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Piecewise Mental Rotation

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Brief Report

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Abstract

In mental rotation tasks, participants have to decide whether two images show the same object or scene. These images can be presented side by side or in temporal succession, and they usually differ in the viewing angle from which they show the object or scene. Response time is typically found to increase linearly with increasing disparity in viewing angle, suggesting that participants perform mental rotation at constant angular speed. The present study introduces the paradigm of piecewise mental rotation, in which two images are presented simultaneously, and one of them may be rotated in the image plane. These images are identical except for one local difference, which participants have to detect. Therefore, participants do not have to form a holistic mental representation of the scene, but they can perform successive, piecewise comparisons of local image content to facilitate the comparison process. Task-specific eye-movement analysis is shown to provide insight into global and local alignment processes during task performance. The new paradigm seems to be appropriate for studying the interaction of visual attention, working memory, and mental transformation and its optimization within a complex task.

Piecewise Mental Rotation

Mental rotation is one of the most prominent experimental paradigms in cognitive psychology (e.g., Shepard & Metzler, 1971; see Shepard & Cooper, 1982, for a review). In their famous original studies, Shepard and his colleagues presented participants with two side-by-side line drawings of three-dimensional objects. The participants' task was to decide whether these objects were identical or mirror images of each other. This task was non-trivial, because the two images would usually show the objects from different viewing angles, and this angular disparity could be along the x-, y-, or z-axis. The crucial finding from these studies was that the participants' response time increased linearly with greater disparity in the viewing angle, suggesting that participants mentally rotated one of the images to align it with its counterpart.

Although in these studies it was convincingly argued that the linear increase in response time reflected a constant speed of mental rotation operations, using response time and error rate as the only psychophysical measures was a serious restriction. Clearly, it would have been desirable to obtain more fine-grained psychophysical measures to study mental transformations in this paradigm. As a consequence, subsequent studies examined eye movements during mental rotation tasks (Carpenter & Just, 1978; Just & Carpenter, 1976) to gain insight into the temporal sequence of attended stimulus parts. Just and Carpenter, 1976, for example, used eye-movement analysis to distinguish between three successive stages during mental rotation tasks: search, transformation & comparison, and confirmation. The transformation & comparison stage revealed an especially strong linear dependence on the angular disparity, providing further support for the mental rotation hypothesis. However, in these investigations, a researcher had to manually attribute individual fixations to one of the three stages according to a set of rules, which introduced the possibility of subjective interpretation of eye-movement trajectories.

Recently, triggered by the availability of realistic 3-D computer graphics and improved methods for the recording and automated analysis of eye movements, the mental rotation paradigm received attention from scientists once again (e.g., Nakatani & Pollatsek, 2004; Nakatani, Pollatsek, & Johnson, 2002). In these studies – termed mental scene rotation - participants typically had to memorize the projection of a 3-D scene composed of several discrete, non-overlapping objects. Subsequently, this scene was replaced with another one, viewed from the same or a different angle. The participants' task was to decide whether the two scenes were identical or contained a difference, which was either a rotation or a displacement of one of the objects. Using an automated eye-movement analysis, Nakatani and Pollatsek (2004) found that the increase in response time with greater rotation angle was caused by increased local verification rather than by greater global alignment difficulties. Moreover, rotation of objects led to longer response time than did their displacement.

It is important to notice that both the original mental rotation task and the scene rotation task require participants to generate a complex, holistic mental representation of the stimulus, which encodes its visible components and their relationships. In most natural tasks, however, it seems that only minimal visual working memory load is imposed at any given time (e.g., Ballard, Hayhoe, & Pelz, 1995). Obviously, if the required information is easily accessible by sensors, the effort of building a comprehensive internal representation can be avoided (Ballard, 1991; Ballard et al., 1995). Loosely speaking, it is more efficient to use the visual scene as an external memory instead of internally representing a substantial part of it. Saccadic eye movements, used to access this external memory, are very quick and therefore "inexpensive" as compared to "expensive" working memory use.

