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THE INFLUENCE OF OBJECT COMPLEXITY AND ROTATION ANGLE ON EYE MOVEMENTS DURING MENTAL ROTATION

The scientific objective of the study was to identify factors modifying the eye movements observed during the performance of mental rotation tasks. On the one hand, differences were sought in indicators concerning eye movements between the phases of the perception of an object in the original and rotated positions; on the other hand, the study tested the influence of object complexity on the strength of similarity between perception and visualization in terms of the times of eye fixation in corresponding regions of interest. The results showed longer mean fixation times as well as a lower number and frequency of eye fixations when visualizing objects compared to viewing them. It can therefore be concluded that mental images required longer and deeper data processing than viewed objects did. The similarity of perception and visualization in terms of visual fixation times in corresponding regions of interest was stronger for simple objects than for complex ones. Moreover, it was demonstrated that for larger rotation angles the number of fixations was higher and their frequency was lower compared to smaller angles, which suggests an increase in perceived task difficulty and an increase in cognitive engagement with the increase in rotation angle.

Keywords: mental rotation, eye movements, comparing eye scanpaths.

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MENTAL ROTATION

Performing mental operations (e.g., mentally scanning the memorized scene, enlarging/diminishing an object) is a subjective experience (Chlewiński, 1997), which constitutes a significant impediment to research on this phenomenon. Partly overcoming this limitation was made possible already by the research conducted by Shepard and colleagues (Shepard & Metzler, 1971). In their experiments on mental rotation, two visual stimuli were presented to the participants (consecutively or simultaneously). The first object (a two-dimensional representation of an object) was the original material. The second one was the experimental stimulus, being either the original object rotated around an axis perpendicular to the surface of the object, or its mirror image, also rotated. The participants' task was to recognize whether the object presented to them was the same stimulus as the original one or its mirror image. The participants' response time increased with the increase of object rotation angle, which showed that the mental rotation of the object proceeded similarly to its physical rotation.

Thanks to research on the mental rotation of complex irregular polygons, the linear relationship between response time and object rotation angle was demonstrated again (Cooper, 1975). An advantage of the visualization instruction applied in this study is the clearly specified relationship between the obtained results and the mental image, as the participants generated such images in a deliberate, intentional way. On the other hand, a direct visualization instruction leads to a difficulty in interpreting the results of the study. The participants may deliberately try to behave in accordance with the experimenters' expectations, regardless of what cognitive processes are actually involved in the performance of the task. The problem of participants conforming to the experimenters' expectations has accompanied many areas of research on mental processes (see Orne, 1962), but it is present in a special way in research on imagery (see Intons-Peterson, 1983). This makes it so important to find objective indicators of cognitive processes also in a situation of no instruction being provided in the task. It seems that eye movements may be this kind of indicator.

Eye movement tracking may also resolve issues connected with the course of mental operations. Mental rotation speed is usually assumed to be constant. However, de'Sperati (2003) demonstrated that, during the performance of a visualization task, the saccades initially performed had higher amplitudes while those performed towards the end of rotation angle assessment were shorter and more precise. Although the research schema he applied involved a considerably simplified situation (two points on a circumference creating a particular angle), it is possible on the basis of the results he obtained to challenge the hypothesis postulating constant mental rotation speed.

Factors differentiating mental rotation task performance

Numerous factors, both personality-related and object-related, differentiate the course of mental rotation task performance. Individual differences in the ability to perform accurate and fast mental rotation have been sought; the influence of the characteristics of the rotated stimulus on the course of the operation has been tested. Researchers have tested, for instance, the impact of familiarity with objects, the impact of inducing movement direction through the perception of a moving object (Corballis & McLaren, 1982), and the influence of training (Ehrlich, Levine, & Goldin-Meadow, 2006). Differences in the level of mental rotation performance depending on participants' gender have been found many times (e.g., Alexander & Evardone, 2008; Burton, Henninger, & Hafetz, 2005; Rafi & Samsudin, 2009), and for this reason gender is usually included in studies as a controlled variable. Interestingly, differences between women and men did not occur when the rotated material was human silhouettes (Alexander & Evardone, 2008).

One of the disputable factors modifying mental rotation time is object complexity. The influence of object complexity on mental rotation times was found in the studies by Bethell-Fox and Shepard (1988) as well as by Folk and Luce (1987), while Cooper (1975) and Cooper and Podgorny (1976) observed an absence of this influence. Moreover, there are differences in the ways in which these authors explain the obtained results in relation to the holistic vs. piecemeal distinction. However, these differences may stem from divergent interpretations of the relations between object complexity and the holistic or piecemeal character of mental rotation. It seems that researchers use the terms "holistic" and "piecemeal" in different ways. Folk and Luce (1987) tend to speak of holistic/piecemeal representation (referring to the level of its complexity, the number of memorized elements of the image), which means there could be no differences between simple and complex objects in the case of piecemeal representation. Cooper and Podgorny (1976) speak of holistic/piecemeal rotation operation. When the entire object is rotated, it is not important how complex it is, whereas complexity may have an effect in the case of piecemeal rotation. No effect of complexity would attest the holistic character of mental rotation. It is therefore worth looking for a method that would make it possible both to determine the level of representation complexity and to verify the manner in which mental transformations are performed during rotation. Tracking eye movements seems to be this kind of tool.

