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Mental rotation of cubes with a snake face: The role of the human-body analogy revisited

Author names and affiliations:

Hiroyuki Muto^{1*}, Masayoshi Nagai²

¹Research Organization of Open Innovation and Collaboration, Ritsumeikan University, Japan

²Department of Comprehensive Psychology, Ritsumeikan University, Japan

ORCID: 0000-0002-0007-6019 (Hiroyuki Muto)

*Correspondence concerning this article should be addressed to Hiroyuki Muto, Research Organization of Open Innovation and Collaboration, Osaka Ibaraki Campus of Ritsumeikan University, 2-150 Iwakura-cho, Ibaraki-shi, Osaka 567-8570, Japan. E-mail: h.muto[at]zm.commufa.jp

Note: This manuscript is a preprint (last updated on February 4, 2020). The final article will be published in *Visual Cognition*:

Muto, H., & Nagai, M. (in press). Mental rotation of cubes with a snake face: The role of the human-body analogy revisited. *Visual Cognition*.

Abstract

Previous research has demonstrated repeatedly that the mental rotation of human-like objects can be performed more quickly than the mental rotation of abstract objects (a body analogy effect). According to existing accounts, the body analogy effect is mediated by projections of one's own body axes onto objects (spatial embodiment), and the mental emulation of the observed body posture (motoric embodiment). To test whether motoric embodiment facilitates the mental rotation of human-like objects, we conducted an experiment using a snake-like object that had its own body axes but would be difficult to emulate. Twenty-four participants performed the mental rotation of snake-shaped cubes with or without a snake face as well as human-shaped cubes with or without a human face. Results showed that the presence of a face increased mental rotation speeds for both human-shaped and snake-shaped cubes, confirming both the human-body and snake analogy effects. More importantly, the snake analogy effect was equal to the human-body analogy effect. These findings contradict the motoric embodiment account and suggest that any object that can be regarded as a unit facilitates holistic mental rotation, which in turn leads to improved performance.

Keywords: mental rotation, embodied cognition, spatial transformation, analogy

Introduction

Mental spatial transformations such as mental rotation (Shepard & Metzler, 1971) are closely linked to sensorimotor processing or embodied (e.g., Gardony, Taylor, & Brunyé, 2014; Muto, Matsushita, & Morikawa, 2018; Sekiyama, 1982; Wexler, Kosslyn, & Berthoz, 1998; Wohlschläger & Wohlschläger, 1998; for a review, Zacks & Michelon, 2005). Within a framework of embodied cognition, previous research has demonstrated repeatedly that the mental rotation of objects resembling human bodies was performed more quickly and with less errors than the mental rotation of abstract objects (a body analogy effect) using computer-based chronometric tasks (Amorim, Isableu, & Jarraya, 2006; Jansen, Lehmann, & Van Doren, 2012; Krüger, Amorim, & Ebersbach, 2014; Makinae & Kasai, 2017; Makinae, Yamazaki, & Kasai, 2015; Sayeki, 1981; Voyer & Jansen, 2016); moreover, similar effects were observed in studies using paper-and-pencil psychometric tests (e.g., Alexander & Evardone, 2008; Doyle & Voyer, 2018). The present study explores the underlying mechanisms of the body analogy effect during mental rotation.

According to Amorim et al. (2006), embodying to-be-rotated objects helps people to perform mental rotation in a more holistic rather than piecemeal way, because the human body is regarded as a unit, not an abstract object, which improves mental rotation performance (see also Khooshabeh, Hegarty, & Shipley, 2013). Consistent with this, previous studies reported that women, who tend to use a piecemeal mental rotation strategy (Heil & Jansen-Osmann, 2008), showed larger body analogy effects than men (Doyle & Voyer, 2018; Makinae & Kasai, 2017; Makinae et al., 2015; but see Voyer & Jansen, 2016). More specifically, Amorim et al. (2006) proposed two possible accounts of how the body analogy facilitates holistic mental rotation. First, participants can take advantage of directional cues of the embodied object by mapping their own body axes (i.e., front–back, left–right, and up–down) onto the human-like object (called “spatial embodiment”). Second, participants can utilize their own sensorimotor information by mentally emulating the observed posture of the