To study mental rotation under such natural working memory load conditions, the current study presented side by side two complex, natural images that were identical to each other except for one local difference between them (see Figure 1). The participants' task was to find this difference under varying angular disparities - referred to as rotation angles in clockwise direction - between the two images. These rotations were restricted to the image plane (z-axis) so that no relevant features were occluded, resized, or otherwise distorted. Consequently, unlike previous mental rotation studies, this task did not require a holistic, high-level representation of the scene but just the sequential comparison of "pieces" of local information. Therefore, like in most natural tasks, participants were free to balance their working memory versus eye movement use (cf. Inamdar & Pomplun, 2003). With each step of comparison – that is, each attentional switch between the two images - participants had to compensate for the image rotation at two levels. At the global level, saccades between the images had to be targeted at the position that contained the information to be compared with the current memory content. At the local level, the memorized information needed to be mentally rotated to be matched with the display information.

--- insert Figure 1 about here ---

Eye-movement recording was used to gain detailed insight into the participants' performance of these subtasks. Based on previous studies in the related paradigm of comparative visual search (e.g., Galpin & Underwood, 2005; Pomplun, Sichelschmidt, Wagner, Clermont, Rickheit, & Ritter, 2001), we expected the piecewise rotation task to be dominated by frequent, rapid switches between the two images. Such fast-paced eye-movement tasks, however, are likely to induce substantial decoupling of eye movements and spatial visual attention (e.g., Pomplun, Shen, & Reingold, 2003). Consequently, the fixation position data were assumed to be rather noisy, which prevented us from dividing the task performance into consecutive stages as done by Just and Carpenter (1976).

For the quantitative analysis of eye movements, a set of variables was computed that has proven its utility within the paradigm of comparative visual search (e.g., Galpin & Underwood, 2005; Pomplun et al., 2001). Besides the standard measures - response time and error rate - these variables included fixation duration, number of saccadic switches between the two images, number of successive fixations within the same image, and area coverage. Fixation duration is a measure for the cognitive processing demands imposed by the currently inspected information (see Rayner, 1998). Longer duration indicates that more extensive processing is taking place. The number of switches between images tells us how many steps of comparison of local information are performed before the mismatch is detected. Thus, the number of switches typically increases with greater task difficulty and decreases with greater effective working memory load. The number of successive fixations between these switches is assumed to measure the difficulty of finding the relevant area in image B after switching to it from image A. Although previous research (e.g., Pomplun et al., 2001) indicates that memory load can also influence this variable, this effect is typically much smaller than the one induced by matching difficulty. Another measure for this matching difficulty, but also for general task difficulty, is area coverage. It is computed as the average percentage of an image covered by the smallest rectangle that encloses the positions of all successive fixations during a single inspection of that image. Interestingly, while greater general task difficulty decreases area coverage, greater matching difficulty supposedly increases it, due to the longer visual search path produced during the matching process.

Moreover, to measure the matching of positions and local features between the two images by the participants' eye movements, each image was divided into 18×18 squares, whose size was chosen to match the precision of our eye tracker. For a given stimulus consisting of images A and B, a fixation in square (x, y) in image A was counted as a position match if, during the preceding or subsequent inspection of image B, at least one fixation hit the corresponding square (x, y). A color match was counted for those fixations that had a preceding or subsequent counterpart with regard to the color shared by the majority of pixels in the two squares (i.e., their RGB components were identical when using eight intervals per component). Similarly, an orientation match was registered for those fixations with a counterpart that shared the same predominant orientation of local edges when using 90 orientation intervals (using the orientation measure described in Pomplun, to appear). For the computation of position, color, and orientation matches, the rotated images in the displays, including the positions of fixations on them, were reverted to the upright position. This way, corresponding squares between the two images in a display always had identical position, color, and orientation values, unless they contained the mismatch. Generally speaking, a greater proportion of matches in any of these three dimensions is assumed to indicate a more important role of that dimension in guiding the global matching process. However, notice that in the present context there are qualitative differences between the three chosen dimensions, which are discussed below.

