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THE IMPACT OF RETINAL SIZE
ON MENTAL TRANSFORMATIONS IN IMAGERY:
ROTATION, SYNTHESIS, COMBINATION

The following paper is an answer to a research question regarding the impact of retinal size (understood as the tangent of the object's physical size and its distance from the subject) on mental transformations. A total of 182 people took part in three designed experiments, which included three types of operations: 1) synthesis as an operation changing the structure of the object; 2) rotation as an operation preserving the structure of the object; and 3) a combination of the two. The impact of retinal size on the course of rotation was confirmed. Furthermore, it turned out that this impact significantly influenced the effectiveness of all three mental operations. A tendency regarding the impact of physical size on synthesis was demonstrated (participants performed mental transformations in the most optimal way on 15 cm (5.9 in) objects – such that can be held in a hand in the real world). It was noticeable that the optimal distance to the object, preferred by participants, was 30 cm (11.8 in). In the real world, such a distance enables them to transform objects freely within arm's reach. The obtained results support the analogousness of the mental world to the world in which we live.

Keywords: imagination, mental rotation, mental synthesis, simultaneous operations, retinal size, object size vs. mental operations.

The following paper focuses on the issues related to the impact of retinal size on the efficiency of operations on mental images, which are understood as internal representations developing in the absence of perceptual data. Imagination is a top-down process, initiated by needs and objectives. The image is built on the

basis of a mental instruction, triggered by the direction "imagine" (explicit instruction) or by a metaphor or sound (implicit instruction). The process of perception is different, as its perceptual hypothesis develops on the basis of retinotopic maps – on the basis of data from receptors (Francuz, 2007).

Transformations on mental representations can take two forms (Nowak, 1991):

1) simple transformations – rotations and shifts that cause a change in the spatial relations between the representations of objects but do not change their shapes.

2) transformations changing the structure of the object – rotations and shifts that change the spatial relations between parts of the representation, i.e., change the shape.

3) besides single operations that either preserve or change the structure of the object, one can also investigate combinations of operations, i.e. simultaneous operations, consisting in the simultaneous occurrence of at least two operations in one mental act.

Transformations can be performed on spatial representations or sensory images (Nowak, 1991). Spatial representations exist in the objective space and are independent of the point of observation. However, transformations conducted on sensory images are observed from a specific point of view and thus are organized in relation to the observing subject. I suggest that the transformations of sensory images should be treated as a change of the rules that govern generating a sensory image out of a representation.

In other words, if we examine rotation as an operation preserving the structure of the object, one could argue that from the perspective of the subject the rotated object does change its structure. This is indeed true from the subjects' perspective but not in the objective space. Thus, it is essential to assume that the differentiation between operations preserving the structure of the object and those changing it applies to spatial representations.

MENTAL ROTATION AS AN EXAMPLE OF OPERATION PRESERVING THE OBJECT'S STRUCTURE

In research on rotation conducted according to the classic paradigm proposed by Shepard, the following were used as stimuli: letters (Cooper & Shepard, 1973), polygons (Cooper, 1975), and three-dimensional objects (Shepard & Metzler, 1971). A linear relationship was demonstrated between the degree of

figure rotation and reaction time: the more degrees the figure is rotated by, the longer the response time. This is true for rotations by up to 180 degrees. The greater the angle of rotation from 180 to 360 degrees, the shorter the response time. This is the classic result, called the pendulum effect. It clearly proves the economy of brain functioning (Cooper & Shepard, 1973; Cooper, 1975; Shepard & Metzler, 1971).

The long history of research on mental rotation has led to many interesting conclusions, e.g., the impact of symmetry was excluded (Taosheng & Cooper, 2003); there was a long debate on the impact of size (Biederman, 1987, Bundesen & Larsen, 1975; Kosslyn, 1980; Kubovy & Podgorny, 1981) but no coherent conclusions were reached; the impact of distinctiveness was confirmed (e.g., Sternberg, 2001); the significance of morphology was revealed – mental rotation of marble objects takes longer than that of wooden ones, especially in the case of women (Francuz, Oleś, & Chumak, 2008). The influence of the modality in which rotation takes place (Lawson, 2009) and the influence of training were examined. Furthermore, it was proved that by exercising one can significantly improve the ability to rotate figures (Jolicoeur, source not available, as cited in Sternberg, 2001).

