participants, the "S" button was set on their right-hand side and the "D" button on their left side. For the other half of the participants, the "S" button was set on their left side and the "D" on their right. The stimuli were presented in white on a black background with 5.5 cm in height subtending 4.55° of visual angle.

Each trial started with a blank white screen for 250ms, followed by a fixation cross (black on white background), 1.0 cm x 1.0 cm presented for a random interval ranging between 200-250ms. After the offset of the fixation cross, a pair of stimuli were presented on a white screen until the participant responded and maximally for 8,000ms (see Fig. 2). After 1,500ms the next trial began. Participants had to indicate whether the two objects were the same (identical though rotated) or mirror images, by pressing one of the two response keys. During the entire procedure, the participants were asked to keep their hands on the keyboard. Each block was followed by a debriefing session, in which participants orally reported on the strategy they used in the previous block.

A run-in of 16 trials served as practice allowing participants to familiarize with the task before each block. Instead of the ten-cube stimuli used in the experiment proper (see Fig.1), eight-cube Standard and non-Standard objects were used[3] in these run-in trials to avoid the practice effect.

Data Analysis

As is typical in studies of MR[4] statistical analyses were carried out on identical trials only. Prior to the analysis, trials with reaction times exceeding two standard deviations above or below the mean per condition and per participant were excluded (2.3% of the data, on average). Mixed ANOVAs were carried out on both the mean RTs of correct responses and the average accuracy rates with angular disparity (0°, 40°, 80°, 120°, 160°) and stimulus complexity (Standard and non-Standard) as within-subject factors and age (younger or older) as a between-subject factor. Trend analyses were considered when a main effect of angular disparity was observed and Bonferroni-corrected post-hoc analyses were performed to analyse the difference between two consecutive angular disparities. Whenever appropriate degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity.

As the aim of the present experiment was to investigate how ageing affects the strategy selection in unfamiliar object MR, a linear regression line was fitted into individual

[3] Practice affects the MR processing; the RTs drop rapidly after sufficient practice (Mumaw et al., 1984). According to Mumaw et al. (1984), this practice effect modulates the strategy selection in MR by applying the more efficient holistic strategy in well-learned stimuli, whereas using piecemeal transformation in trials before the practice. However, it is notable that such practice effect works for trained types of stimuli only but not for the untrained ones. Therefore different stimuli types were used for practice.

[4] It has been suggested that distinct brain mechanisms are responsible for the discrimination between mirror images and between rotated identical images (e.g. Martinaud et al., 2016). Furthermore, electrophysiological evidence has shown that an additional "flip-over" process is required for the rotation of mirror stimuli in addition to the planar rotation engaged during the rotation of identical stimuli (e.g. Hamm, Johnson, & Corballis, 2004). Because the additional out-of-plane (or non-planar) rotation occurring during the mental transformation of mirror images is still poorly understood and is difficult to isolate from the ongoing planar rotation, we analysed only trials with identical objects , in line with existing literature (e.g Khooshabeh, Mary, & Thomas, 2013).

participants' mean RTs in each experimental condition to calculate the estimated slope and intercept once the main effect of angular disparity was found in RTs measure in each age group. Mixed ANOVAs were applied to these two measurements with age (younger vs. older) as a between-subject factor and stimulus complexity (Standard vs. non-Standard) as a within-subject factor. When age was found to interact with stimulus complexity, independent t-tests were first applied to each experimental condition to explore the ageing effect in each condition. To further characterize the strategies applied in different conditions by different age group, the effect of stimulus complexity was further tested with paired t-tests in each age group. Bonferroni corrections were applied to control for the familywise error rates for multiple comparisons (McDonald, 2007).

Results

Accuracy

A main effect of angular disparity was found in the accuracy rates, F (2.2, 78.6) = 32.14, $p <$ .001, $\eta^2 = .47$. The accuracy rate linearly decreased with the angular disparity, F (1, 36) = 56.02, $p < .001$, $\eta^2 = .61$. Furthermore, a main effect of stimulus complexity was found, F (1, 36) = 11.85, $p = .001$, $\eta^2 = .25$. Performance was more accurate on trials with Standard (M = 78.9%, SE = 2.3) than non-Standard stimuli (M = 71.2%, SE = 1.9). In addition, younger participants' performance was more accurate (M = 83.1%, SE = 2.5) than older participants' one (M = 67.0%, SE = 2.5) as revealed by a main effect of age group, F (1, 36) = 21.58, $p <$ .001, $\eta^2 = .38$. However, no differential performance across the age groups was observed when processing the Standard and non-Standard objects, F (1, 36) = 1.60, $p = .21$, through all the angular disparities in each condition neither, F (3.2, 113.4) = 1.77, $p = .14$.