Oculomotor indicators of mental rotation

The mental rotation operation is connected with a few crucial questions that are not easy ones to answer only on the basis of response times. Mental rotation tasks usually take less than 5 seconds and may be broken down into a sequence of very fast mental operations whose duration is often estimated at between 50 and 800 milliseconds. Consequently, in order to gain insight into the order and duration of the phases, research was undertaken in which eye movements during the performance of mental rotation were tracked (Just & Carpenter, 1976). The main idea behind the analyses of eye positions is that fixation reflects what is the object of interest at a particular moment. If several symbols are processed in a particular order, vision should be fixed on their referents in the same order, and the duration of fixation on each referent may be related to the time of processing a particular symbol (Mariwa, Xu, & Pomplun, in press). Just and Carpenter (1976) succeeded in dividing the mental rotation task (with a simultaneous presentation of objects: in the original and rotated positions) into stages: search, transformation, and verification.

An example of a mental rotation study in a sequential configuration is the experiments conducted by Nakatani and Pollatsek (2004). Their participants looked at a scene consisting of three objects placed on a desktop, and next they looked at a comparison scene. The comparison scene was identical, except for the viewpoint (rotation was performed around one of three rotation axes: *X* – the horizontal axis, *Y* – the vertical axis, *Z* – the axis perpendicular to the plane of the image), or different (one or more objects in the comparison scene had swapped places or had been rotated around their own axis). The participants were supposed to compare these scenes. A characteristic effect was obtained – reaction times were longer when rotation angles of the comparison scene increased. Also, the size of the effect of rotation differed across rotation axes.

Total reaction times were divided into three components: initial latency, first-pass time, and second-pass time. Initial latency is the time between the appearance of the comparison scene and the initiating saccade. The first pass is defined as completed when one of the objects has been viewed for a second time or when the response has been given immediately, after only one look at the elements of the scene (without “return visits”). Second-pass time was the sum of fixation times from the first “return visit” until the moment of the participant’s response. As in analyses of eye movement recording in studies on reading (see Rayner, 1998), the authors assumed that the time of the first pass of the eye through the scene corresponded to the initial coding of the comparison scene, while the time of the second pass corresponded to the subsequent processing.

Comparing the studies conducted by Just and Carpenter (1976) and by Nakatani and Pollatsek (2004), one can find certain differences and limitations pertaining to both the research procedure and the methods of analysis. Just and Carpenter (1976) analyzed the mean number and times of fixations when both stimuli were presented simultaneously, which enabled the participants to refer back to perceptions (relying on memory to a smaller degree) and easily compare objects. Nakatani and Pollatsek (2004) presented the stimuli sequentially; however, they did not analyze mean fixation times but first-pass and second-pass times. In their study, the authors divided response times into two stages and did not analyze changes in the general characteristics of eye movements. Moreover, their analyses concerned the time of looking at particular elements of the scene, without addressing the specific way of looking at them. It is therefore worth asking the question about the changes in the characteristics of eye movements depending on rotation angle during sequential presentation of objects.

It seems that in a situation of both images being available to perception individuals perform the task at the lowest cognitive effort possible. The participants behave in accordance with the “switch-over adaptation” model, performing more switch-overs between images (more shifts of the eyes from one stimulus to the other) in order to reduce the involvement of working memory (Mariwa et al., in press). Although Mariwa and colleagues (in press) conclude that the applied paradigm of research on mental rotation using simultaneous presentation and introducing a local change makes it possible to assess the interaction of visual attention, working memory, and mental transformation, there is a certain limitation involved. With this kind of procedure, it is difficult to distinguish the function of eye movements and their relation to the visualization process, since the perception process takes place simultaneously. This is a limitation found in all the existing studies on mental rotation using eye movement measurement.

Eye movement indicators such as the number of fixations, their duration or distribution may be an indirect indicator of the cognitive processes (e.g., object perception or visualization) taking place during eye movements. These general characteristics are independent of where the eye is fixed, which makes this kind of measurement different and independent of analyses of interest regions. The number of fixations may indicate participants' interest in the image they are viewing. Fixation time is often interpreted in terms of the intensity of processing of the material that the eyes are fixed on at a particular moment. These indicators make it possible to compare the intensity of processing of the material being viewed with the intensity of processing of that which is retrieved from memory (visualized). What is therefore interesting is this: Are there differences between object perception and visualization in the general indicators of eye movements?