Taosheng and Cooper (2003) suggested an interesting modification of the classic methodology of research on rotation, including interactions between shape and movement. Participants in the experiment watched a series of 64 three-dimensional objects, rotated during the presentation by 120 degrees per second. After the presentation, a memory test was conducted which included figures presented during the experiment and completely new ones. Half of the familiar objects were rotated in the right direction, i.e., the same as during the presentation, and the other half were rotated in the wrong direction (what is important, participants had not been informed in advance that they would participate in a memory test; they were only told to think if a given figure could be used as a manual tool for sawing/crashing or rather as a handy tool to lean/rest on). The results revealed statistically significant differences between the level of accurate identifications (is the figure familiar or unfamiliar?) and the direction of rotation. If during the identifications test the figure was rotated in the same direction as during the first presentation, people identified it more accurately. Rotation in the opposite direction significantly hindered identification. Thus, movement turned out to be very important to the identification of objects. Stone (1999) conducted an analogous study and obtained identical results. He used objects presented in two dimensions.

MENTAL SYNTHESIS AS AN EXAMPLE OF OPERATION CHANGING THE OBJECT'S STRUCTURE

Synthesis is a process of combining elements, the effect of which is the creation of a combined, integrated, organized, standardized whole. This whole has properties or characteristics being the result of the synthesis, which not necessarily can be derived from the analysis of individual elements (Reber, 2002, p. 727). Finke (1990) conducted regular research on synthesis and demonstrated that it allowed to obtain interesting objects with new features and that synthesis as an operation played a key role in the creative process. Participants were presented with three figures and told to combine them so as to make up something interesting and useful. They could rotate figures freely and change their size, but they could not introduce any changes to the shape of the object. As soon as after one minute, participants had to interpret their drawings according to a given category, for example furniture, toy, or medical device. It turned out that 90% of the participants created a visual pattern which, according to competent judges, was recognizable, and 1/3 of the participants created at least one object assessed as creative (cf. Nęcka, 2001). Finke (1985, 1990) conducted research using various objects: lines, geometric figures, and alphanumeric symbols. Moreover, he manipulated the content of instructions and, above all, the time of presenting the interpretative category to the participant.

Glushko and Cooper (1978) also conducted regular research on synthesis and proved that the number of elements subjected to synthesis had no impact on operation time. The more elements the subject had to connect, the longer the time of this transformation was.

In the above-mentioned experiments, the size of the objects was not manipulated.

RETINAL SIZE

According to the hypothesis that is pivotal to the presented research, retinal size has an impact on the course of the mental operations mentioned. Images on the retina are projected in two dimensions, even though people live in a three-dimensional world. The perception of distance is a complex process. The brain uses various types of clues, e.g., information derived from retinal differences. When the image is projected on the retina, information coming from both eyes is combined, and shape as well as distance from the object are determined. The

objects that are next to/in front of/behind the object on which vision is focused are also projected on the retina. There are minimal differences between the images projected on the two eyes – differences that are used to determine distance or depth; the brain determines how the objects are situated in relation to one another (behind/in front of) (Kosslyn & Rosenberg, 2006). Another clue is occlusion (also called interposition). If one object covers another, it is a signal that the covered object is more distant (cf. Janowski, 2007).

The perception of size is much simpler than the perception of distance. The process of perception enables us to determine size very precisely, to observe accurately that an object is 5 cm (2 in) or 1 m (3.3 ft) long. However, a person is unable to determine the absolute size of the object. It seems that the visual system codes only information about relative relations between the size of objects and that the coding is of allocentric nature, which means that it takes place in relation to other objects and not to the subject (Milner & Goodale, 2006; Króliczak, 2010). This can lead to many illusions. An object located in many contexts is perceived as an object of various sizes (cf. the Ebbinghaus illusion).

Data about spatial relations are processed in the visual system called dorsal – as opposed to data about shape, color, or pattern, processed in the ventral visual system. Thanks to the analysis of information about space, there occurs a "parametrization of the observer's motor behavior … Thus, the dorsal system is in charge of analyzing the observer's so-called self-centered space, whose metric is not relativized to the scopes of operation of the perceptive system, but is absolute … (otherwise) the observer would have significant difficulties in making any precise movement in relation to the objects that are most often seen in various perspective shortcuts" (Francuz, 2007, p. 158; see also Króliczak, Heard, Goodale, & Gregory, 2006).