Response Times

As shown in the left panel of Fig.2, a main effect of stimulus complexity was also found in the RTs, F (1, 36) = 13.29, p = .001, η^2 = .27. Slower RTs were observed in the processing of the non-Standard objects (M = 4883.9, *SE* = 282.9) than in the Standard ones (*M* = 4090.5ms, *SE* = 262.9). Moreover, a main effect of age was found in the RTs, F (1, 36) = 36.76, p < .001, η^2 = .51. Younger participants were faster (*M* = 2698.7ms, *SE* = 354.2) than older participants (*M* = 6005.8ms, *SE* = 354.2). In addition, age was found to interact with stimulus complexity, F (1, 36) = 5.51, p = .025, η^2 = .13. Separate ANOVAs carried out for each age group revealed an effect of stimulus complexity in the older participants, F (1, 18) = 13.46, p = .002, η^2 = .43, with longer RTs observed for non-Standard objects (*M* = 6657.8ms, *SE* = 503.7) as compared to Standard ones (*M* = 5353.7ms, *SE* = 496.0). No such effect of stimulus complexity was found in younger participants, F (1, 18) = 1.27, p = .276, η^2 = .07.

Consistently with the literature (Shepard & Metzler, 1971), a main effect of angular disparity was observed in the RTs, F (2.5, 89.2) = 48.11, p < .001, η^2 = .57, which fitted a linear trend, F (1, 36) = 74.19, p < .001, η^2 = .67. Angular disparity was further found to interact with age group, F (2.5, 89.2) = 4.219, p = .012, η^2 = .105. Main effects of angular disparity was present in both younger (F (2.3, 42.2) = 38.76, p < .001, η^2 = .68) and older participants (F (2.4, 43.8) = 23.58, p < .001, η^2 = .57). The RTs could be fitted for a linear trend in both younger (F (1, 18) = 64.65, p < .001, η^2 = .78) and older participants (F (1, 18) = 33.56, p < .001, η^2 = .65).

-----Insert Figure 2 about here-----

Slope and intercept

A main effect of age was observed on the estimated slope, F (1, 36) = 8.88, p = .005, η^2 = .20 (see Fig.2, top right panel). MR rates were significantly slower in older (*M* =19.7ms/degree, *SE* = 1.8) than younger participants (*M* = 12.0ms/degree, *SE* = 1.8). In addition, age was found to interact with the stimulus complexity on the estimated slope measure, F (1, 36) = 16.40, $p < .001$, $\eta^2 = .31$. Follow-up comparisons carried out separately for Standard and non-Standard stimuli revealed that younger and older participants performed similarly in the Standard condition, t (25.5) = -.50, $p_c = .656$, but differed significantly in processing the non-Standard stimuli, t (26.8) = -4.89, $p_c < .001$.

To further explore the strategy adopted by different age group, additional comparisons were carried out separately for younger and older participants. An effect of stimulus complexity on the slopes was revealed in both groups (younger: t (18) = 2.76, $p_c = .026$; older: t (18) = -3.08, $p_c = .012$). As shown in the top right panel of Fig.2, older participants were slower in rotating the non-Standard stimuli (*M* = 23.8ms/degree, *SE* = 2.5) compared to the Standard ones (*M* = 15.5ms/degree, *SE* = 2.9). By contrast, younger participants were faster in mentally rotating non-Standard (*M* = 9.9ms/degree, *SE* = 1.3) as compared to Standard stimuli (*M* = 14.1ms/degree, *SE* = 1.3).

In the estimated *intercept* measure (see Fig.2, bottom right panel), a main effect of stimulus complexity was found, F (1, 36) = 22.13, $p < .001$, $\eta^2 = .38$. A larger intercept was observed in the non-Standard objects (*M* = 3588.5ms, *SE* = 174.7) than in the Standard ones (*M* = 2917.5ms, *SE* = 142.9). In addition, an age effect was observed in the intercept, F (1, 36) = 75.8, $p < .001$, $\eta^2 = .68$, with larger intercept for the older participants (*M* = 4496.1ms, *SE* = 201.9) as compared to the younger participants (*M* = 2009.9ms, *SE* = 201.9). However, no interaction between stimulus complexity and age group was found on the estimated intercept, F (1, 36) = .11, $p = .742$.