Moreover, it can be said that while in studies on static visualizations attempts were made indeed to capture the movements and location of the eyes when generating visualizations without the presence of a visual stimulus at that particular moment (e.g., Brandt & Stark, 1997), in studies on mental rotation the main object of analysis was the record of eye movements when looking at a scene rotated by a certain number of degrees or during the simultaneous presentation of two scenes. The sequential presentation of the original and rotated image enables measuring eye movement separately for each stage of task performance.

As regards the influence of object complexity on mental rotation, there are studies directly addressing this phenomenon. Based on a comparison of the results of two studies, and based on analyses of the duration times of each mental rotation stage, Carpenter and Just (1978) found that the difference between response times for simple and complex objects does not stem from a slower rotation of complex objects, since the transformation stage proceeded similarly for both stimuli. Differences occurred at the stages of search and confirmation. However, these conclusions follow only from a meta-analysis of two studies. Just and Carpenter did not include object complexity in their research as an independent variable; there are no statistical analyses of the influence of complexity on eye movements. This issue is therefore worth addressing in research. Moreover, the sequential presentation of objects for rotation may additionally reveal the effect of complexity when the compared object has to be retrieved from memory.

MENTAL ROTATION OF SIMPLE AND COMPLEX OBJECTS: THE PRESENT STUDY

The present study concerned the measurement of eye movements during the performance of a mental rotation task. It enters into a debate with studies present in the literature on mental rotation using eye movement measurement (Just & Carpenter, 1976; Mariwa et al., in press; Nakatani & Pollatsek, 2004).

The results of previous research (Bałaj & Francuz, 2012) show the existence and continuance of similarity between eye movements during the viewing and visualization of a static object in a mental scanning task when the participants are instructed to try to visualize the memorized object. Still, there may be doubts as to whether or not, when hearing the visualization instruction, the participants try to behave in such a way as to meet the expectations of the researcher who has given them the instruction (cf. Intons-Peterson, 1983). A question therefore arises of whether the participants would move their eyes if they were spontaneously generating visualizations without having been instructed to generate them.

In the present study, eye movements measured in the interval between the perception of the object in the zero position and the perception of that object in a new position make it possible to avoid the influence of direct instruction to generate visualizations. This made it possible to measure eye movements without a physical stimulus present and without a visualization instruction being given. The measurement of eye movements was also performed during the performance of the mental rotation task – namely, from the moment of the presentation of the rotated object to the moment of the participant's response concerning whether the object viewed was identical to the one in the original position.

Method

The research method was based on classic mental rotation studies, with mental rotation task performance accuracy and time as indicators. Additionally, eye movements during the performance of different phases of the task were measured. The technique chosen was sequential presentation of the object in the original and rotated positions. The sample was composed of 20 people (aged $M = 23.18$, $SD = 2.4$). The results of 10 women and 10 men were included in analyses. The experiment was conducted in the Psychoneurophysiological Laboratory at the Department of Experimental Psychology of the John Paul II Catholic University of Lublin.

The experimental material was presented in a random order on an LCD screen with a resolution of 1920 x 1200 pixels. The stimuli were two-dimensional figures. The objects were placed inside a circle. The experimental stimuli had been designed using Adobe Photoshop CS3. Applications enabling their presentation were written using e-Prime software, version 2.0. This software also enabled communication with iView X, a program tracking eye movements. BeGaze software enabled the visualization and processing of data from eye movement tracking. Data were analyzed statistically using the STATISTICA 8.0 package.

The measurement equipment consisted of an eye-tracker (*SMI iView X Hi Speed*; measurement frequency – 1250 Hz, measurement resolution – 0.01°), a keyboard with a modified key configuration, two computers (for the presentation of stimuli and for the measurement of eye movements), two monitors (for the presentation of stimuli and for the researcher to control the experiment).

Statistical model. The object of statistical analysis was the indicators of the dependent variables, namely: (1) (a) the parameters of eye movements tracked during the perception of the rotated object and the performance of the mental rotation task – ANOVA with repeated measurement (for the independent variable – rotation angle); (b) similarity between perception and visualization (a record of eye movements in the form of fixations in specific regions of interest, registered during the perception of the object in the original position and during visualization), correlational analysis and a test of differences between correlations (the replacement of *r* coefficients with Fisher's *z* and a comparison using a *t*-test); (c) the parameters of eye movements (the number of fixations, the frequency of fixations, etc.) registered during the perception of the object in the original position and during visualization – a *t*-test for dependent data; (2) mental rotation accuracy (0-1 responses) – log-linear analysis of contingency tables (for qualitative independent variables) and (3) mental rotation time (response time in a visualization task after logarithmic transformation) – ANOVA with repeated measurement.