THE IMPACT OF RETINAL SIZE
ON THE COURSE OF MENTAL OPERATIONS

In a very interesting experiment – analogous, in the main elements of the procedure and the figures used, to the research on rotation conducted by Cooper and Shepard (1973) – Nakata and Suzuki (1988) presented participants with figures in three sizes, at three distances, at three degrees of rotation, and in two lighting conditions (darker, lighter). The researchers were interested not only in the physical size of objects presented on slides, but also in the image on the retina. The experimenters wanted the image on the retina to take three sizes: small,

average, or large. This was obtained by manipulating the actual size of figures and distance from the slide. Nakata and Suzuki's (1988) research revealed no relations between reaction time and distance, lighting, or size of the object. Lighting, distance, and physical size of the object had no impact on mental rotation. However, an increase in the number of errors accompanying an increase in rotation angle was found (similarly to the experiments of Cooper and Shepard, 1973). Moreover, a dependence of reaction time on the size of the object on the retina was observed. Reaction times were longer (100 to 200 ms) for small figures in comparison to average and large figures.

Studies by Bundesen and Larsen (1975) as well as Kubovy and Podgorny (1981) confirmed the lack of role of the object's physical size in mental transformation.

The results of the above-mentioned studies contradict the results obtained by Schwartz (cited by Kosslyn with the source not given, 1980). He demonstrated the significance of the real size of the object in mental rotation. Furthermore, he suggested that the "retinal size" of the object may play a part, too, predicting hypothetically that the larger the object, the longer the reaction time should be.

Plenty of data indicate the similarity between the processes occurring in the physical and mental world (Mostowski, 1974; Finke, 1985; Nowak, 1991; Kosslyn, 1995). The greater the distance between objects in the real world, the longer it takes to shift attention from one object to another in the mental world; the smaller the objects, the harder it is for participants to answer questions regarding details of their structure (Kosslyn, 1995). If transformations on smaller objects take more time, and if the distance from the object has influence on extending reaction time, one can assume that reaction times will increase more in the case of small retinal sizes – obtained, for example, for a 5 cm (2 in) object projected from a distance of 90 cm (2.95 ft) – than in the case of large retinal sizes, obtained, for instance, for a 15 cm (5.9 in) object projected from a distance of 30 cm (11.8 in).

The research question that inspired the presented research was this: Does retinal size influence the efficiency of performing mental operations? The study focused on the efficiency not only of rotation but also of synthesis, which arouses much less interest of researchers. Another aim was to construct an experiment relating to simultaneous mental operation. Retinal size was to be the main object of research as its impact on the course of mental operations has been described in an ambiguous manner in the literature.

The following research hypotheses were subjected to empirical verification:
H 1: Mental rotation of objects of greater retinal size will be done faster and more correctly than mental rotation of objects of smaller retinal size.

H 2: Mental synthesis of objects of greater retinal size will be done faster and more correctly than mental synthesis of objects of smaller retinal size.

H 3: A simultaneous mental operation on objects of greater retinal size will be done faster and more correctly than such operation on objects of smaller retinal size.

Moreover, it was expected that the distance and size of objects had an impact on the course of all of the above operations.

THE METHOD
OF THE PRESENT RESEARCH

Participants

A total of 182 people took part in the experiments. Research groups were balanced in terms of age and education (students, aged 20-24). Men constituted precisely one third of all the participants. While selecting the sample in terms of gender, groups were created in such a way that the number of participants in one was a multiple of that in another. People with uncorrected vision defects were excluded from the study because problems with vision could constitute a significant secondary variable.

Material

Five objects were used in the experiment concerning mental rotation. Each was presented at three angles of rotation (0, 90, 180, and 270 degrees) and appeared both as a mirror image and without inversion. Each participant had to perform 30 tasks altogether.

For the purpose of the experiment concerning synthesis, 14 objects were prepared and presented randomly, in series of three. Each participant had to perform 15 tasks altogether. During the pilot study there had been 20 tasks, but this formula turned out to be too exhausting for participants as this was already an engaging and time-consuming activity.