Discussion

No age effect was observed in MR rates when processing the relatively simpler Standard objects. However, a differential performance across age groups was observed when processing the non-Standard objects. Older participants showed a steeper slope in the non-Standard than in the Standard condition suggesting that they used piecemeal transformation in processing the more complex non-Standard objects. Younger participants adopted a holistic strategy while performing the MR task with Standard objects. The observation that their MR rates were faster in more complex non-Standard stimuli suggests that they simplified this task and transformed the partial image of these stimuli in their minds' eyes. This finding is consistent with the expected performance of good imagers who can automatically simplify the representation of non-Standard objects and transform such partial images in their minds' eyes as demonstrated by shallower slopes in the RTs function measured in the non-Standard as compared to the Standard condition (Zhao & Della Sala, 2018).

Taken together, the results of the first study suggest that the different performance observed in younger and older participants can be explained by the different rotation strategies used by the two groups of participants.

Experiment 2

MR performance is strongly affected by the specific features of the stimuli that have to be mentally rotated. For example, more time is necessary to process 3D arm-like cube objects than 2D polygon stimuli (Shepard & Metzler, 1988). In the following experiment, we further explored the issue of strategy selection investigating whether the rotation strategy differences observed in Experiment 1 between younger and older participants could be generalised to different types of stimuli (i.e. 2D polygons). In this study, the complexity level of the polygons was manipulated through systematic changes to their number of vertices in line with earlier works on 2D polygons (Cooper, 1975; Coop & Podgorny, 1976).

Methods

Participants

Another 20 younger (19 to 24 years old, mean = 21.2 years old, 10 females) and 20 older participants (66 to 84 years old, mean = 71.3 years old, 10 females) were recruited for this experiment. Their VVIQ scores fell within the normal-to-good range (range: 100 to 160). All participants were right-handed, with no history of neurological disorders and reported having normal or corrected-to-normal vision. None took part in Experiment 1.

Stimuli

Polygons were selected as the stimuli for the present experiment. To be consistent with Exp.1, two types of stimuli were used, Standard and non-Standard (Fig.3). The Standard stimuli were integrated polygons with twelve vertices. The non-Standard stimuli were generated by dividing the Standard objects into three segments. Accordingly, the non-Standard objects still contain twelve vertices but consist of three separate segments.

On each trial a pair of objects was presented with a different orientation, from 0°, 60° to 120° (three angular disparity) clockwise or counter-clockwise (two orientations of rotation). Half of the trials was set as a pair of identical objects and the other half was set as a pair of mirrored objects. In each block, both identical and mirror pairs were randomly presented with five repetitions. In total two blocks of 120 trials were presented separately for Standard and non-Standard stimuli. The order with which these two blocks were presented was counterbalanced across participants in each ageing group.

-----Insert Figure 3 about here-----

Procedure

The procedure of Exp.2 is shown in the right panel of Fig.3. Each trial began with a white screen presented for 250ms, followed by a fixation cross (black on white background) lasting for a randomly selected interval between 200ms and 250ms, then a pair of polygon stimuli was presented for a maximum of 4,000ms or until a response was given by the participant. In case of missed responses, a new trial was presented. Participants had to indicate whether these two polygons were the same (identical though rotated) or different images (mirror) by pressing the “S” or “D” buttons. During the whole procedure, the participants were asked to keep their hands on the keyboard.

A run-in of 15 trials served as practice allowing participants to familiarize with the task. In this practice session, two different 12-vertices polygons (Standard and non-Standard) not used in the following experimental blocks were generated and used to avoid practice effect.

Data analysis

The data analysis was identical to that performed in Exp.1.

Results

Accuracy

A significant main effect of angular disparity was observed, F (2, 76) = 40.12, $p <$ .001, $\eta^2 = .51$. The accuracy rate linearly decreased with angular disparity, F (1, 38) = 66.73, $p < .001$. No main effect of stimulus complexity, F (1, 38) = .01, p = .968, and no interaction between stimulus complexity and angular disparity, F (2, 76) = .13, p = .877, were found in the accuracy rates.