human-like object (called “motoric embodiment”). These accounts of spatial and motoric embodiment have been supported by a lack or even negative effects when rotating human-like objects with anatomically impossible postures, which had confusing body axes and were difficult to emulate (Amorim et al., 2006, Experiment 6; Krüger et al., 2014; Makinae & Kasai, 2017; Sayeki, 1981). Additionally, Amorim (2006, Experiment 5) found that performance did not improve when mentally rotating desk lamps, which were highly familiar and had an up–down axis. These findings and previous explanations imply that human bodies with normal posture are optimal stimuli to facilitate mental rotation.

However, previous investigations of motoric embodiment have been limited to showing that using impossible postures have a less facilitatory effect on mental rotation than possible postures (Amorim et al., 2006; Krüger et al., 2014; Makinae & Kasai, 2017; Sayeki, 1981)¹. In other words, it remains unclear whether motoric embodiment *facilitates* the mental rotation of possible postures. To address this issue, the present study adopted a snake-like object as a stimulus, rather than using impossible body postures. Since the snake’s body structure is quite different from a human (e.g., an elongated and legless form), it should be difficult to mentally emulate a snake’s posture (motoric embodiment). On the other hand, since snakes have their own front–back, left–right, and up–down axes that can be defined at least by their face, people could project their own body axes onto the snake (spatial embodiment). Thus, if the facilitatory body analogy effect typically observed for human-like objects can be explained by motoric embodiment at least partially, the “snake analogy” should have a weaker effect on mental rotation performance than the human-body analogy. Given

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¹ Taking a different approach, Jansen et al. (2012) reported that male soccer players showed shorter overall RTs for the mental rotation of human bodies than non-athletes, suggesting a potential role of motor expertise in this task. However, as they found no difference in mental rotation speeds (i.e., angle dependence) between groups, it seems premature to regard their results as evidence for motoric embodiment.

that the mental rotation of cubes with body parts (i.e., heads, hands, and feet) placed in anatomically impossible positions was more difficult than the mental rotation of cubes without body parts (Krüger et al., 2014), it is even possible that the snake analogy would undermine mental rotation performance, because a snake's possible posture is an impossible posture for humans.

Method

Participants

We recruited 25 undergraduate and graduate students via advertisements at Ritsumeikan University. All had normal or corrected-to-normal vision, were naïve to the study's purpose, and received prepaid cards to purchase books for their participation. Since one participant did not obey the experimenter's instructions correctly, her data were excluded from the following data analysis. Thus, data from 24 participants (mean age = 21.2 years, range = 20–25 years; 12 females and 12 males; all right-handed) were analyzed. This experiment was approved by the ethics board of Ritsumeikan University.

We conducted a power analysis using G*Power 3.1.9.4 (Faul, Erdfelder, Lang, & Buchner, 2007). A sample size of $N = 24$ was needed to detect an effect size of Cohen's $f = 0.30$ ($\eta_p^2 = .083$) for the two-way interaction between shape and face on RT slope at a significance level of $\alpha = .05$ and

Fig. 1. Stimulus images used in the experiment. The image size of an object comprising 10 white cubes was 231 (width) $\times$ 290 (height) pixels.

power of $1 - \beta = .80$. We chose this effect size given that Amorim et al. (2006) reported effect sizes of RT slope difference between human bodies and cubes ranging from $f = 0.27$ to $f = 0.82$ (for picture plane rotations). Additionally, this sample size allowed us to detect a smaller effect size of $f = 0.23$ ($\eta_p^2 = .050$) for the three-way interaction between shape, face, and angle on RT.

Stimuli and apparatus

We created an object that consisted of 10 white cubes (231×290 pixels), and then made four images by adding a light gray cube with or without a face to each of the two specific positions of the object, so that the object with a face looked like a human or a snake (Fig. 1). The human-like object was similar to those used by Makinae and Kasai (2017) and Makinae et al. (2015). Then, we made mirror-reflected versions of the original four images. By rotating these eight images by 0° , $\pm 40^\circ$, $\pm 80^\circ$, $\pm 120^\circ$, and $\pm 160^\circ$ in the picture plane, we made 72 stimulus images (available at <https://doi.org/10.17605/OSF.IO/MNCDE>). All stimuli were presented against a gray background on a 24-inch LCD monitor (resolution $1,920 \times 1,080$ pixels). The viewing distance was approximately 60 cm.