Analysis 1a

Three rotation angle sizes within half a revolution were chosen for the study (60°, 120°, 180°). Many studies showed that rotation can take both directions, and that the dependency of response time on rotation angle increases linearly until the angle of 180° and then decreases until the angle of 360°. Therefore, in order to reduce the number of trials, only half a revolution is often analyzed in studies. The material for analyses was provided by the measurements of the eye movements (indicators analyzed: the number, frequency, and duration of fixations; amplitude and duration of saccades) performed from the moment the rotated object appeared until the moment of the participant's decision in the mental rotation task – that is, until the moment of response on whether the object seen had been only rotated or both rotated and transformed into a mirror image.

Analysis 1b

In order to test the influence of object complexity (in accordance with the studies by Bethell-Fox & Shepard, 1988; Bałaj & Francuz, 2012), I used simple and complex objects in the present study. The initial stage of the operationalization of this variable was generating many objects consisting of the same number of elements (gray squares connected on at least one side), but differing in the total number of sides (cf. Bałaj & Francuz, 2012). A set of 61 objects was obtained. The simplest six and the most complex six objects were selected. The simple objects had 8 to 10 sides, whereas the complex ones had 14 to 16 sides. Object complexity was an object-related independent variable, which means that all the participants performed tasks on simple objects as well as on complex ones.

The degree of similarity between perception-based and visualization-based scanning was measured by determining the value of Pearson's *r* correlation between the eye fixation times in 25 regions of interest (making up a square circumscribed on the circle inside which the presented stimulus was located) registered when the object was viewed in the original position and when it was visualized.

Analysis 1c

An analysis of differences between perception and visualization in terms of selected eye movement parameters. Situations of viewing and visualizing an object were compared in terms of eye movements (the number, frequency, and duration of fixations; the speed, amplitude, and duration of saccades).

Analysis 2

In order to explain the accuracy of mental rotation task performance, I performed a log-linear analysis. The influence of the following factors was tested: (1) Rotation angle size (60°, 120°, 180°), (2) Object complexity (simple vs. complex objects), (3) Mirror image of the object (mirror image vs. the actual object), (4) Gender (controlled variable).

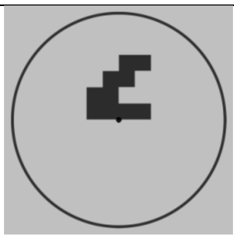
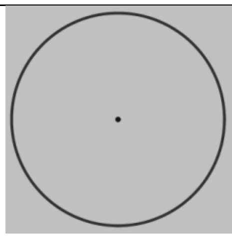
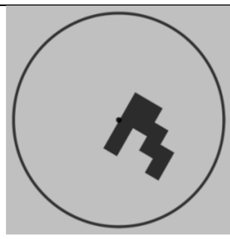
Analysis 3

A verification of the influence of the selected independent variables on mental rotation task performance speed (i.e., response times). Independent variables – as in the model with the accuracy indicator: (1) Rotation angle, (2) Object complexity, (3) Mirror image, (4) Gender. Dependent variable: Decision time in the mental rotation task.

Procedure

The study was carried out on an individual basis and took about 30 minutes per person. First, the participants' ocular preference was established. The main study was conducted in accordance with the standard procedure of mental rotation research with sequential presentation of visual material. The participants were shown an object, and then, after a moment's interval, they were shown the object in a different position (either rotated by a particular number of degrees or rotated and additionally transformed into a mirror image). The participants' task was to give a response concerning the identicalness of the rotated object currently seen with the one seen previously. The procedure is presented in Table 1.

Table 1
The Scheme of the Procedure

Phase	The task proper – repeated 36 times (12 objects x 3 rotation angles)		
	Perception		Mental rotation task
Elements on the screen			
Time	2 sec.	2 sec.	Response time
Partici-pant's task:	Object perception		Rotated object recognition (giving a response)
Measure-ment of	Eye movements	Eye movements	Eye movements Task performance accuracy and time

Eye movement measurement took place during the viewing of the object in the zero position and during the presentation of an empty circle – the latter was the stage of visualization without the visualization instruction being provided. These two measurements were correlated with each other in terms of eye fixation time in corresponding regions of interest. Eye movements were also measured in the phase of viewing the rotated object and giving a response. At this stage, eye movement parameters were analyzed according to the size of the rotation angle.

Results

The results of the study will be presented separately for eye movement indicators (both correlations and difference tests) and for the accuracy and times of mental rotation task performance.