A significant main effect of age, F (1, 38) = 21.38, $p < .001$, $\eta^2 = .36$, revealed that younger participants were more accurate (M = 91.3%, SE = 2.7) than older participants (M = 73.4%, SE = 2.7). The factor age did not interact with stimulus complexity, F (1, 38) = .20, p

= .657. In addition, no significant age x stimulus complexity x angular disparity was observed, F (2, 76) = 1.88, p = .160.

Response Times

The performance across younger and older participants is summarised in Fig.4. A main effect of stimulus complexity, F (1, 38) = 5.31, p = .027, η^2 = .12, revealed longer RTs for Standard objects (M = 2043.4ms, SE = 56.4) than non-Standard ones (M = 1887.3ms, SE = 52.0). Consistent with the outcome of Exp.1, an age-associated delay was found, F (1, 38) = 110.97, $p < .001$, η^2 = .75. Older participants showed longer RTs (M = 2411.7ms, SE = 59.9) than younger ones (M = 1519.1ms, SE = 59.9). However, age was not observed interacted with stimulus complexity, F (1, 38) = 1.25, p = .271.

A main effect of angular disparity was observed in RTs, F (2, 76) = 156.92, $p < .001$, η^2 = .81, which was confirmed fit for a linear trend, F (1, 38) = 228.80, $p < .001$, η^2 = .86. In addition, age was found interacted with angular disparity, F (2, 76) = 3.48, p = .036, η^2 = .08. Main effects angular disparity were presence in both younger (F (1, 19) = 8.96, $p < .001$, η^2 = .85) and older participants (F (1, 19) = 44.07, $p < .001$, η^2 = .70). In both age group, RTs could be fitted for a liner (younger: F (1, 19) = 154.40, $p < .001$, η^2 = .89; older: F (1, 19) = 38.51, $p < .001$, η^2 = .67).

-----Insert Figure 4 about here-----

Slope and Intercept

As shown in the top right panel of Fig.4, a main effect of age was observed in the estimated *slope* in RTs function, F (1, 38) = 8.14, p = .007, η^2 = .18. Older participants' performance was slower (M = 8.21ms/degree, SE = .562) than younger participants' one (M = 5.9ms/degree, SE = .6).

Moreover, age was found to interact with stimulus complexity, F (1, 38) = 37.38, $p <$ .001, η^2 = .50. Follow-up analyses carried out separately for Standard and non-Standard objects revealed that there was no age-associated difference in processing Standard objects, t (38) = .17, p_c = .867. However, MR rates for non-Standard objects were significantly slower in older (*M* = 9.8ms/degree, *SE* = .7) than in younger participants (*M* = 5.1ms/degree, *SE* = .4), t (38) = -5.43, $p_c < .001$. Furthermore, additional pairwise comparisons were carried out on the estimated slopes measured for Standard and non-Standard stimuli separately for each age group. A significant main effect of stimulus complexity was observed in younger participants, t (19) = 3.41, p_c = .018, indicating that they were faster in processing non-Standard (*M* = 5.1ms/degree, *SE* = .4) than Standard objects (*M* = 6.8ms/degree, *SE* = .5). A main effect of stimulus complexity was also observed in the older group, t (19) = 31.11, $p_c <$ .001. Here, it reflected the fact that older participants took longer to process non-Standard objects (*M* = 9.8ms/degree, *SE* = .7) as compared to Standard ones (*M* = 6.6ms/degree, *SE* = .8).

The *intercepts* in RTs functions in younger and older participants are depicted on the bottom right panel of Fig.4. A main effect of age was found on the estimated intercept, F (1, 38) = 64.73, $p < .001$, η^2 = .63, with a larger intercept observed for older (*M* = 2063.7ms, *SE* = 69.8) than younger participants (*M* = 1269.2ms, *SE* = 69.8). However, age was not observed to interact with stimulus complexity, F (1, 38) = .44, p = .513.

Discussion

Similar systematic age-related differences were observed in the MR rate of 2D polygon stimuli and in 3D stimuli (Exp.1). More specifically, while no difference between younger and older individuals was present for the MR rate of Standard stimuli, older participants showed significantly slower rotation rates than the younger while transforming the more complex non-

Standard stimuli. The presence of stimulus complexity effects in each age group revealed that both younger and older participants adopted different strategies in processing 2D polygons with different complexity levels. However, while older participants showed steeper MR rates for the multi-part non-Standard polygons as compared to the simpler Standard ones, younger participants had faster MR rates for the more complex non-Standard polygon stimuli than for the Standard ones.