Six pairs of objects were used during the experiment concerning combined operations. Objects in each pair were put together in three ways – top to top,

bottom to bottom, and side to side – and each pair was rotated in three ways: by 90, 180, or 270 degrees. Each subject had to perform a total of 18 tasks; 18 stimuli were prepared for assessment: nine correct and nine incorrect ones. "Incorrect" shall mean incorrect rotation (rotation by a number of degrees other than in the visual instruction) or incorrect combination (a different combination of elements than in the visual instruction).

The research was designed using Affect 4.0 software, dedicated to psychological and psychophysiological measurements. The presented objects were light-colored and shown against a grey background in order to avoid high contrast causing eye strain (black-white). Each participant was given a piece of paper and a pencil.

PROCEDURE

EXPERIMENT I

The procedure suggested in the first experiment makes explicit reference to Shepard, Metzler, and Cooper's research methodology (Cooper & Shepard, 1973; Cooper, 1975; Shepard & Metzler, 1971).

I. Directions with examples appear on the screen. A test task follows.

II. On the screen, in controlled time, spatial, and lighting conditions, a point of fixation is exposed (1 sec.), and then the image of a two-dimensional polygon appears. The participant looks at it for as long as they need to (Fig. 1).

III. The image disappears and there is a break of controlled length (3 sec.), a mask wiping out the afterimage.

IV. A polygon subjected to rotation (that is, rotated by a specified number of degrees) or rotation and inversion (that is, additionally, as if reflected in a mirror) appears on the screen. This is the object being the basis for assessment and decision.

V. The participant decides if the derivative object is the original image rotated only – or both a mirror image and a result of rotation.

VI. The participant's reaction time (the time of decision) and the correctness of the answer are measured.

Figure 1. Sample object used in the rotation experiment.

EXPERIMENT II

The research procedure in the second experiment was inspired by Finke's research (1985, 1990). The decision to abandon creating objects on the computer was caused not only by the necessity of excluding the impact of proficiency in drawing by means of graphic software. In the computer version, participants conducted transformations by manipulating objects on the screen. In the paper version, they had to perform various operations in their imagination.

Directions and the test task, not taken into account in subsequent analyses, appear on the screen.

I. Three objects from the pool of the prepared stimuli appear on the screen (Fig. 2).
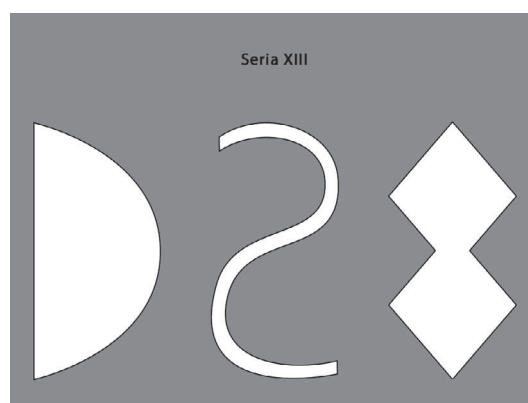

Figure 2. Sample object used in the synthesis experiment.

II. The participant creates a useful and identifiable object out of them. They can use a pencil and a sheet of paper. After the task has been completed, they push the button. The program calculates the time that passed between the presentation of the stimuli and the pushing of the button. The participant goes on to perform the next task of the same kind.

III. Objects are assessed by competent judges, who determine if a given object is recognizable and if it is original (subjective originality). Additionally, based on the frequency indicator, so-called objective originality is determined.
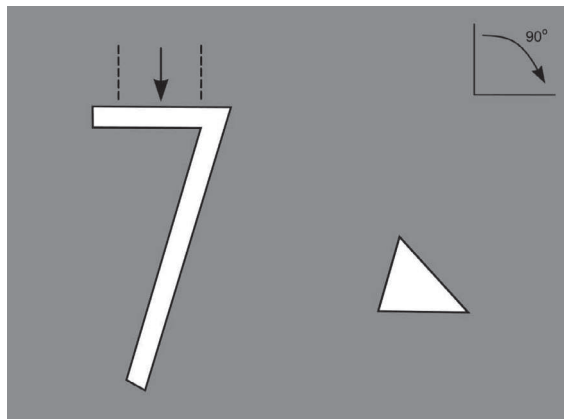
EXPERIMENT III

The author's own pattern of research on simultaneous mental operation was proposed in the experiment.