What behavior can we expect in the current task? Let us outline several plausible models for the global task (Models G1 to G3) and the local task (Models L1 to L3). A list of all models and their predictions is provided in Table 1. Regarding the global level, given the results obtained by Nakatani et al. (2004), it seems possible that participants are able to quickly establish a mental mapping of corresponding positions between the two images. During the subsequent comparative search process, this mapping may guide the switching saccades rather precisely. According to this hypothesis (Model G1, “Spatial Mapping”), neither area coverage, number of successive fixations, nor the proportions of position, color, or orientation matches should vary with the rotation angle between the two images.

--- insert Table 1 about here ---

Another possibility is that no such mapping exists, but that the programming of a saccade switching from image A to image B is guided by coarse memory of the previously inspected area in B, as well as by local features in B that match the current memory content. After the switch, visual search through local features is necessary to find the position in B that contains the information to be matched. Local features in a visual search display that are shared with the search target are known to guide saccades in artificial displays (e.g., Findlay, 1997; Scialfa & Joffe, 1998; Williams & Reingold, 2001) and in natural scenes (Pomplun, to appear). Assuming that greater rotation angles require more extensive search, this model implies that area coverage and the number of successive fixations increase with greater rotation angle, while the proportion of position matches decreases. Color is typically the dominant dimension in guiding visual search (e.g., Williams & Reingold, 2001), so if visual feature guidance plays an important role in the global matching, we would expect the image rotation to be less detrimental to the proportion of color matches than to the proportion of position matches. Guidance by orientation of edges can also be expected (e.g., Pomplun, to appear; Scialfa & Joffe, 1998). However, this guidance may be misleading, because in the case of rotation the corresponding areas in the two images differ in orientation. If there is this kind of misleading orientation guidance (Model G2, “Feature

Matching”), we would expect the proportion of orientation matches to be greater for rotation angles 0° and 180° (matching orientations) than for angles 90° and 270° (greatest mismatches). It is possible, though, that participants are able to account for the special role of orientation in the present task and adjust their behavior accordingly. This could be achieved by either disregarding the local orientation information or compensating for its disparity induced by the image rotation. If this is the case (Model G3, “Orientation Adjustment”), the proportion of orientation matches should not show the pattern predicted by Model G2. Instead, this proportion should be constant or slightly decrease with greater rotation angle, but to a smaller extent than does the proportion of position matches.

With respect to the local task level, the freedom in the current task may allow participants to memorize such little chunks of local information before every switch that no mental rotation of the memory content is necessary for its matching with the display content. Such minimization of working memory load could be predicted based on the results obtained by Ballard et al. (1995). It would also be in line with Model G3 (“Orientation Adjustment”), assuming that participants avoid orientation information and instead prefer to memorize rotation-invariant chunks of information. According to this prediction (Model L1, “No Rotation”), the number of switches – i.e., the number of memorization and comparison steps performed until target detection - and the duration of fixations should not depend on the rotation angle.

It is possible, however, that local mental rotation processes are required, similar to the global ones observed in the classical tasks. Consequently, greater rotation angles would increase task difficulty, and participants could adapt their behavior in two possible ways: First, they could memorize the same amount of information regardless of the rotation angle (Model L2, “Memory Adaptation”). In this case, we would expect fixation duration to increase with greater angles, due to the increased cognitive processing demands (cf. Pomplun et al., 2001), while the number of switches would remain constant. Second, participants could memorize less information at a time when the rotation angle increases, preferring to perform more comparison steps rather than increasing their memory load (Model L3, “Switch Adaptation”). This would be in line with the findings by Ballard et al. (1995), Inamdar and Pomplun (2003), and Nakatani et al. (2004). According to Model L3, fixation duration should not depend on the rotation angle, whereas the number of switches between images should increase with greater angles.

Method

Participants. Sixteen students of the University of Massachusetts at Boston, aged 21-35, participated in the experiment. They had normal or corrected-to-normal vision and were naïve with regard to the purpose of the study. Each of them received an honorarium of $10 for their participation.