Eye movements in the mental rotation task

Analysis 1a. Testing differences in terms of general indicators of eye movements measured in the phase of perception of the object rotated by different numbers of degrees (various angles).

Analyzing eye movements from the last phase of the experiment (rotated object perception and giving a response in the mental rotation task), it is possible to find differences in selected eye movement characteristics depending on rotation angle. A lower number of fixations were observed for a smaller rotation angle compared to a larger rotation angle (60° M = 5.03, SD = 3.39; 120° M = 5.3 SD = 3.61; 180° M = 5.49 SD = 3.35). Differences in the number of fixation depending on rotation angle turned out to be statistically significant (F = 4.14, df = 2, p = .016, partial η^2 = .009). The significance of linear contrast (F = 8.03, df = 1, p = .005, partial η^2 = .016) and the nonsignificance of squared contrast (F = 0.08, df = 1, p = .775, partial η^2 = 0) suggest that the observed relationship has a linear character: the larger the rotation angle, the higher the number of fixations.

A higher frequency of fixations was observed for a smaller rotation angle compared to a larger rotation angle (60° M = 2.76, SD = 0.96; 120° M = 2.64, SD = 0.89; 180° M = 2.57, SD = 0.9). Differences in the frequency of fixations depending on rotation angle turned out to be statistically significant (F = 9.6, df = 1.96, p = .001, partial η^2 = .020). The significance of linear contrast (F = 16.32, df = 1, p = .001, partial η^2 = .033) points to the linearity of the observed relationship between rotation angle and fixation frequency.

No significant differences depending on rotation angle were observed for the remaining eye movement parameters (mean time of fixations and saccades, amplitude of saccades).

Analysis 1b. Testing differences in the strength of the similarity of fixation times in corresponding regions of interest depending on object complexity.

The time devoted to perception and visualization was the same; in the example illustrated in Figure 1, it is therefore possible to notice certain similarities as well as differences between eye movements during object perception vs. visualization. What is worth stressing is the fact that the participants were not instructed to generate a visualization but moved their eyes spontaneously as if they were still looking at the object they had previously seen.

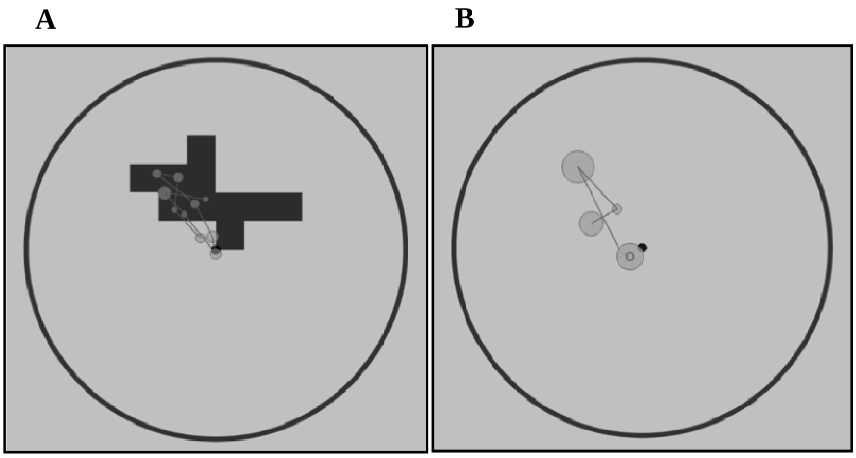


Figure 1. A sample record of eye movements while viewing (A) and visualizing (B) an object.

Correlations were computed – separately for simple and complex objects. Next, the significance of the difference between these correlations was computed.

Mean fixation time in regions of interest ranged between 641 and 735 ms. The observed distributions were symmetrical. Statistically significant (p = .002) differences between the strength of correlations of eye movements in perception vs. visualization were observed for simple objects (r = .45, p = .001) and for complex ones (r = .36, p = .001). Stronger similarity of eye movements during perception and visualization was found in the case of simple objects than in the case of complex ones.

Analysis 1c. Testing differences between the perception of a figure in the original position and its visualization in terms of general parameters of eye scanpaths.

More fixations were observed during object perception, and their frequency was higher as well. The mean fixation time in the case of visualization was longer compared to perception (Table 2).

Table 2
Descriptive Statistics and the Test of Differences Between the Means of Fixation Indicators

	N	Mean	Standard deviation	*t*	*df*	*p*
Number of fixations – perception	1440	6.04	1.95	33.45	1439	.001
Number of fixations – visualization	1440	4.15	1.83			
Fixation frequency (per sec.) – perception	1440	2.96	0.95	34.10	1439	.001
Fixation frequency (per sec.) – visualization	1440	2.02	0.89			
Mean fixation time (ms) – perception	1440	349	288	-20.21	1439	.001
Mean fixation time (ms) – visualization	1440	574	410			

The mean duration of saccades in perception (*M* = 36.85, *SD* = 7.12) was longer than in the case of visualization (*M* = 35.63, *SD* = 9.4). These differences were statistically significant (*t* = 3.91, *df* = 1243, *p* = .001). Eye movements in perception and visualization did not differ in the mean amplitude of saccades.