The similar pattern of results related to the rotation rates of 3D (Exp.1) and 2D (Exp.2) objects suggests that the dimensionality of the visual stimuli does not affect the strategy selection adopted by younger and older individuals during the mental rotation of unfamiliar objects.

General Discussion

In the present study, younger and older participants performed two MR tasks with different types of unfamiliar objects: 3D cube stimuli (Exp.1) and 2D polygons (Exp.2). In both experiments, stimulus complexity was manipulated by increasing the number of segments that constituted each object. Non-Standard stimuli were characterized by higher complexity as compared to Standard ones (three segments versus one segment, respectively). As expected, the analysis of both RTs and accuracy rates showed the presence of a complexity effect with faster response time and increased accuracy observed for Standard than non-Standard visual stimuli regardless of age (Bethell-Fox & Shepard, 1988; Heil & Jansen-Osmann, 2008).

Consistent with previous literature (e.g., Band & Kok, 2000; Borella et al., 2014), an age-associated delay in RTs was found during the MR of unfamiliar objects in both experiments of the present study. This general age related difference was further supported by the analysis of the estimated intercepts and slopes calculated by applying the linear regression into each participant's RTs as a function of angular disparity. During the MR of both polygons (Exp. 2) and cubes (Exp. 1), a larger *intercept* was observed in older than in younger participants. This result suggests that older adults are slower in the initial phase of stimuli encoding or identification, or in the final decision making stage (or both), which is in line with previous observations (e.g., Dror & Kosslyn, 1994).

In addition, as reported in other MR studies with unfamiliar objects (e.g., Hertzog & Pypma, 1991; Puglisi & Morrell, 1986), there was an effect of age on the *slopes* derived from the RTs functions: the MR rate was slower in older than younger adults for both the polygons and cubes rotation tasks.

The systematic differences between the MR rates of younger and older participants varied with stimuli complexities as indicated by the interaction of age × stimulus complexity observed for the slopes. During the MR of simple (Standard) objects, MR rates were comparable across younger and older participants. By contrast, an age-associated difference in MR rates was evident for the more complex (non-Standard) objects: older participants processed these objects more slowly than younger ones. The difference between younger and older adults in the MR of multi-part objects (non-Standard) could be interpreted as evidence that younger individuals utilized a more efficient strategy in this task than older participants.

The rotation strategy was investigated by exploring the stimulus complexity effect on the MR slopes in each age group based on Cooper's complexity effect hypothesis (1975; see also Cooper & Podgorny, 1976). The results showed the presence of a main effect of stimulus complexity on the slopes for both younger and older participants suggesting that participants with normal-to-good ability in vividness of visual imagery applied different strategies in MR tasks when stimuli of different complexity had to be rotated. However, while younger participants showed slower MR rates for simple than complex stimuli, an opposite pattern of results was observed for older participants with slower MR rates for complex as compared to simple objects. This suggests that different strategies were used by younger and older individuals during the rotation of Standard and non-Standard objects, as discussed below. Importantly, similar results were found in each age group during the MR of both 3D cube objects (Exp.1) and 2D polygon stimuli (Exp.2).

For *older* participants, a steeper slope was observed in processing non-Standard objects than in processing Standard objects. According to the stimulus complexity hypothesis (Cooper, 1975), this result suggests that older participants transformed the multi-part non-Standard objects piece-by-piece rather than holistically. This finding is in striking contrast with that of Dror et al. (2005) who reported that older participants did not change their strategy as a function of stimulus complexity and maintained a holistic strategy to process both simple and complex objects. These inconsistent findings may be accounted for in terms of stimulus familiarity. Dror et al. (2005) used familiar objects whereas in the present experiment we used unfamiliar polygons and arm-like cube objects. The holistic strategy is more likely to be used when the stimuli are familiar or over-learned (Bethell-Fox & Roger, 1988) as these representations are already stored in memory. Older participants might have no difficulty in creating the representation of such familiar objects even when these are more complex and they can therefore rotate the whole image to complete the task. By contrast, additional cognitive resources might be needed to mentally represent unfamiliar objects as compared to familiar ones. In the present study, in which unfamiliar stimuli posed high cognitive demands, older participants used a piece-by-piece strategy to rotate complex non-Standard objects. Given their deficits in feature binding in working memory (Brockmole et al., 2008; Chalfonte & Johnson, 1996; Mitchell, Johnson, Raye, & D'Esposito, 2000), it is possible that older participants encountered selective difficulties in representing the multi-part (non-Standard) unfamiliar objects as a unit and therefore had to use a piece-by-piece strategy to complete the tasks, despite the higher cognitive demands posed by this strategy.

