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Developmental Psychology

Human-body Analogy Improves Mental Rotation Performance in People Aged 86 to 97 Years

Hiroyuki Muto[1,2,3][a], Yasuyuki Gondo[1], Hiroki Inagaki[4], Yukie Masui[4], Takeshi Nakagawa[5], Madoka Ogawa[4], Wataru Onoguchi[6], Yoshiko Ishioka[7], Keitaro Numata[8], Saori Yasumoto[1]

[1] Graduate School of Human Sciences, Osaka University, Osaka, Japan, [2] Research Organization of Open Innovation and Collaboration, Ritsumeikan University, Ibaraki, Japan, [3] Institute for the Future of Human Society, Kyoto University, Kyoto, Japan, [4] Tokyo Metropolitan Institute of Gerontology, Tokyo, Japan, [5] National Center for Geriatrics and Gerontology, Obu, Japan, [6] Faculty of Letters, Arts and Sciences, Waseda University, Tokyo, Japan, [7] Jindal School of Liberal Arts and Humanities, O.P. Jindal Global University, Haryana, India, [8] Department of Preschool Education, Osaka Seikei College, Osaka, Japan

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Mental rotation is a spatial ability allowing one to represent and rotate an object in one's mind, and its performance declines with age. Given previous findings indicating that likening a to-be-rotated object to a human body improves mental rotation performance in young adults, we examined whether this human-body analogy would improve older adults' mental rotation performance. We also tested whether the human-body analogy effect is age-dependent. In the present study, we analyzed data from 423 community-dwelling older adults (age range: 86–97 years; 219 men and 204 women) who answered two items of a paper-and-pencil mental rotation test: one on abstract cube objects (control condition) and one on cube objects with a human face (embodied condition). The results revealed that more participants correctly answered the item in the embodied condition (32.2%) compared to that in the control condition (19.6%), indicating that the human-body analogy is effective in an oldest-old population (i.e., people aged over 85 years). Notably, we found age differences in human-body analogy effects. While accuracy for mental rotation of abstract objects declined with age, accuracy for embodied objects was preserved with age. These findings suggest that the human-body analogy may prompt older adults to adopt a holistic, rather than a piecemeal, rotation strategy.

Introduction

To imagine the visual world from a perspective other than their own, people can create and transform visual representations (e.g., mentally rotate objects or their own perspectives; Zacks & Michelon, 2005). Transformations of visuospatial images are important spatial abilities that play roles in a wide range of everyday activities, including tool use (e.g., Schwartz & Holton, 2000), navigation (e.g., Hegarty et al., 2006; Wolbers & Hegarty, 2010), social interactions (e.g., Erle et al., 2018; Erle & Topolinski, 2015, 2017), and academic and occupational success (e.g., Castro-Alonso & Uttal, 2019; Kozhevnikov et al., 2013; Uttal et al., 2013). Further, it is well known that mental transformations of visuospatial images are at least partially subserved by sensorimotor processes necessary for corresponding physical transformations (e.g., Gardony et al., 2014; Muto et al., 2018, 2021; Sekiyama, 1982; Wexler et al., 1998; Wohlschläger & Wohlschläger, 1998), consistent with embodied cognition theories (Waller, 2014; Wilson, 2002).

Mental Rotation and Human-Body Analogy

Regarding visuospatial transformations, mental rotation of objects has received the most attention. In classic experiments, participants were asked to determine whether a pair of objects presented in various orientations were identical or mirror reflections of each other. Typical results indicated a linear function between mean response time and the angular disparity of two objects, suggesting that people mentally rotate one of two objects at a constant rate, until it aligns with the other (Shepard & Metzler, 1971; for a recent review, see Searle & Hamm, 2017). Mental rotation has also been studied using paper-and-pencil tests such as the Vandenberg and Kuse Mental Rotation Test (Peters et al., 1995; Vandenberg & Kuse, 1978).

a Correspondence: mutopsy@omu.ac.jp
Hiroyuki Muto is now at Graduate School of Sustainable System Sciences, Osaka Metropolitan University, Sakai, Japan.