Apparatus. Stimuli were presented on a 21-inch Dell P1130 monitor using a screen resolution of 1600×1200 pixels and a refresh rate of 85 Hz. Eye movements were measured with an SR Research EyeLink-II system that provides an average error of 0.5° of visual angle and a sampling frequency of 500 Hz.

Materials. The experiment encompassed seven search displays for training and 96 different search displays for the psychophysical measurements. Each display showed a side-by-side pair of nearly identical color images of a complex scene, with each image subtending an area of 500×500 pixels or 11.4×11.4 degrees of visual angle (see Figure 1 for two sample displays). Every display contained exactly one local mismatch between its two images, which could either be an item in the scene changing its position or identity (type A mismatch) or an item that appeared in one of the images but was missing in the other one (type B mismatch). One of the images was always shown in upright (0°) orientation, while the other one was rotated clockwise by either 0° (that is, it was also upright), 45°, 90°, 135°, 180°, 225°, 270°, or 315°. Since the rotation could be performed on either the left or the right image, there were 15 different ways of presenting a display. During the experimental session, each participant was presented with each type of display six times, except for the type that showed two upright images, which was presented 12 times. This was done because if no effect by the side of rotation on any dependent variables were found, the data for left-side and right-side rotation could be collapsed and yield an equal amount of data samples for each rotation angle. Across the 16 participants, each of the 96 image pairs was shown exactly once in each of the 14 possible ways that included rotation, but twice in the non-rotated way. The order of presentation was completely randomized.

Procedure. Each participant performed seven training trials, followed by the 96 experimental trials. Every trial began with the presentation of a central fixation marker used for drift correction of the eye-tracker headset (see Stampe, 1993). Participants were to fixate on that marker and simultaneously press a button on a game pad to start the trial. Their subsequent task was to determine the type of mismatch (A or B) as quickly and as accurately as possible by pressing one out of two designated game-pad buttons. The trial was terminated through this button press or through timeout after 30 seconds. After the trial, participants received auditory feedback about the actual type of mismatch that had been shown.

Results

First of all, it was investigated whether the side of rotation (left vs. right) had a significant effect on any of the independent variables. To do this, for each variable a repeated-measures two-way

Analysis of Variance (ANOVA) with the factors “rotation side” (2 levels) and “rotation angle” (8 levels) was performed. For none of the variables there was a main effect of rotation side, all $F(1, 15) < 1$, or an interaction between the two factors, all $F(7, 105) < 1$. Therefore, all data were collapsed over the factor rotation side for further analysis.

The analysis of participants’ manual responses showed that in 79.1% of all trials the type of mismatch was correctly reported, while in the remaining trials this report was either incorrect or did not occur before the timeout. This proportion of correct responses did not significantly depend on the rotation angle, $F(7, 105) = 1.86$, $p > 0.05$. Another global performance measure, response time, did depend on the rotation angle, $F(7, 105) = 7.32$, $p < 0.001$, almost perfectly showing the linear increase of response time with rotation angle that is known from the classical mental rotation experiments (see Figure 2a). Response time was significantly shorter for small rotation angles (11.31 s) than for large ones (14.27 s), $t(15) = 8.98$, $p < 0.001$ (in all analyses, small angles were 315°, 0°, and 45°, and large angles were 135°, 180°, and 225°).

--- insert Figure 2 about here ---

On average, fixation duration was 231 ms; interestingly, this value was not significantly influenced by the rotation angle, $F(7, 105) < 1$. The number of switches between images, however, was found to depend on the rotation angle, $F(7, 105) = 3.69$, $p < 0.005$ (see Figure 2b). It was significantly lower for small angles (11.56) than for large ones (13.88), $t(15) = 6.43$, $p < 0.001$. The number of successive fixations within the same image was also found to be significantly influenced by the rotation angle, $F(7, 105) = 9.77$, $p < 0.001$ (see Figure 2c). There were a smaller number of successive fixations for small angles (2.97) than for large angles

(3.30), $t(15) = 7.47$, $p < 0.001$. Moreover, the rotation angle also exerted a significant effect on the proportion of the image covered by these successive fixations, $F(7, 105) = 8.20$, $p < 0.001$ (see Figure 2d). The proportion was clearly smaller for small angles (0.062) than for large ones (0.087), $t(15) = 7.82$, $p < 0.001$.

