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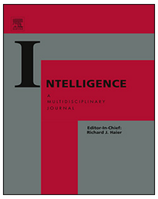

Mental rotation and fluid intelligence: A brain potential analysis

Vincenzo Varriale[a,*], Maurits W. van der Molen[b], Vilfredo De Pascalis[a]

[a] Department of Psychology, "Sapienza" University of Rome, Rome, Italy
[b] Department of Psychology, University of Amsterdam, Amsterdam, The Netherlands

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ABSTRACT

The current study examined the relation between mental rotation and fluid intelligence using performance measures augmented with brain potential indices. Participants took a Raven's Progressive Matrices Test and performed on a mental rotation task presenting upright and rotated letter stimuli (60°, 120° or 180°) in normal and mirror image requiring a response execution or inhibition depending on instructions. The performance results showed that the linear slope relating performance accuracy, but not speed, to the angular rotation of the stimuli was related to individual differences in fluid intelligence. For upright stimuli, P3 amplitude recorded at frontal and central areas was positively associated with fluid intelligence scores. The mental rotation process was related to a negative shift of the brain potential recorded over the parietal cortex. The linear function relating the amplitude of the rotation-related negativity to rotation angle was associated with fluid intelligence. The slope was more pronounced for high- relative to low-ability participants suggesting that the former flexibly adjust their expenditure of mental effort to the mental rotation demands while the latter ones are less proficient in doing so.

1. Introduction

The theory of fluid and crystallized intelligence is a dominant position in the psychometric tradition of the human intellect (Cattell, 1963, 1971; Horn, 1976). Fluid intelligence relates to the capacity of solving problems for which prior learning or experience are of little or no use while crystallized intelligence refers to consolidated knowledge and rules that emerged from learning and acculturation. Other influential models distinguished between verbal and educational abilities versus spatial, practical and mechanical abilities (Vernon, 1964, 1965) or proposed a three-strata theory with broad domain abilities at the second level, a single general cognitive ability at the third level and test-specific variation at the first level (Carroll, 1993). Johnson and Bouchard (2005) compared the three major psychometric models of intelligence and observed that all three models provide a good fit of the data. The best fit, however, was provided by a four-strata model consisting of a general cognitive ability at the fourth level and three general domain factors at the third level; verbal, perceptual and mental rotation. The authors concluded that this model emphasizes the importance of visualization processes involved in mental rotation as relatively independent contributors to the manifestation of general human intelligence (cf. Johnson & Bouchard, 2005; p. 409).

Mental rotation is one of the best-studied paradigms, both in experimental psychology and cognitive neuroscience (e.g., Hoppe et al., 2012). In their seminal study of mental rotation, Shepard and Metzler (1971) presented their participants with pairs of drawings of three-dimensional assemblages of cubes. In each pair, the assemblages were identical but they differed by a certain amount of rotation and one could be a mirror image of the other. The participant's task was to decide as quickly as possible by pressing a button whether the two assemblages were identical (except for different rotations) or mirror images. The results showed that the time it took to decide that the two assemblages were identical increased with the angular rotation difference between them. This observation suggested to Shepard and Metzler (1971) the hypothesis that participants formed a mental image of one of the assemblages and then, by rotating this image, assessed whether it can be aligned with the other assemblage. This hypothesis was confirmed in a series of follow-up studies in which they systematically varied critical features of the original paradigm (Shepard & Cooper, 1982, for a review). Most of these studies did not involve the comparison of simultaneously visible stimuli thereby ruling out an alternative interpretation of their original finding suggesting that increase in decision time with rotation angle was due to the need of making more eye-movements back and forth between the two assemblages rather than to the mental rotation of one of the assemblages (e.g., Just & Carpenter, 1976). In one of those studies, for example, Cooper and Shepard (1973) presented their participants with rotated letters in normal and mirror image and asked them to decide whether the letter was in its normal form or mirror image. Again, the results showed that decision time increased with rotation angle.

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[*] Corresponding author.
E-mail address: vincenzo.varriale@uniroma1.it (V. Varriale).

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Considerable effort has been invested in delineating brain regions activated in the mental rotation paradigm (Zacks, 2008, for a meta-analytic review). Collectively, these studies point to the posterior parietal region that is implicated in mental rotation across a variety of specific implementations of the mental rotation paradigm. Interestingly, several studies observed that activation in this brain region nicely scales with rotation angle and decision time (e.g., Gauthier et al., 2002; Gogos et al., 2010). Other studies examined the electrocortical concomitants of mental rotation, as event-related brain potentials due to their high temporal resolution, are particularly suitable for examining the neural processes associated with mental rotation. These studies consistently revealed a negative modulation of the brain potential associated with mental rotation, which has been referred to as the rotation-related negativity (RRN, for reviews Heil, 2002; Riečanský et al., 2013). The maximum amplitude of the RRN is observed over the parietal cortex and occurs about 350 ms after the onset of the visual stimulus that has to be rotated. The RRN reduces the amplitude of the positive brain potential elicited by the visual stimulus and, thus, it can be quantified best as a difference wave between conditions that do and don't ask for mental rotation. Importantly, RRN amplitude co-varies with RT as a function of angular rotation (e.g., Milivojevic, Johnson, Hamm, & Corballis, 2003). This finding has been taken to suggest that the RRN provides a neural signature of the processes involved in mental rotation (e.g., Wijers, Otten, Feenstra, Mulder, & Mulder, 1989). This interpretation received support from findings indicating that after practice the linear increase of RT and RRN amplitude associated with rotation angle disappear (Provost, Johnson, Karayanidis, Brown, & Heathcote, 2013).