I. Directions with examples appear on the screen. The first sample tasks are not taken into account in the analysis of results (Fig. 3).

II. Two objects appear on the screen together with visual directions on how they are to be combined and the number of degrees by which the new object, created in the process of synthesis, is to be rotated. The participant performs the synthesis and rotation (no time limit).

III. After a two-second mask, a correct or incorrect solution appears on the screen.

Figure 3. Sample objects used in the experiment concerning simultaneous operations in the imagination.

IV. The participant decides if the object is the same as the one they obtained as a result of their own transformations performed according to the directions.

V. The program measures both the time of transformation (simultaneous synthesis and rotation) and the time of decision.

The operant, diversifying experimental groups as part of the measurement of each of the mental operations discussed, was the retinal size of the presented stimuli, including the physical size of the presented object and the distance of participants from the object. The angular size of the object (i.e., the angle of view) in radians is virtually equal to the tangent of the angle, so it is permissible to use the approximation expressed with the following formula: $\omega \approx tg\ \omega = H/Z$. Retinal size may also be calculated from the proportion based on the above formula $H/Z = H1/Z1$, where we assume that the length of a typical eyeball is $e = 24$ mm (0.95 in), and the nodal point is 7 mm (0.28 in) from the cornea. Thus, the distance between the nodal point and the retina is $z' = 24-7 = = 17$ mm (0.67 in). Two physical sizes of objects were adopted: 5 cm (1.97 in) and 15 cm (5.9 in). Stimuli were presented from two distances: 30 cm (11.8 in) and 90 cm (2.95 ft). Thus, three retinal sizes of objects were obtained: H' = .85º (15; 30), H' = .28º (15; 90), H' = .28º (5; 30), H'= .09º (5; 90).

FINDINGS

The Impact of Retinal Size
on the Efficiency of Mental Rotation

In order to test the hypotheses, variance analysis was conducted for independent groups ANOVA (2 x 2), in which the grouping factors were size (5 cm and 15 cm) and distance (30 cm and 90 cm), and univariate analysis of variance was performed in which the grouping factor was retinal size (H' = .85º; H' = .28º; H' = .09º). Such dependent variables as reaction time and correctness of answers were considered.

Significant statistical differences – $F(1, 179) = 4.268$; $p < .05$ – were revealed, indicating an impact of distance on reaction time in rotation tasks. It was demonstrated that, in rotation tasks, the longer their distance was from objects, the longer it took participants to perform mental operation on them. In all tasks the same direction of dependence was revealed. For all cases, the condition of homogeneity of variances was fulfilled. A significant – $F(1, 179) = 2.048$; $p < .05$ – impact of interaction between the physical size of the object and

distance on reaction time was demonstrated. However, no impact of physical size on the course of rotation was found.

The hypothesis on the impact of retinal size on reaction time in rotation tasks was confirmed, $F(1, 179) = 1.573$; $p < .05$. The previously revealed interaction between distance and physical size may additionally strengthen this hypothesis.

In post hoc tests it was revealed that differences between experimental groups 1 and 3 were mostly responsible for the significant differences. These are the experimental groups in which stimuli of the same sizes but located at different distances were used. The longer the distance between the subject and the stimulus was, the longer the reaction time. The smaller the retinal size of the object, the longer the reaction time.

The Impact of Retinal Size
on the Course of Simultaneous Operations

In the ANOVA test, in which size (5 cm and 15 cm) and distance (30 cm and 90 cm) constituted grouping factors, the following measurements were included: a) correctness of the answer; b) time of performing the combination; c) reaction time for answering if the displayed object was the object created as a result of the correct combination. Moreover, univariate analysis of variance was conducted, in which the grouping factor was retinal size (H' = .85º; H' = .28º; H' = .09º). A significant impact of interaction between distance and size on reaction time (assessment of combination correctness) was demonstrated in simultaneous tasks: $F(1, 179) = 2.511$; $p < .001$. In some tasks, only the impact of distance was revealed. The relationship was analogous to the one in the operation of rotation: the longer the distance was between the participant and the object, the longer it took the participant to perform a mental operation on that object.