Possible differences in the vividness of visual imagery ability may offer an alternative reconciliation between our findings and those of Dror et al. (2005). The vividness of visual imagery affects MR performance (Logie et al., 2011) and people with different visual imagery abilities adopt different strategies under different MR task demands (Zhao & Della Sala, 2018). This ability was not considered in Dror et al.'s study (2005) while it was controlled for both younger and older participants in the current study.

The *younger* normal-to-good imagers in the present experiment showed a shallower slope in processing non-Standard than in processing Standard objects. This result resonates with the good imagers' performance in our previous study (Zhao & Della Sala, 2018) as well as other results one could glean from the literature (Yuille & Steiger, 1982). It suggests that younger participants, at least those who have normal-to-good level of vividness of visual imagery, may simplify the representation of the multi-part non-Standard stimuli and maintain such simplified images for further mental manipulation (Liesefeld & Zimmer, 2013). This explanation indeed corresponds to our participants' comments in the debriefing session. Most of the younger participants (18 out of 19 in Exp. 1 and 18 out of 20 in Exp. 2) reported focusing on the main body (see details in Fig.1 & Fig.3) and one of the two small segments only. Thus, consistent with existing literature these findings demonstrate that younger individuals with normal-to-good vividness of visual imagery have the ability to simplify their representation of more complex visual stimuli then rotate this in their minds' eyes.

One may argue that it is possible that younger participants were able to represent the multi-part objects as a whole image in their minds and to rotate this faster than the simpler integrated objects. However, a recent study has revealed that there is a limit to the number of things that humans can bind and that maximally two objects or features could be bound and transformed as a whole in the visual representation (Xu & Franconeri, 2015). In both experiments of the present study the multi-part stimuli consisted of three segments. It is therefore unlikely that these were treated as a single object.

Apart from the strategy selection account, an alternative explanation for this age difference in MR rate could be that older participants were more cautious with a more complex experiment condition (larger rotation angle) than younger individuals in processing more demanding MR tasks of non-Standard stimuli, hence showing steeper MR slopes. If this were the case older participants should be proportionally more accurate in larger angular disparity in this more complex non-Standard condition as compared to younger adults. Indeed, existing evidence has suggested that older individuals are more likely than younger ones to prioritize response accuracy at the expense of speed (Hertzog, Vernon, & Rypma, 1993). As such, age difference should be more evident with larger rotation angles in the more demanding condition with more complex non-Standard objects. However, no three-way interaction was observed between age, angular disparity and stimulus complexity in the accuracy rates of either experiment, and therefore this alternative account is not supported by the present data.

Another possible account for this age-related slowing in MR rates may relate to differences in familiarity with the use of computers. This factor is associated with better performance in some tasks (Bottiroli, & Cavallini, 2009; Iverson, Brooks, Ashton, Johnson, & Gualtieri, 2009) but not all the computerized cognitive tasks (Iverson et al., 2009). It is possible that the computer familiarity effect is also present in this study and contributes to explain general age-related differences in overall speed or accuracy. However, it is unlikely that computer familiarity has an impact on the pure MR process as indicated by the RT slopes, which is our primary interest in the present study relying on performance across the different rotation angles after the time for response selection and execution has been subtracted.

All in all, these results suggest that age affects the strategy selection in MR process with unfamiliar objects, especially when the objects consist of multiple parts. In processing unfamiliar integrated objects, older participants did not show differential MR rates compared to younger participants. However, during the MR of multi-part objects, older participants were not as proficient as younger participants in maintaining precise object representations for the MR processing. Instead, they transformed the multi-part objects piece by piece to comply with the requirements of the MR task. The use of a different strategy at an older age provides an explanation for the slower MR rates observed in older participants. However, this result may differ with different stimuli and with different experimental paradigms (e.g., Vandenberg and Kuse (V/K) test; Vandenberg & Kuse, 1978; Peters et al., 1995) in which working memory is required to a greater extent (Peters & Battista, 2008). In addition, the small sample size might be a limitation of the current study, which calls for replication.