Procedure

The experiment was implemented using PsychoPy2 1.82.01 (Peirce, 2009) and conducted individually in a laboratory. Each trial began with a black fixation cross for 500 ms. Afterward, two stimulus images were presented side by side on the center of the display. One of the two images was always presented at 0° (a standard stimulus) and the other was the same as, or the mirror-reflected version, of the standard stimulus presented at 0° , $\pm 40^\circ$, $\pm 80^\circ$, $\pm 120^\circ$, or $\pm 160^\circ$ ². Participants were asked to judge whether the two objects were the same or different from each other and press the “.”

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² We selected these angular disparities to ensure a sufficient number of trials in each condition and excluded a 180° rotation for which the shortest rotation path was equivocal.

or “0” key on a numeric keypad for the same or different pairs, respectively, as quickly and accurately as possible. The next trial began immediately after participants made a response, or when 10 s had elapsed.

The experiment contained 576 experimental trials of 9 angles (0° , $\pm 40^\circ$, $\pm 80^\circ$, $\pm 120^\circ$, or $\pm 160^\circ$) $\times$ two shapes (human or snake) $\times$ two face conditions (the presence/absence of a face) $\times$ two positions of the standard stimulus (left or right) $\times$ two versions of the standard stimulus (original or mirror-reflected) $\times$ two trial types (the same or a different pair) $\times$ two repetitions. The trial order was randomized for each participant. The experimental trials were divided into 8 blocks of 72 trials and participants were given the opportunity to take a break before they began a new block by pressing the “.” or “0” key. Prior to the experimental trials, participants performed 72 practice trials selected randomly from the experimental trials. During the practice trials, a “Miss!” message appeared for 200 ms after participants made an error or 10 s had elapsed. No feedback was provided during the experimental trials. The experiment took about 40 min on average.

Results

Following previous mental rotation studies, we analyzed data from same-pair trials only because we could not define rotational angles for different pairs (i.e., two objects never match no matter how much they are rotated), and thus, the angle effect for different pairs is difficult to interpret in terms of mental rotation (e.g., Gardony et al., 2014; Just & Carpenter, 1976; Shepard & Metzler, 1971). Before calculating mean RTs per condition, we excluded data from incorrect trials (4.22%) and data from trials where the RT was longer than 3,883 ms (three standard deviations above the mean; 2.36%). There was no extremely short RT (min = 404 ms). Individual mean RTs were calculated for each of the 20 conditions that consisted of the combination of shapes (human or snake), faces (present or absent), and rotational angles (0° , 40° , 80° , 120° , and 160°). The RTs per condition averaged across participants are presented in **Fig. 2**.

Fig. 2. Means and standard errors of response times.

We conducted a $2 \times 2 \times 5$ repeated-measures analysis of variance (ANOVA)³ for the RT data, with the shape, face, and angle as factors. We also calculated Bayes factor (BF) values using JASP 0.9.2.0⁴ (JASP Team, 2018) and reported them. The main effect of the angle was significant, $F(1.38, 31.73) = 119.61$, $p < .001$, $\eta_p^2 = .839$, $\varepsilon = .345$, $BF_{10} = 8.69 \times 10^{135}$, which reflected the linear relationship between RT and the angle of rotation. The main effect of the shape was also significant, $F(1, 23) = 44.59$, $p < .001$, $\eta_p^2 = .660$, $\varepsilon = 1.000$, $BF_{10} = 5.57 \times 10^6$, which indicated faster responses to human-shaped (1,127 ms) than snake-shaped (1,241 ms) objects. Importantly, a

³ To guard against the violation of sphericity, we used Chi-Muller's ε , by which the degrees of freedom and p -values were corrected. To keep the overall significance levels of $\alpha = .05$ for multiple comparisons, we applied Holm's sequentially rejective Bonferroni procedure.