Consistent with the embodied cognition framework, humanized or "embodied" objects are known to be mentally rotated more quickly and accurately than abstract objects. Several chronometric studies involving young adults (mostly university students) have demonstrated such human-body analogy effect using different stimuli such as realistic human bodies (Amorim et al., 2006; Jansen et al., 2012; Voyer & Jansen, 2016) and cube objects with human-like features (e.g., head, face, or limbs) that were made to look like human bodies[1] (Amorim et al., 2006; Krüger et al., 2014; Makinae et al., 2015; Makinae & Kasai, 2017; Muto, 2021; Muto & Nagai, 2020; Sayeki, 1981; Voyer & Jansen, 2016). Furthermore, psychometric studies that used paper-and-pencil tests have shown that participants can answer items for embodied objects (e.g., figure dolls, photographs of human figures) more accurately than those for abstract objects (e.g., Alexander & Evardone, 2008; Doyle & Voyer, 2018). Thus, at least in young adults, studies have robustly observed the facilitatory effect of the human-body analogy on mental rotation.

A predominant explanation for the human-body analogy effect is that embodied objects elicit a more efficient rotation strategy than abstract objects do. Previous studies identified two different strategies for mental rotation: holistic and piecemeal rotation strategies (e.g., Geiser et al., 2006; Heil & Jansen-Osmann, 2008; Khooshabeh et al., 2013). A holistic rotation strategy involves mentally rotating an object as a whole and enables faster and more accurate mental rotation; however, a piecemeal rotation strategy involves mentally rotating parts of an object one by one and is linked to slower and less accurate mental rotation (Geiser et al., 2006; Heil & Jansen-Osmann, 2008; Khooshabeh et al., 2013). Consistent with this notion, embodied objects are considered to elicit an efficient holistic mental rotation strategy, as human bodies are more likely than abstract objects to be regarded as a whole (Amorim et al., 2006; Krüger et al., 2014; Muto & Nagai, 2020; Voyer & Jansen, 2016).

Age-Related Decline in Mental Rotation Performance

From a developmental perspective, a number of studies on older adults have reported age-related decline in mental rotation performance, which has been repeatedly demonstrated by chronometric studies (e.g., Band & Kok, 2000; Berg et al., 1982; Briggs et al., 1999; Cerella et al., 1981; Dror et al., 2005; Dror & Kosslyn, 1994; Gondo et al., 1998; Hertzog et al., 1993; Hertzog & Rypma, 1991; Kemps & Newson, 2005; Muto et al., 2022; Puglisi & Morrell, 1986; Zhao et al., 2019, 2020) and psychometric studies (e.g., Borella et al., 2014; Iachini et al., 2019; Jansen & Heil, 2009; Rahe et al., 2018; Veldema & Jansen, 2019). This decline is associated with depletion of cognitive resources, such as working memory capacity (Borella et al., 2014; Briggs et al., 1999) or processing speeds (Salthouse, 1985).

Recently, Zhao et al. (2020) compared effects of stimulus complexity on mental rotation of abstract objects (three-dimensional cubes and two-dimensional polygons) between younger (19–24 years) and older (65–84 years) adults. Results indicated that while younger adults rotated complex (fragmented) objects more quickly than simple (united) objects, older adults had slower mental rotation speeds for complex objects, compared to simple objects. This finding suggested that older adults tend to adopt a piecemeal, rather than a holistic, rotation strategy, because of insufficient cognitive resources required to mentally represent and rotate a complex object as a whole.

Additionally, using familiar objects that were more likely to be recognized as a whole than abstract objects, Dror et al. (2005) demonstrated that older adults (59–83 years) consistently adopted a holistic rotation strategy, regardless of stimulus complexity, whereas younger adults (16–20 years) tended to adopt a piecemeal rotation strategy, as evidenced by differential effects of stimulus complexity on mental rotation speed. The authors interpreted this finding as evidence that older adults adopt effortless cognitive strategies to compensate for a lack of cognitive resources, as consistent use of a holistic strategy for familiar objects is less demanding than flexibly adopting a piecemeal strategy, depending on stimulus complexity. Therefore, these previous studies demonstrated that worse performance on mental rotation tasks in older adults could be explained by a lack of cognitive resources and adoption of cognitively economical strategies.