Analysis 2. The accuracy of mental rotation task performance

The accuracy of mental rotation task performance was analyzed using log-linear analysis. Rotation angle size, mirror image, and gender were found to have a significant influence on the accuracy of mental rotation task performance (Tab. 3). These variables were also found to have an interactive influence.

Table 3
Marginal and Partial Relationship Tests for Mental Rotation Accuracy

Effect	*df*	Partial χ^2	Partial *p*	Marginal χ^2	Marginal *p*
Accuracy	1	591.94	.001	591.94	.001
Accuracy x mirror	1	15.64	.001	15.34	.001
Accuracy x angle	2	15.89	.001	15.59	.001
Accuracy x complexity	1	0.37	.545	0.35	.551
Accuracy x gender	1	12.63	.001	12.36	.001
Accuracy x mirror x angle	2	7.04	.030	7.26	.027
Accuracy x mirror x gender	1	5.99	.014	6.20	.013

The best-fitted model includes the relationships between accuracy and mirror image, between accuracy and rotation angle, and between accuracy and gender. It is therefore legitimate to say that mental rotation task performance accuracy is best explained by the influence of rotation angle size, mirror image, and gender. This model is well fitted to the data, as shown by the results of the chi-square test ($\chi^2 = 18.05$, $df = 38$, $p = .997$).

The tasks that did not involve comparison with a mirror image were performed more accurately (112 errors) compared to the tasks that did involve that comparison (171 errors). In a situation of performing mental rotations that required comparing objects rotated by larger angles the participants made more errors (in rotation by 60° – 69 errors; in rotation by 120° – 97 errors, in rotation by 180° – 117 errors). Women made fewer errors (168) compared to men (115) in the mental rotation task. Object complexity did not affect the accuracy of mental task performance.

Analysis 3. Mental rotation time

As regards the speed of performing mental rotation, a significant influence of rotation angle size was observed ($F(2) = 16.02$, $p = .001$, partial $\eta^2 = .47$) as well as an interactive influence of object complexity and participants' gender ($F(1) = 6.96$, $p = .017$, partial $\eta^2 = .28$).

In the presented study, a characteristic effect of rotation angle size on the speed of performing the mental rotation task was observed. Longer response times were observed for larger rotation angles (60° $M = 7.42$; 120° $M = 7.51$; 180° $M = 7.63$). The significant results of linear contrast ($F(1) = 22$, $p = .001$, partial $\eta^2 = .55$) and the nonsignificance of squared contrast ($F(1) = 0.45$, $p = .51$, partial $\eta^2 = .02$) indicate that the relationship between response time and rotation angle has a linear character.

For simple objects, men ($M = 7.41$) performed mental rotation faster than women ($M = 7.6$). This pattern is not observed in the case of complex objects (men $M = 7.51$, women $M = 7.55$).

DISCUSSION

For larger rotation angles, more fixations and a longer mean fixation time was found. Thus, the study demonstrated the number, frequency, and mean duration time of fixations to be dependent on rotation angle. These results are consistent with those obtained by Nakatani and Pollatsek (2004). No significant differences were found in mean duration times and amplitudes of saccades depending on rotation angle.

A longer mean time of fixations and their lower frequency suggest that fewer fixations are performed in the same time unit for larger rotation angles and that their duration times are longer. This pattern can be interpreted in terms of stronger cognitive involvement in the processing of the observed visual material (cf. Rayner, 1998). What is interesting is that the observed relationships exhibit a configuration similar to the characteristic patterns of mental rotation task performance times increasing with the increase of the rotation angle. Linear contrasts turned out to be significant. The results concerning differences in eye movement parameters depending on rotation angle size should be approached with caution due to the low values of eta-squared.

The present study revealed a significant relationship between eye fixation time in corresponding regions of interest during object viewing and visualization. These correlations are particularly important because the participants were not given a visualization instruction. Despite the lack of instruction, individuals moved their eyes in a similar way during the absence of the stimulus as they did when looking at the same object.

The authors of studies reported in the literature have demonstrated the similarity between perception and visualization for a variety of objects and scenes, but the strength of this relationship has not been compared depending on object complexity (cf. Brandt & Stark, 1997; Laeng & Teodorescu, 2002; Spivey & Geng, 2001). As hypothesized, significant differences depending on object complexity were found in the strength of the relationship between perception and visualization. A stronger similarity of eye movements in perception and visualization was found in the case of simple objects than in the case of complex ones. It is possible to explain this result by referring to the phenomenon observed earlier, namely to the fact that complex objects tend to require more complex eye movements (cf. Duchowski, 2007). In the case of complex objects, there is also a greater number of possible elements to note or overlook, which leads to a lower similarity of eye movements.