The proportion of matching fixation positions varied significantly with the rotation angle, $F(7, 105) = 8.39$, $p < 0.001$ (see Figure 2e). The matching was better for small angles (0.091) than for large angles (0.062), $t(15) = 3.34$, $p < 0.005$. In contrast, the proportion of color matches (0.706) did not depend on the rotation angle, $F(7, 105) = 1.59$, $p > 0.1$. Interestingly, the proportion of orientation matches did depend on the rotation angle, $F(7, 105) = 2.10$, $p < 0.05$ (see Figure 2f). While there was no difference in this proportion between small and large angles, $t(15) < 1$, the planned comparison between the parallel (0° and 180°) and perpendicular angles (90° and 270°) revealed a significant difference (0.481 versus 0.431, respectively), $t(15) = 4.16$, $p < 0.005$.

Discussion

Regarding the global rotation, the current data are clearly inconsistent with the proposed Model G1 (“Spatial Mapping”), as area coverage, number of successive fixations, and the proportion of position and orientation matches were all found to depend on the rotation angle. This result suggests that, in contrast to the findings by Nakatani et al. (2004), the current rapid, piecewise comparison task is slowed down by global matching processes, not just by local ones. The empirical data actually match the predictions made by Model G2 (“Feature Matching”), which receives further support from the absence of a rotation effect on color matches and from the predicted pattern of orientation matches. Thus it appears that visual feature guidance contributes to the process of finding the relevant image region after a switch between images. Since the assumption underlying Model G3 (“Orientation Adjustment”) – the proportion of orientation matches slightly or not at all decreasing with greater rotation angle - was not confirmed, it seems that participants cannot disregard local orientation or account for its difference between rotated images, at least not completely.

The participants’ local visual behavior does not match the predictions made by Model L1 (“No Rotation”), because the number of switches clearly increases with greater rotation angle. This result confirms that greater rotation angles increase the demands not only for the global, but also for the local matching task. Model L2 (“Memory Adaptation”) does not capture this effect of the rotation angle either, and it does not predict the invariance of fixation duration. Participants do not seem to adapt to the rotation-induced greater local task difficulty by memorizing more information at a time. Instead, they perform more switches and do not change their fixation duration, which was predicted by Model L3 (“Switch Adaptation”).

Clearly, the demands imposed by the current task increase with greater rotation angle in a linear way, just as they do in the classical mental rotation task. While the classical task requires a holistic representation of the scene, the locally confined mismatch in the current task allows participants to perform a series of quick local comparisons instead. The eye-movement analysis suggests that participants make extensive use of this piecewise comparison strategy. This can be understood in terms of the tradeoff between “expensive” visual working memory use and “inexpensive” eye movements (e.g., Ballard et al., 1995; Inamdar & Pomplun, 2003). Participants respond to the increased task demands, as imposed by greater rotation angle, by making additional eye movements instead of increasing their working memory load. The current data also reveal that both the global matching (finding the corresponding area in the other image) and the local matching (comparing the local information with the current working memory content) impose greater demands with increasing rotation angle. Instead of establishing a mapping between corresponding points in the two images at stimulus onset, participants appear to largely rely on visual search to find the relevant region in the other image. This search is guided by local stimulus features such as color and orientation of edges. Due to its shift between images, local orientation can misguide search for all rotation angles except 0° and 180°. This difficulty with regard to orientation is in line with the finding by Nakatani et al. (2004) that, in their task, local orientation differences were harder to detect than displacements of objects.

In conclusion, the present results provide a first assessment of rapid, piecewise mental rotation of real-world images. This paradigm promises to shed light onto the interaction of attentional, representational, and transformational processes and its optimization within a complex task. Future research needs to identify the “pieces”, that is, the memorized local features and global positions, to establish a more detailed model of the piecewise rotation performance.