⁴ We used g-prior distributions with r scale values of 1/2 and 1 for fixed and random effects, which are JASP's default prior distributions.

significant main effect of the face revealed faster responses to objects with a face (1,119 ms) than faceless objects (1,249 ms), $F(1, 23) = 96.54, p < .001, \eta_p^2 = .808, \varepsilon = 1.000, BF_{10} = 1.55 \times 10^9$. These main effects were qualified by three significant two-way interactions. A significant interaction between the shape and the face, $F(1, 23) = 15.79, p < .001, \eta_p^2 = .407, \varepsilon = 1.000, BF_{10} = 23.4$, showed a stronger effect of the face (i.e., RT differences between the face and faceless conditions) for snake-shaped (190 ms) than human-shaped (70 ms) objects. In addition, angle effects were smaller for objects with a face than faceless objects⁵, $F(3.64, 83.79) = 4.36, p = .004, \eta_p^2 = .159, \varepsilon = .911, BF_{10} = 0.121$, and smaller for human-shaped than snake-shaped objects, $F(3.43, 78.81) = 7.83, p < .001, \eta_p^2 = .254, \varepsilon = .857, BF_{10} = 1.46$. No three-way interaction of the shape, face, and angle was detected, $F(3.85, 88.48) = 2.06, p = .095, \eta_p^2 = .082, \varepsilon = .962, BF_{10} = 0.082$, suggesting that likening an object to a snake mitigated the angle effects to the same extent as the human-body analogy.

To further inspect the effects of adding a snake or human face to objects on the mental rotation speed, we conducted a 2×2 repeated-measures ANOVA for the slopes of the RT-angle linear functions, with the shape and face as factors. The slopes were calculated per condition and participant using linear regression. The slope analyses revealed that human-shaped objects were rotated more quickly (5.57 ms/degree) than snake-shaped objects (6.59 ms/degree), $F(1, 23) = 20.31, p < .001, \eta_p^2 = .469, \varepsilon = 1.000, BF_{10} = 1.96 \times 10^3$. Importantly, the mental rotation speed was faster when a face was added (5.81 ms/degree) than for faceless objects (6.35 ms/degree), $F(1, 23) = 8.32, p = .008, \eta_p^2 = .266, \varepsilon = 1.000, BF_{10} = 3.17$. The slope improvement amount when an object had a face (i.e., the slope differences) did not differ between human-shaped (0.47 ms/degree) and

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⁵ Although this effect was significant, a BF value showed the opposite result (i.e., support for the null hypothesis). This inconsistency may be due to a multicity control method in JASP (see de Jong, 2019). Given the previous findings on the body analogy effect and the present results from the slope analyses, it should be rational to interpret this effect as existent.

snake-shaped objects (0.59 ms/degree), $F(1, 23) = 0.07$, $p = .790$, $\eta_p^2 = .003$, $\varepsilon = 1.000$, $BF_{10} = 0.301$.

Discussion

The present experiment replicated the body analogy effect by showing that the addition of a human face to human-shaped cubes increased a mental rotation speed over faceless human-shaped cubes with a spatial cue (i.e., a light gray cube). Further, the present experiment first demonstrated that snake-shaped cubes with a snake face could be rotated more quickly than faceless snake-shaped cubes. Importantly, this snake analogy effect was found equal to the human-body analogy effect. According to Jeffreys (1961; see also Dienes & Mclatchie, 2018), BF_{10} values less than 1/3 can be considered substantial evidence of a null hypotheses. Following this criterion, the equivalence of the effects of the human-body analogy and the snake analogy on the mental rotation speed was qualified by the lack of the three-way interaction of the shape, face, and angle in the RT analyses ($BF_{10} = 0.082$) and the lack of the two-way interaction of the shape and face in the RT slope analyses ($BF_{10} = 0.301$). The fact that even a snake-like object whose posture should be difficult to emulate induced a facilitatory effect equivalent to that induced by the human-body analogy contradicted the motoric embodiment account or the claim that the body analogy effect was mediated by the mental emulation of the observed posture.