More fixations were observed during object perception than during visualization. Their frequency was higher during perception as well. It can therefore be said that perception-based scanning was faster than visualization-based scanning of the object. The mean fixation time in visualization was longer compared to perception. This result is consistent with the findings obtained by Zangemeister and Liman (2007). Because during visualization the object was unavailable to perception, the material processed was object representation in the form of a visualization. The longer time of fixation may be interpreted in terms of stronger cognitive involvement in the processing of material during visualization-based scanning compared to perception-based scanning. This is how an increase in the duration time of fixations is usually interpreted. For example, in research on reading the total time of the "first pass" is treated as the main measure of interest in the text (cf. Rayner, 1998). An explanation of the longer duration times of fixations can also be sought in the greater difficulty of constructing a mental image compared to perception (cf. Brandt & Stark, 1997).

Unlike the study by Brandt and Stark (1997), the present one revealed no differences between perception and visualization in the amplitude of saccades. Differences were observed in the mean duration time of saccades and fixations. Thus, the study confirmed the hypothesis concerning differences between perception and visualization in terms of the following indicators: the number of fixations, the frequency of fixations, the mean time of fixations, and the mean time of saccades. These results point to differences in the depth of information processing between object viewing and visualization. However, this hypothesis should be rejected with regard to the amplitude of saccades, which is related to the local/global character of visual scanning.

Mental rotation task performance accuracy is best explained by the influence of rotation angle size, mirror image, and gender. The tasks that did not involve comparison with a mirror image were performed more accurately compared to the tasks that did involve that comparison. In a situation of performing mental rotations that required comparing objects rotated by larger angles, the participants made more errors.

In the present study, a characteristic effect was found pertaining to the influence of rotation angle size on the speed of mental rotation task performance (cf. Shepard & Metzler, 1971).

Comparisons between women and men yielded interesting results regarding the accuracy and duration times of mental rotation performance. Women made fewer errors than men did. For simple objects, men performed mental rotation faster than women did. This pattern was not found for complex objects. Perhaps women regarded even the simple objects as more complex and, consequently, had longer rotation times compared to men. However, it is equally probable that, compared to women, men were able to better distinguish simple objects from one another and that is why they rotated them faster (cf. Folk & Luce, 1987).

Perhaps in those studies in which no significant differences were observed between women and men (e.g., in the case of the rotation objects representing human silhouettes; Alexander & Evardone, 2008) it is possible to explain the lack of effect precisely as stemming from the complexity of the objects that mental rotation is performed on. The lack of influence of complexity on the accuracy of mental rotation task performance can be explained by the insufficient level of similarity between objects, since the choice of rotation strategy depends on the level of similarity between the objects being compared (e.g., an image only slightly different from the actual stimulus is presented instead of a mirror image). If they are very similar to each other, then the participants will rotate them holistically. The experiments carried out by Folk and Luce (1987) showed that comparing complex stimuli and ones that are difficult to differentiate between proceeds more slowly than comparing simple stimuli, and the number of errors made in that case is higher.

The study by Carpenter and Just (1978) revealed that it is not the rotation of complex objects as such that proceeds more slowly. The cause of longer times for more complex objects is the fact that for more complex stimuli it is more difficult to find appropriate elements for rotation (the first stage), especially when the rotation angle increases. For the same reason, it is more difficult to confirm the correctness of one's suppositions in the final stage. The authors suggest that in certain situations (when detailed comparison is not necessary) only a fragment of a figure may be rotated, and then the effect of complexity may not occur at all. This kind of situation might have been the case in the experiment discussed.

– To sum up, it can be said that the measurement of eye movements during visualization opens up plenty of possibilities for research on this still little known process.

– During the performance of a mental rotation task, the number of fixations is higher and their frequency is lower for larger rotation angles than for smaller ones.

– The processes of perception and visualization were found to be similar in terms of eye fixation times in corresponding regions of interest when no visualization instruction was given.

– The influence of complexity on the strength of the perception–visualization relationship was demonstrated. Compared to complex objects, visualizations of simple objects showed stronger similarity to perception in terms of visual fixation times in corresponding regions of interest.

– The present study also makes it possible to determine the differences between perception-based and visualization-based scanning in terms of general eye movement characteristics. In visualization, mean fixation times were found to be longer and their number and frequency were lower. This suggests deeper processing of material during mental operations compared to the situation of viewing objects.