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References

Ballard, D.H. (1991). Animate vision. Artificial Intelligence Journal, 48, 57-86.

Ballard, D.H., Hayhoe, M.M., & Pelz, J.B. (1995). Memory representations in natural tasks. Journal of Cognitive Neuroscience, 7, 66-80.

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). Hilldale, NJ: Erlbaum.

Findlay, J. M. (1997). Saccade target selection during visual search. Vision Research, 37, 617-631.

Galpin, A.J. & Underwood, G. (2005). Eye movements during search and detection in comparative visual search. Perception & Psychophysics, 67, 1313-1331.

Inamdar, S. & Pomplun, M. (2003). Comparative search reveals the tradeoff between eye movements and working memory use in visual tasks. In R. Alterman & D. Kirsh (Eds.), Proceedings of the Twenty-Fifth Annual Meeting of the Cognitive Science Society, 2003, Boston, Massachusetts, pp. 599-604.

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

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

Nakatani, C. & Pollatsek, A. & Johnson, S.A. (2002). Viewpoint-dependent recognition of scenes. The Quarterly Journal of Experimental Psychology, 55A, 115-139.

Pomplun (to appear). Saccadic Selectivity in Complex Visual Search Displays. Vision Research.

Pomplun, M., Shen, J. & Reingold, E.M. (2003). Area activation: A computational model of saccadic selectivity in visual search. Cognitive Science, 27, 299 - 312.

Pomplun, M., Sichelschmidt, L., Wagner, K., Clermont, T., Rickheit, G. & Ritter, H. (2001). Comparative visual search: A difference that makes a difference. Cognitive Science, 25, 3-36.

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

Scialfa, C. T., & Joffe, K. (1998). Response times and eye movements in feature and conjunction search as a function of eccentricity. Perception & Psychophysics, 60, 1067-1082.

Shepard, R.N. & Cooper, L.A. (1982). Mental images and their transformations. Cambridge, MA: MIT Press.

Shepard, R.N. & Metzler, J. (1971). Mental rotation of three-dimensional objects. Science, 191, 952-954.

Stampe, D. (1993). Heuristic filtering and reliable calibration methods for video-based pupil tracking systems. Behaviour Research Methods, Instruments, & Computers, 25, 137-142.

Williams, D.E., & Reingold, E.M. (2001). Preattentive guidance of eye movements during triple conjunction search tasks. Psychonomic Bulletin and Review, 8, 476-488.

Figure Captions

Figure 1: Sample displays and superimposed visual scanpaths recorded for one of the participants. Fixation positions are indicated by circles whose diameters are proportional to the fixation duration. Numbers indicate the temporal order of fixations, and saccades are represented by straight lines connecting consecutive fixations. (a) Display without rotation and with difference type A – in the front, a notebook with pen on top of it changes its position between the two images; (b) display with a 90° clockwise rotation of the right image and with difference type B – the right image contains a clip that is missing in the left image.

Figure 2: Mean values and standard errors of six different variables as functions of the rotation angle in the stimulus. Notice that the values for 360° are identical to those for 0° and were only added to illustrate the symmetry of the data. (a) Response time; (b) number of gaze switches between the two images; (c) number of successive fixations in the same image (i.e., between gaze switches); (d) proportion of the image area covered by a set of successive fixations on that image; (e) proportion of fixations having a positional counterpart in the immediately preceding or subsequent visit to the opposite image; (f) proportion of fixations having such a matching counterpart with regard to the local orientation of edges.

Table 1: The proposed models and their predictions for (a) the local and (b) the global matching in the piecewise rotation task. Each cell indicates the predicted behavior of a given variable for an increasing angle of rotation between the two images.