Individual differences in mental rotation received attention right from the inception of the Shepard and Metzler (1971) paradigm. Considering the importance credited to mental rotation in the psychometric analysis of intelligence (e.g., Johnson & Bouchard, 2005), one would expect that due attention is being paid to the analysis of intelligence differences in mental rotation. Surprisingly, it is not, and most of the available evidence is indirect. Although there is an abundant literature showing that individuals with higher psychometric intelligence have shorter and less variable RTs (e.g., Jensen, 2006), a demonstration of the cognitive components that are sensitive to individual differences in psychometric intelligence would be very illuminating (e.g., Deary, 2001). The mental rotation paradigm offers just such a possibility as it allows for the isolation of a cognitive component—mental rotation—of central importance to psychometric intelligence. Moreover, the mental rotation paradigm conveniently allows varying task difficulty without changing task complexity (Sliwinski & Hall, 1998). An early study, however, failed to demonstrate a strong relation between spatial-visualization ability and mental rotation rate (Lansman, Donaldson, Hunt, & Yantis, 1982). More recently, Hoppe et al. (2012) reported that mental rotation rate differentiated between mathematically gifted adolescents and a control group. It should be noted that both groups differed also in general intelligence. A study reported by Tachibana, Namba, and Noguchi (2014) seems most informative. These authors observed that fluid intelligence scores, derived from the Raven's Progressive Matrices test (Raven, Raven, & Court, 1998), correlated negatively with the slope relating response speed to the angular rotation of stimuli; that is, the cost involved in the need to mentally rotate a stimulus was less for high- relative to low-ability individuals. This study prompted us to further assess the relation between fluid intelligence and mental rotation.

The primary goal of the current study is to further assess the relation between fluid intelligence and mental rotation by using a standard letter rotation task and by recording the EEG during task performance. Based on previous research we predict that the speed of responding will increase with the rotation angle of the letter stimulus while accuracy will decrease (e.g., Provost et al., 2013). In addition, we predict that RRN amplitude will increase with rotation angle (e.g. Heil, 2002). This pattern of results will provide us with a template for the evaluation of the influence of fluid intelligence. Following Tachibana et al. (2014), we will assess the relation between fluid intelligence and mental rotation by plotting, for each participant, RT as a function of angular rotation of the test stimulus and will then apply a linear regression to those data. The slope of the regression function provides then an index of mental rotation rate, with a steeper slope suggesting a slower mental rotation rate. We anticipate replicating the findings reported by Tachibana et al. (2014), that is, a negative relation between fluid intelligence and the slope of the function relating response speed to the angular rotation of the stimulus. This pattern indicates that, relative to lower ability individuals, higher ability individuals have a faster mental rotation rate (indexed by a flatter slope of the mental rotation function linking RT to the rotation angle of the stimulus). In addition, we expect a negative relation between fluid intelligence and the slope of the function relating error rates to the angular rotation of the stimuli. This pattern indicates that, relative to lower ability individuals, higher ability individuals commit less errors and this inter-individual difference increases with the rotation angle of the stimulus. This prediction is based on the recurrent observation of a positive relation between fluid intelligence and response accuracy (e.g., De Pascalis, Varriale, & Matteoli, 2008; Dix & van der Meer, 2015; van der Meer et al., 2010). Most importantly, we will assess whether the relation between fluid intelligence and the slope of mental rotation is paralleled by a similar effect on RNN amplitude. More specifically, we predict a negative relation between fluid intelligence and the steepness of the function relating RNN amplitude to the angular rotation of stimuli. This pattern would indicate less neural activation in higher, relative to lower ability, individuals with an increasing intelligence-related difference associated with larger rotation angles of the stimulus. This prediction is derived from notions, such as the neural-efficiency hypothesis (Neubauer & Fink, 2009), suggesting that higher ability individuals display less brain activation while performing cognitive tasks of low to medium complexity (see also Dunst et al., 2014; Gray, Chabris, & Braver, 2003). It should be noted, however, that a score of studies observed efficient performance to be related with lower activation in frontal areas together with higher activation in parietal regions (e.g., Rypma & Prabhakaran, 2009). Along these lines, one would anticipate that brighter individuals would exhibit a larger, not smaller RNN amplitude given that the neural source of this brain potential is presumably located in the parietal cortex (e.g., Zacks, 2008). Finally, we will assess the parietal P300 component of the brain potential elicited by upright stimuli given the recurrent observation that fluid intelligence is positively related to P300 amplitude in studies using a score of experimental paradigms (e.g., Amin, Malik, Kamel, Chooi, & Hussain, 2015; Beauchamp & Stelmack, 2006; De Pascalis et al., 2008; Russo, De Pascalis, Varriale, & Barratt, 2008; Troche, Indermühle, & Rammsayer, 2012; Wronka, Kaiser, & Coenen, 2013). P300 amplitudes to rotated stimuli were not considered because of the confound with a negative going of the brain potential associated with these stimuli (e.g., Heil, Bajrić, Rösler, & Hennighausen, 1996; Heil, Rauch, & Hennighausen, 1998; Wijers et al., 1989). Indeed, this negative going of the brain potential is used to compute the RRN.

2. Methods

2.1. Participants

Forty right-handed male and female paid participants were recruited via flyers from the university premises. Participants were invited to take part in the study only if they reported to be drug abstinent and free of medication and medical conditions. One participant was excluded from data analysis because of excessive noise in the EEG and two additional participants were excluded because their performance on the mental rotation task exceeded the group mean by two standard deviations for both response accuracy and speed. The resulting sample consisted of 37 participants (12 males) with a mean age of 20.38 years