The use of different research procedures (e.g., simultaneous or sequential presentation of figures in mental rotation tasks) leads to differences in the degree of engagement of cognitive processes (such as perception, working memory, or visual attention). Comparisons of eye movements in these two situations in one experiment could make it possible to detect differences in the course of mental rotation subprocesses. Moreover, in the case of simultaneous presentation, the participant can decide how much information to compare at a time, which means the extent to which perception and working memory are involved partly depends on him or her. By contrast, in the case of sequential presentation, having only the rotated object at his or her disposal, the participant is forced to rely on a mental representation of the figure. A modification of the procedure also enables changing the proportions between the subprocesses of mental rotation, thus making it possible to compare them.

The present study was limited to relatively simple figures and mental operations, which, in natural conditions, could be merely a fragment of the creative process (e.g., the creation of a sculpture or a painting). Eye movement tracking may be applicable also in research on the stages of more complex cognitive processes.

REFERENCES

Alexander, G. M., & Evardone, M. (2008). Blocks and bodies: Sex differences in a novel version of the Mental Rotations Test. *Hormones and Behavior, 53*, 177-184.

Bałaj, B., & Francuz, P. (2012). Siła podobieństwa w ruchach oczu wykonywanych podczas oglądania i wyobrażania sobie obiektów – czynniki modyfikujące. *Polski Przegląd Medycyny i Psychologii Lotniczej, 2*(18), 63-76.

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*, 12-23.

Brandt, S. A., & Stark, L. W. (1997). Spontaneous eye movements during visual imagery reflect the content of the visual scene. *Journal of Cognitive Neuroscience, 9*, 27-38.

Burton, L. A., Henninger, D., & Hafetz, J. (2005). Gender differences in relations of mental rotation, verbal fluency, and SAT scores to finger length ratios as hormonal indexes. *Developmental Neuropsychology, 28*, 493-505.

Carpenter, P. A., & Just, M. A. (1978). Eye fixations during mental rotation. In J. W. Senders, D. F. Fisher, & R. A. Monty (Eds.), *Eye movements and the higher psychological functions* (pp. 115-133). Hillsdale, NJ: Lawrence Erlbaum.

Chlewiński, Z. (1997). Podstawowe problemy teoretyczno-metodologiczne w badaniach nad wyobraźnią. *Kolokwia Psychologiczne, 6,* 27-57.

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 comparison processes: Effects of complexity and similarity. *Journal of Experimental Psychology: Human Perception and Performance, 2*, 503-514.

Corballis, M. C., & McLaren, R. (1982). Interaction between perceived and imagined rotation. *Journal of Experimental Psychology: Human Perception and Performance, 8*, 215-224.

de'Sperati, C. (2003). Precise oculomotor correlates of visuospatial mental rotation and circular motion imagery. *Journal of Cognitive Neuroscience, 15*, 1244-1259.

Duchowski, A. T. (2007). *Eye tracking methodology*: *Theory and practice* (2nd ed.). London: Springer-Verlag.

Ehrlich, S. B., Levine, S. C., & Goldin-Meadow, S. (2006). The importance of gesture in children's spatial reasoning. *Developmental Psychology, 42*(6), 1259-1268.

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, 3*, 395-404.

Intons-Peterson, M. J. (1983). Imagery paradigms: How vulnerable are they to experimenters' expectations? *Journal of Experimental Psychology: Human Perception and Performance, 9*, 394-412.

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

Laeng, B., & Teodorescu, D. S. (2002). Eye scanpaths during visual imagery reenact those of perception of the same visual scene. *Cognitive Science, 26*, 207-231.

Mariwa, H. P., Xu, Y., & Pomplun, M. (in press). Piecewise mental rotation. Submitted to *Quarterly Journal of Experimental Psychology.*

Nakatani, C., & Pollatsek, A. (2004). An eye movement analysis of "mental rotation" of simple scenes. *Perception and Psychophysics, 66*, 1227-1245.

Orne, M. T. (1962). On the social psychology of the psychological experiment: With particular reference to demand characteristics and their implications. *American Psychologist, 17*, 776-783.

Rafi, A., & Samsudin, K. (2009). Practising mental rotation using interactive Desktop Mental Rotation Trainer (iDeMRT). *British Journal of Educational Technology, 40*, 889-900.

Rayner, K. (1998). Eye movements in reading and information processing: 20 years of research. *Psychological Bulletin, 124*, 372-422.

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

Spivey, M. J., & Geng, J. J. (2001). Oculomotor mechanisms activated by imagery and memory: Eye movements to absent objects. *Psychological Research, 65*, 235-241.

Zangemeister, W. H., & Liman, T. (2007). Foveal versus parafoveal scanpaths of visual imagery in virtual hemianopic subjects. *Computers in Biology and Medicine, 37*, 975-982.