(a)

Model	**Area coverage**	**Number of successive fixations**	**Proportion of position matches**	**Proportion of color matches**	**Proportion of orientation matches**
G1 (Spatial Mapping)	constant	constant	constant	constant	constant
G2 (Feature Matching)	increases	increases	decreases	decreases less than position matches	greater for 0°, 180° than for 90°, 270°
G3 (Orientation Adjustment)	increases	increases	decreases	decreases less than position matches	decreases less than position matches

(b)

Model	**Number of switches**	**Fixation duration**
L1 (No Rotation)	constant	constant
L2 (Memory Adaptation)	constant	increases
L3 (Switch Adaptation)	increases	constant

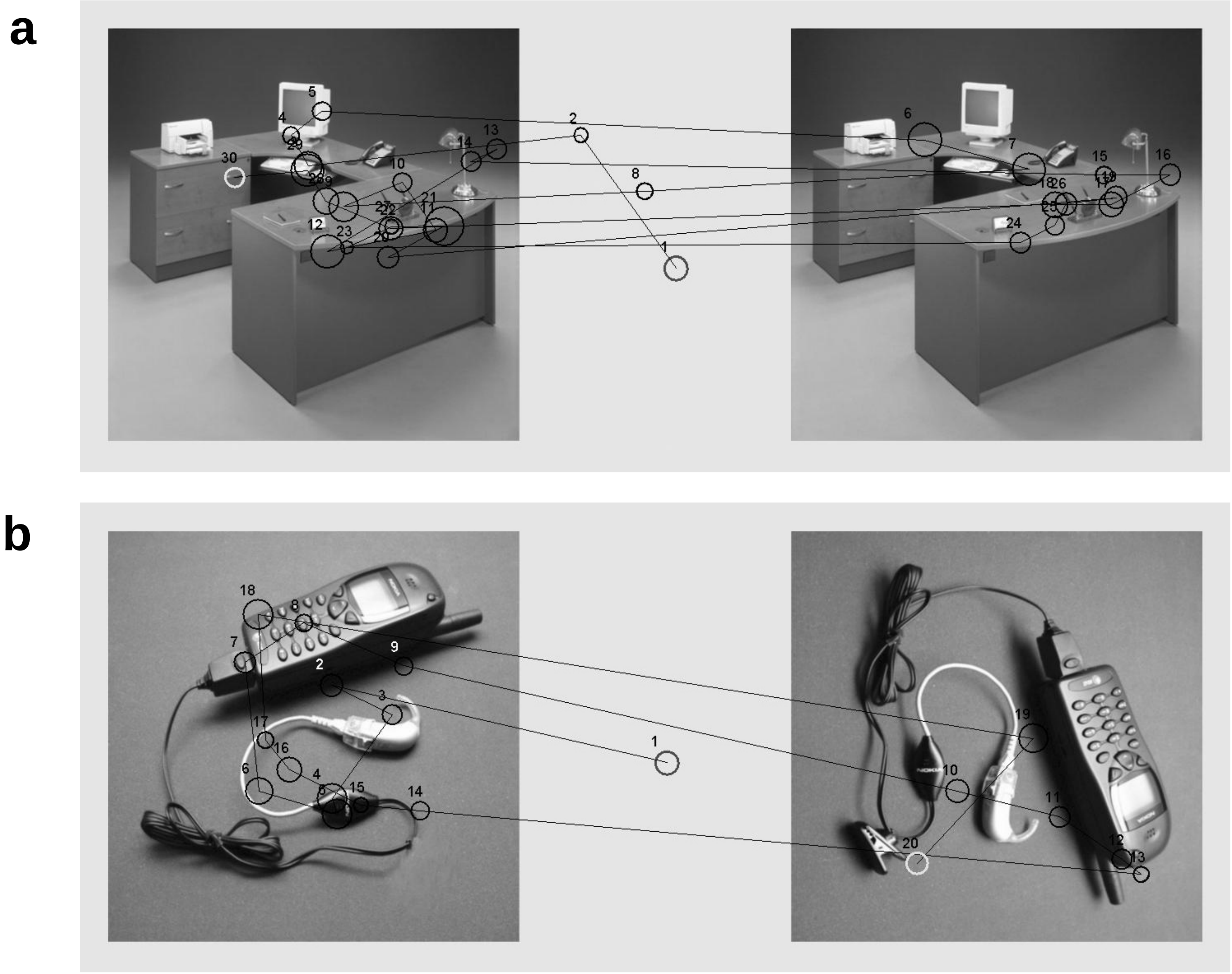
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Figure 1