The Present Study

Synthesizing existing literature on the human-body analogy effect and age-related decline in mental rotation performance, we hypothesized that the human-body analogy mitigates cognitive demands for mental rotation, thus improving performance in older adults. Older adults are assumed to experience difficulties in mentally rotating abstract objects holistically and are thus inclined to execute piecemeal rotation, which is slower and less accurate than holistic rotation (Dror et al., 2005; Zhao et al., 2020). However, human bodies are much more familiar than abstract objects and should thus be easier to mentally rotate holistically (Amorim et al., 2006; Krüger et al., 2014; Muto & Nagai, 2020; Voyer & Jansen, 2016), even by older adults with reduced cognitive resources. These considerations led us to making two predictions. First, mental rotation performance in older adults should be improved through the human-body analogy, similar to findings for younger adults. Second, the human-body analogy should be age-related and more advantageous in relatively older adults assumed to have fewer cognitive resources.

1 Experiments 3–4 in Amorim et al. (2006) used cubes with a human head as stimuli, which were called "head cubes." Meanwhile, some studies (Makinae & Kasai, 2017; Muto et al., 2021; Muto & Nagai, 2020), as well as the present study, used cubes with human-like face patterns rather than adding a "head" to cube objects. Thus, for accuracy, we decided to use the more general term "embodied objects."

As already mentioned, previous studies have used different embodied stimuli such as real human bodies, cubes with body parts (head and limbs), and cubes with human faces. Using realistic body stimuli may help improve mental rotation performance via rich sensorimotor information. However, it also has disadvantages in terms of determining whether observed facilitation effects could be attributed to embodiment or other factors because, as Muto (2021) indicated, such stimuli differ from control stimuli in too many ways (e.g., luminance contrast, contour, smoothness, availability of location cues). Since the present study focuses on a rigorous method for identifying the embodiment effect, we decided to use cubes with a face as embodied stimuli and cubes with an abstract pattern as control stimuli, which were also used by Muto (2021).

To our knowledge, the present study is the first to investigate the human-body analogy effect in older adults. Although Iachini et al. (2019) examined effects of stimulus concreteness on mental rotation performance in children (6–9 years), younger adults (20–28 years), and older adults (60–82 years), and indicated that age-related decline was less pronounced for concrete compared to abstract stimuli, their study adopted different methods across conditions. Their participants selected an abstract two-dimensional line identical to a target from four alternatives in the abstract condition, whereas the participants made a left/right judgment about each single stimulus in the concrete conditions (with human hands, human faces, and animal faces). Given that a number of studies indicated that different response methods elicited different types of visuospatial transformation (Hoyek et al., 2014; Muto & Morikawa, 2018; Sekiyama, 1987; Zacks et al., 2000; Zacks & Michelon, 2005; Zacks & Tversky, 2005), it is still unclear whether minimal manipulation of stimulus concreteness improves mental rotation performance in older adults.

Specifically, the present study targeted the oldest-old population (i.e., people aged 85 years and over) for two reasons. First, this age group has reduced working memory capacity compared with the younger-old group (Elliott et al., 2011), which is helpful for testing our hypothesis on the association between the human-body analogy effect and age-related decline in working memory capacity. Second, mental rotation studies focusing on the oldest-old have so far been scarce. Given society's expanding older population and increased longevity, it must be important to examine spatial cognition among the oldest-old and devise ways to improve it through a simple manipulation of embodying objects.

In the present study, we had to reduce the burden on oldest-old participants. It is well-known that in the oldest-old and near-centenarian populations, sensory and cognitive impairment is common (e.g., Elliott et al., 2011; Toyoshima et al., 2018). Our sample was also expected to show a less healthy bias than samples of older adults recruited through advertisements to participate in laboratory experiments because we conducted our research as part of a massive epidemiological study that randomly sampled a large number of older adults from the local resident registration and conducted a variety of assessments such as medical examinations (in limited time). Simply put, since our sample could be considered more representative than those of common psychological experiments, our older participants were more likely to exhibit cognitive and physical decline than those in other laboratory studies. Hence, we created a paper-and-pencil test and presented participants with only two test items: one for control objects and one for embodied objects. We devised this test for an oldest-old population and expected it to be quite easy for younger adults. Therefore, the present study compared mental rotation performance within an older-age group.