A possible parsimonious explanation for analogy effects (including both the human body and snake analogies) is that holistic mental rotation is facilitated whenever to-be-rotated objects can be regarded as a unit, regardless of whether they are human-like or not. This explanation is consistent with improved mental rotation performance using united objects than fragmented or multiple objects (e.g., Khooshabeh et al., 2013; Wraga, Creem, & Proffitt, 2000). With the snake analogy effect reported here, participants could apply their knowledge of snakes (e.g., they are elongated

and legless animals with individuality and their own body axes) to the object with a snake face, which would enable them to consider the object as a united entity and lead to faster holistic mental rotation. The same explanation can be applied to the human-body analogy effect, as endorsed by many researchers (Alexander & Evardone, 2008; Amorim et al., 2006; Doyle & Voyer, 2018; Krüger et al., 2014; Voyer & Jansen, 2016). The most important implication of the present study is that mental emulation or motoric embodiment contributes little to mental rotation, whereas the projection of one's own body axes or spatial embodiment possibly helps to recognize an object as a unit. Poorer performance of the mental rotation of anatomically impossible rather than possible postures (Amorim et al., 2006; Krüger et al., 2014; Makinae & Kasai, 2017; Sayeki, 1981) can be explained by difficulty in not emulating but perceiving them as a united entity, rather than as fragmented objects (see Khooshabeh et al., 2013). This would prompt piecemeal mental rotation (e.g., first rotating the head, then rotating the legs). Stimulus images of desk lamps used by Amorim et al. (2006), which were somewhat abstract rather than realistic (see Figure 8 of Amorim et al., 2006), might also be treated as separate parts (i.e., a bulb, arms, and a stand) rather than a single object due to an arbitrary connection between parts (like cubes in a typical mental rotation task) with no intrinsic axes except for its up-down axis. Therefore, based on parsimony, the motoric embodiment process cannot necessarily be assumed to account for the body analogy effect.

The present study has several limitations, mainly due to limited stimuli. As our cube-based stimuli were more abstract than realistic objects (e.g., human-like stimuli did not realistically show two arms and two legs), it might be possible that even human-like stimuli did not sufficiently evoke motoric embodiment (alternatively, motoric embodiment could be extended to any animated figures with a face, at least partially). It should be also considered that our human-like and snake-like stimuli differed in shapes (i.e., human-shaped objects were more complex than snake-shaped objects; indeed, our results showed faster responses for human-shaped than snake-shaped objects) and faces (i.e., a frontal human face with eyes, a mouth, and a nose vs. a profile snake face with an

eye and a mouth; see Ebersbach & Krüger, 2016, who found effects of face orientations on left/right identifications of human bodies). To address these issues, we need further investigations with broader stimuli including realistic figures. Moreover, although we did not ask participants whether they had actually perceived stimuli as human-like and snake-like, the potential role of object recognition in analogy effects should be investigated. Despite these limitations, the present results provided novel findings that the analogy effect is more generalizable even to non-human stimuli than previously thought.

To further understand the mechanisms of analogy effects in mental rotation, future studies should narrow down conditions where holistic mental rotation is facilitated. For example, since we adopted a snake-like object, it remains unclear whether the analogy effects occur with animate beings only or not. Given that people can project their own body axes onto inanimate or even nonsense objects as long as they have two or more intrinsic axes (e.g., Muto, Matsushita, & Morikawa, 2019), it is possible that using inanimate objects with their own axes (e.g., a chair, a car) could improve mental rotation via spatial embodiment. Expanding the scope of analogy effects could increase our knowledge of the cognitive mechanism underlying mental rotation, and help identify a method to mitigate cognitive loads during everyday spatial activities.

Acknowledgments

We thank Megumi Higashiyama, Keigo Nakahashi, Miho Nakanishi, Yukina Tanaka, Yujiro Toda, Haruho Umamichi, Takashi Yabuuchi, and Yuki Yamashita for collecting the data (their names are listed alphabetically). This work was supported by a JSPS Grant-in Aid for JSPS Fellows (Number 19J00072).

Supplementary materials

The data and stimuli are available at <https://doi.org/10.17605/OSF.IO/MNCDE>

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