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References

Band, G. P. H., & Kok, A. (2000). Age effects on response monitoring in a mental-rotation task. *Biological psychology, 51*, 201-221.

Bethell-Fox, C. E., & Shepard, R. N. (1988). Mental rotation: effects of stimulus complexity and familiarity. *Journal of Experimental Psychology: Human Perception and Performance, 14*(1), 12-23.

Bottiroli, S., & Cavallini, E. (2009). Can computer familiarity regulate the benefits of computer-based memory training in normal aging? A study with an Italian sample of older adults. *Aging, Neuropsychology, and Cognition, 16*(4), 401-418.

Borella, E., Meneghetti, C., Ronconi, L., & De Beni, R. (2014). Spatial abilities across the adult life span. *Developmental Psychology, 50*(2), 384-392.

Brockmole, J. R, Parra. M., Della Sala, S., & Logie, R. H. (2008). Do binding deficits account for age-related decline in visual working memory? *Psychonomic Bulletin & Review, 15*(3), 543-547.

Brockmole, J. R. & Logie, R. H. (2013). Age-related change in visual working memory: a study of 55,753 participants aged 8-75. *Frontiers in Psychology, 4*, 12.

Cerella, J., Poon, L. W., & Fozard, J. L. (1981). Mental rotation and age reconsidered. Journal of Gerontology, 36(5), 620-624.

Chalfonte, B. I., & Johnson, M. K. (1996). Feature memory and binding in younger and older participants. *Memory & Cognition, 24*(4), 403-416.

Cooper, L. A., & Shepard, R. N. (1973). Chronometric studies of the rotation of mental images. Chronometric studies of the rotation of mental images. In W.G. Chase (Ed.), *Visual Information Processing* (pp. 75–176). New York: Academic Press.

Cooper, L. A. (1975). Mental rotation of random two-dimensional shapes. *Cognitive Psychology, 7*, 20-43.

Cooper, L. A., & Podgorny, P. (1976). Mental transformations and visual comparisons: effects of complexity and similarity. *Journal of Experimental Psychology: Human Perception and Performance, 2*(4), 503-514.

Dror, I. E., & Kosslyn, S. M. (1994). Mental Imagery and Aging. *Psychology and Aging, 9*(1), 90-102.

Dror, I. E., Schmitz- Williams, I. C., & Smith, W. (2005). Order participants use mental representations that reduce cognitive load: mental rotation utilizes holistic representations and processing. *Experimental Aging Research, 31*, 409-420.

Folk, M. D., & Luce, R. D. (1987). Effects of stimulus complexity on mental rotation rate of polygons. *Journal of Experimental Psychology: Human Perception and Performance, 13*(3), 395-404.

Gaylord, S. A., & Marsh, G. R. (1975). Age differences in the speed of a spatial cognitive process. *Journal of Gerontology, 30*, 674-678.

Hamm, J. P., Johnson, B.W., & Corballis, M. C. (2004). One good turn deserves another: an event-related brain potential study of rotated mirror-normal letter discriminations. *Neuropsychologia, 42*, 810-820.

Heil, M. (2002). The functional significance of ERP effects during mental rotation. *Psychophysiology, 39*, 535-545.

Heil, M., & Jansen-Osmann, P. (2008). Sex differences in mental rotation with polygons of different complexity: Do men utilize holistic processes whereas women prefer piecemeal ones? *The Quarterly Journal of Experimental Psychology, 61*(5), 683-689.

Hertzog, C., & Rypma, B. (1991). Age differences in components of mental-rotation task performance. *Bulletin of Psychonomic Society, 29*(3), 209-212.

Hertzog, C., Vernon, M. C., & Rypma, B. (1993). Age differences in mental rotation task performance: the influence of speed/accuracy tradeoffs. Journal of Gerontology: *Psychological Sciences, 48*(3), 150-156.

Iverson, G. L., Brooks, B. L., Ashton, V. L., Johnson, L. G., & Gualtieri, C. T. (2007). Does familiarity with computers affect computerized neuropsychological test performance? *Journal of Clinical and Experimental Neuropsychology, 31*(5), 594-604.