In summary, the present study had two working hypotheses. First, more participants from the oldest-old population would correctly answer in the embodied condition than in the control condition, which would predict a significant main effect of embodiment. Second, mental rotation accuracy for embodied objects would be more preserved with age than accuracy for abstract objects would, which could predict a significant interaction between embodiment and age.

Method

Participants

This study was conducted as part of epidemiological research on health and longevity called the Septuagenarians, Octogenarians, Nonagenarians Investigation with Centenarians (SONIC) Study (Gondo et al., 2017). Participants in the SONIC Study were community-dwelling older adults, who were randomly selected from the Basic Resident Registration of Itami City, Asago City, Itabashi Ward, and Nishitama District in Japan to take part in the SONIC Study at a local community center or private home. All participants provided written informed consent and attended a medical examination. The mental rotation test was meant to be administered to 484 participants enrolled between 2018 and 2019; however, 17 participants did not perform the test because of a lack of time, refusal of cognitive assessments, procedural errors, or low visual acuity. Additionally, we excluded data from 44 participants who had a medical history of stroke, dementia, Parkinson's disease, or cerebral palsy. Thus, we analyzed data from 423 older adults (age range: 86.08–97.92 years, M = 91.11 years; 219 men and 204 women). We calculated months of age based on date of birth and then transformed them to years of age by dividing by 12. Men and women had an equivalent mean age (91.0 and 91.2 years, respectively). They spent an average of 11.0 (SD = 2.9) years on education. Almost no correlation was observed between age and education years in our sample (r = −.018). The present study was conducted in accordance with the declaration of Helsinki and the protocol was approved by the ethics board at the School of Human Sciences of Osaka University. Since this study was conducted as part of a larger epidemiological study, the sample size was not based on a prior power analysis for the specific purpose of the present study.