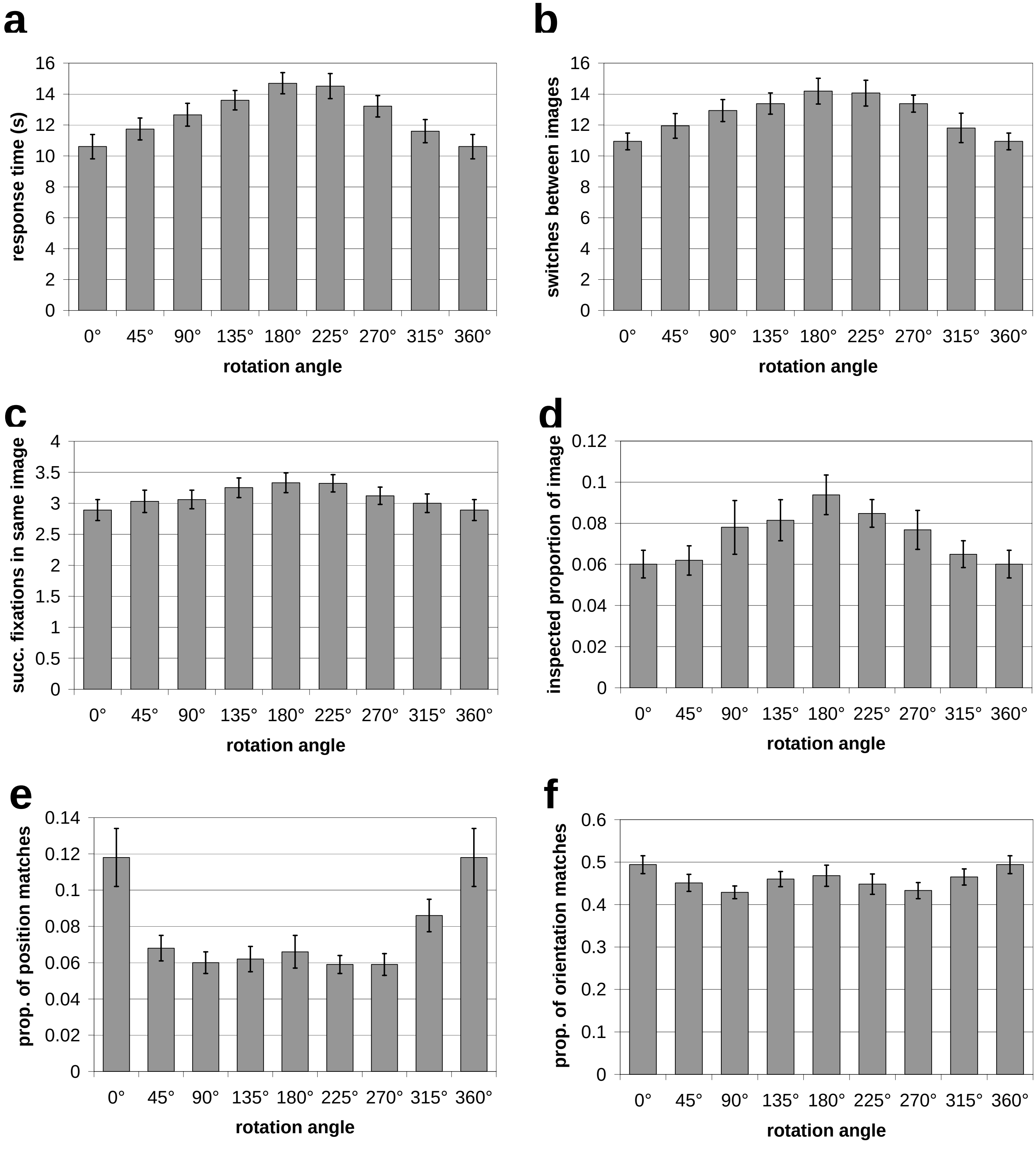
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Figure 2