Neither the impact of the physical size of objects on the course of the simultaneous operation nor the impact of retinal size were not proved.

The Impact of Retinal Size
on the Course of Mental Synthesis

The obtained data were subjected to variance analysis ANOVA (2 x 2), in which size (5 cm and 15 cm) and distance (30 cm and 90 cm) were grouping factors. Dependent variables were also considered, such as: task performance time, the number of recognizable objects created, the subjective originality of the product (assessment conducted by competent judges), and the objective originality

of the product (assessment based on the frequency indicator). The relationship between distance and the number of recognizable objects created as a result of mental synthesis ($F(1, 179) = 6.363$, $p < .05$) was demonstrated. It turns out that the longer the distance, the smaller the number of recognizable objects created. The following tendency was also revealed: the larger the objects, the less time participants needed to perform synthesis.

The results of the univariate analysis of variance in which the grouping factor was the retinal size did not confirm the hypothesis about its impact on the course of the synthesis operation.

Discussion of Results

The presented research confirmed the impact of retinal size only on the course of mental rotation: the smaller the retinal size of the object, the longer the reaction time in rotation tasks. The impact of distance on the course of mental operations turned out to be an interesting result. In the case of mental rotation, reaction time increased together with distance. A similar relationship occurred in the case of simultaneous operation (rotation + synthesis). In mental synthesis, the greater the distance between the subject and the screen, the more difficult it was for participants to create correct recognizable objects. The maximum distance was 90 cm and this enabled participants to perceive the displayed objects freely.

The presented relationships can be interpreted together in the light of knowledge gathered in the literature on isomorphism and the current structural theories of imagination. Isomorphism (Gr. *isos* – equal, *morphe* – shape) of structures is a bijection of the universe of A structure in the universe of B structure that preserves functions, relations, and distinctive elements (Mostowski, 1974). Elements of the mental world correspond to elements of the physical world. When referring to this concept, one may suggest that (1) it is more difficult to operate mentally on distant objects as it is impossible to touch them, grab them, and rotate them; 2) it is easier to rotate a 15 cm object in one's hand and perform mental transformations on it than to rotate and perform mental operations on a small, 5-cm object. On average, a human hand is 16-18 cm (6.3-7.1 in) long, so an object 15 cm long can be easily grabbed. It seems that mental transformation is subject to rules similar to the rules of manual transformation. Structural theories of imagination claim that mental images have the same properties as real physical objects (Finke, 1985). They have depth, colors, and measurements and can change in space. An imagined flower can be of the same colors and undergo the same changes as a perceived plant; for example, it may

lose petals and so occupy different space. Thus, the ease of manipulating an object in the physical world can correspond to the ease of performing transformations on an imagined object.

The results of the presented research belong to the current of experiments that confirm the impact of body pattern and sensomotor instructions on the course of mental operations (Janczyk, Pfister, Crognale, & Kunde, 2012; Falconer & Mast, 2012).

While analyzing possible alternatives in the experimental procedure, it is worth addressing the issue of difference between the levels of operands. Can its increase or decrease intensify the influence between the variables? In the presented research, objects measuring 5 and 15 cm as well as distances of 30 and 90 cm were used. Small and large size and small and large distance differ from each other as many as three times. However, these differences might be insufficient and the influence of variables may be larger than revealed. It seems justified to carry out experiments using objects measuring, for example, 5 cm and 90 cm. Then, the small object would have the size that could be closed inside the palm of hand. The big one (90 cm in diameter when the object was circumscribed around a circle) would escape this manual control. The subject would be under the impression that they can rotate it or shift it in their imagination using not one but two hands. If we assume that the imaginary world corresponds to the real world, the introduction of new values as levels of operands could have a significant influence on the course of experiments. A modification of the procedure in the discussed direction would require displaying objects on a wall, without using computers directly.

Likewise, new distance values could be proposed. Even though the difference between 30 and 90 cm is threefold, a screen situated 30 or 90 cm from the participant is still within their arm's reach. Perhaps it would be justified to use a larger distance, for example 2 meters (6.5 ft), for the purpose of the research. However, in such a case the problem of the visibility of displayed objects arises. For many people, discerning small object from a distance of two meters can be too demanding.

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