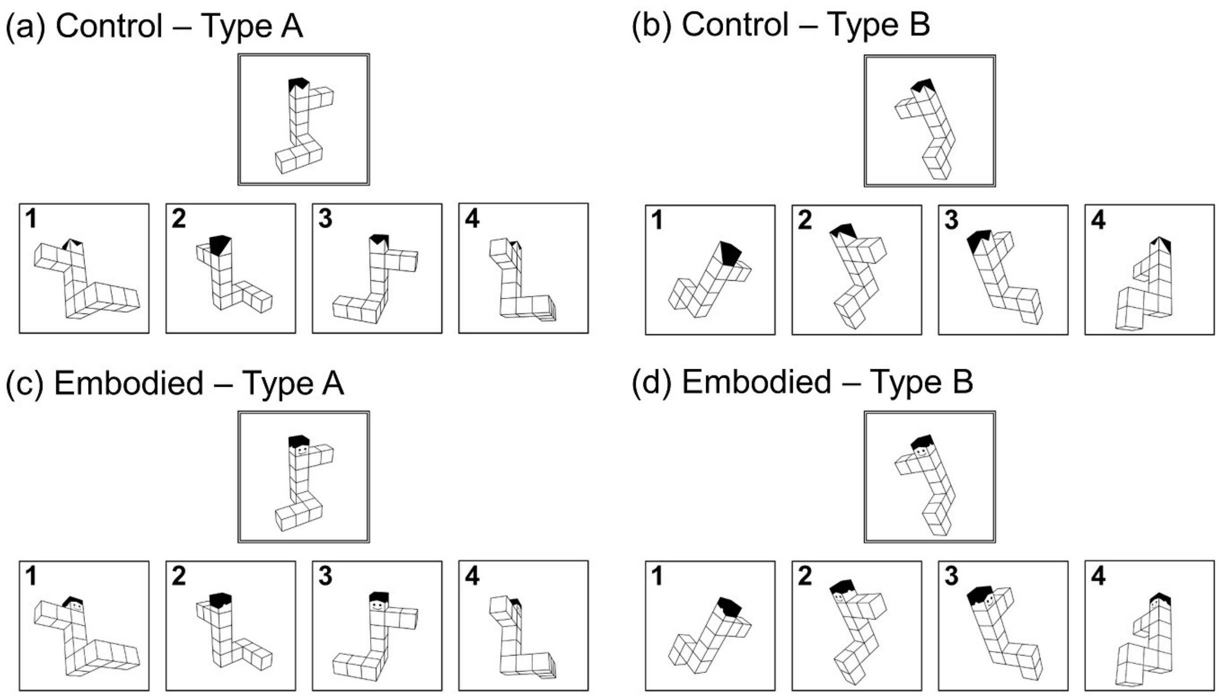

Figure 1. Four test items for the mental rotation test used in the present study.

All test items had two correct answers among four alternatives but participants were not informed of the number of correct answers.

Materials

We created four test items for a paper-and-pencil mental rotation test (**Figure 1**), which resembled items from the Vandenberg and Kuse Mental Rotation Test (Peters et al., 1995; Vandenberg & Kuse, 1978). The four test items combined two conditions (control or embodied) and two test types (A or B). Unlike typical mental rotation tests, we added either a pattern that resembled a human head or an abstract pattern of cubes for the embodied and control conditions, respectively, so that embodied objects looked like a human body. Each item was printed on a horizontal paper and consisted of a reference figure on the upper part and four target figures on the lower part. Two target figures depicted rotated versions of the reference figure (2 and 3 for Type A and 1 and 4 for Type B), and two depicted mirror-reflected versions of the reference figure.

We created four test sets that comprised one item for control objects and one item for embodied objects so that the types (A or B) of items within a test set differed from each other, and item order was counterbalanced (see **Table 1**; all test sets are available as pdf files at https://doi.org/10.17605/osf.io/gt76v). The four test sets were randomly distributed to participants.

Table 1. Four test sets used in the present study.

First item	Second item	*n*
(a) Control-Type A	(d) Embodied-Type B	108
(b) Control-Type B	(c) Embodied-Type A	107
(c) Embodied-Type A	(b) Control-Type B	109
(d) Embodied-Type B	(a) Control-Type A	99

Procedure

The SONIC Study collected variables for cognitive, psychological, sociological, physical, medical, biological, and dental domains from older adults (for details, see Gondo et al., 2017). It administered the mental rotation test as part of its 2018–2019 study. The testing sequence (i.e., test order) was not fixed but was determined case by case for each participant (to efficiently collect data, staff directed participants to an uncrowded booth). Each participant took the mental rotation test individually in a booth separated by partitions or a cubicle and was guided by one of expert investigators of the SONIC Study. All investigators had been sufficiently trained and followed the same procedure according to a written manual.

For each item, participants were asked to choose all target figures depicting an object identical to the reference figure, within a one-minute time limit. They received no feedback. Unlike the original procedure of the Mental Rotation Test (Vandenberg & Kuse, 1978), our participants were not informed of the number of correct answers. This modification was considered necessary to reduce the potential confounding effects of what Hirnstein and Hausmann (2009) called "the leaping response strategy," in which participants stop answering an item immediately after finding two target figures (i.e., ignoring the remaining figures). Each item was scored as correct when participants chose only the two target figures identical to the reference figure during the time limit. We considered that the chance level was $1/2^4 = 6.25\%$ (i.e., when participants randomly determined whether each of the four objects was identical or different).