Jacewicz, M. M., & Hartley, A. A. (1979). Rotation of mental images by young and old college students: the effects of familiarity. *Journal of Gerontology, 34*(3), 396-403.

Just, M. A., & Carpenter, P. A. (1976). Eye fixations and cognitive process. *Cognitive Psychology, 8*, 441-480.

Just, M. A., & Carpenter, P. A. (1985). Cognitive coordinate systems: Accounts of mental rotation and individual differences in spatial ability. *Psychological Review, 92*, 137-172.

Khooshabeh, P., Hegarty, M., & Shipley, T. F. (2013). Individual differences in mental rotation: piecemeal versus holistic processing. *Experimental Psychology, 60*(3), 164-171.

Logie, R. H., Pernet, C. R., Buonocore, A., & Della Sala, S. (2011). Low and high imagers activate networks differentially in mental rotation. *Neuropsychologia*, *49*, 3071-3077.

Liesefeld, H. R., & Zimmer, H. D. (2011). The advantage of mentally rotating clockwise. *Brain and Cognition, 75*(2), 101-110.

Liesefeld, H. R., & Zimmer, H. D. (2013). Think spatial: the representation in mental rotation is nonvisual. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39*(1), 167-182.

Marks, D. F. (1999). Consciousness, mental imagery and action. *British Journal of Psychology, 90*, 567-585.

Martinaud, O., Mirlink, N., Bious, S., Bliaux, E. Champmartin, C., Pouliquen, D., & Gérardin, E. (2016). Mirrored and rotated stimuli are not the same: a neuropsychological and lesion mapping study. *Cortex, 78*, 100-114.

Meneghetti, C., Carbone, E., Di Maggio, A., Toffalii, E., & Rorella, E. (2018). Mental rotation training in older adults: the role of practice and strategy. *Psychology and Aging, 33*(5), pp. 814-831.

Mitchell, K. J., Johnson, M. K., Raye, C. L., & Esposito, M. (2000). fMRI evidence of age-related hippocampal dysfunction in feature binding in working memory. *Cognitive Brain Research, 10*, 197-206.

Pearson, D. G., Deeprose, C., Wallace-Hadrill,S. M. A., Heyes, S. B., & Holmes, E. A. (2013). Assessing mental imagery in clinical psychology: a review of imagery measures and a guiding framework. *Clinical Psychology Review, 33*(1), 1-23.

Peters, M., & Battista, C. (2008). Applications of mental rotation figures of the Shepard and Metzler type and description of a mental rotation stimulus library. *Brain and Cognition, 66*, 260-264.

Peters, M. Laeng, B., Latham, K., Jackson, M., Zaiyouna, R., & Richardson, C. (1995). A redrawn Vandenberg and Kuse mental rotation rotations test: different versions and factors that affect performance. *Brain and Cognition, 28*, 39-58.

Podgorny, P., & Shepard, R. N. (1983). Distribution of visual attention over space. *Journal of Experimental Psychology: Human Perception and Performance, 9*(3), 380-393.

Puglisi, J. T., & Morrell, R. W. (1986). Age-related slowing in mental rotation of three-dimensional objects. *Experimental Aging Research, 12*(4), 217-220.

Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science, 171*, 701-703.

Shepard, S., & Metzler, D. (1988). Mental Rotation: Effects of dimensionality of objects and type of task. *Journal of Experimental Psychology: Human Perception and Performance*, *14*(1), 3-11.

Stoffels, E. J. (1996). Inhibition of concurrent processes in letter and orientation discrimination. *ActaPsychologica, 91*, 153-173.

Xu, Y., & Franconeri, S. L. (2015). Capacity for visual features in mental rotation, *Psychological Science, 26*(8), 1241-1251.

Yuille, J. C., & Steiger, J. H. (1982). Nonholistic processing in mental rotation: some suggestive evidence. *Perception & Psychophysics, 31*(3), 201-209.

Zeman, A. Z. J., Della Sala, S., Torrens, L. A., Gountouna, V., McGonigle, D. J., & Logie, R. H. (2010). Loss of imagery phenomenology with intact visuo-spatial task performance: A case of 'blind imagination'. *Neuropsychologia*, *48*, 145-155.

Zhao, B., & Della Sala, S. (2018). Different representations and strategies in mental rotation. *Quarterly Journal of Experimental Psychology, 71(7*), 1574-1583.