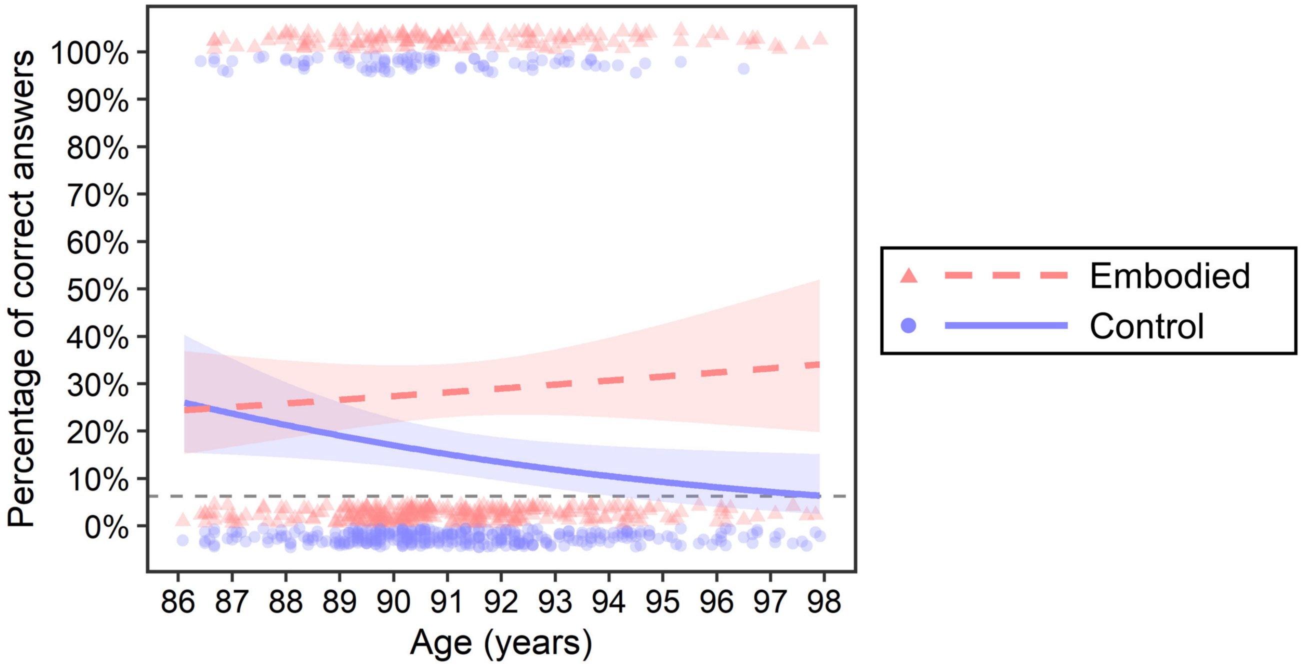

Figure 2. Each participant's accuracy based on whether their answer was completely correct and best-fitted logistic regression curves predicted by a generalized linear mixed model per embodiment condition.

Error bands represent 95% confidence intervals. A gray horizontal dashed line indicates a 6.25% chance level.

Note that this chance level decreases under the assumption that participants select the number of correct answers (0–4) with equal probability and then randomly determine which object is identical. Then, the chance level should be 3.33%, which is a product of the probability of correctly determining the number of identical objects (1/5) and that of selecting the two correct objects from the four alternatives (1/6).

Data Analysis

We conducted a series of generalized linear mixed model (GLMM) analyses using the lme4 (version 1.1.25; Bates et al., 2019) and lmerTest (version 3.1.3; Kuznetsova et al., 2019) R packages. Model details for each analysis are shown in the result section.

Results

Main Analysis

We conducted a GLMM analysis with a logit link function for accuracy data (correct = 1, incorrect = 0). We used age, condition (control = −0.5, embodied = 0.5), and the interaction between age and condition as fixed main effects. These variables were centered to avoid multicollinearity. We also included gender (women = −0.5, men = 0.5) as a covariate in this model to control for well-known gender differences in spatial abilities (Jansen & Heil, 2009; Voyer et al., 1995). Each participant was treated as a random intercept.

Figure 2 presents each participant's data and logistic regression curves, per condition. The GLMM analysis confirmed a significant effect of gender (b = 0.42, 95% confidence interval (CI) = [0.03, 0.84], z = 2.07, p = .038), indicating that men (29.0%) outperformed women (22.5%) regarding accuracy. A main effect of condition was significant (b = 0.81, 95% CI = [0.46, 1.17], z = 4.43, p < .001), indicating that more participants correctly answered the item on embodied objects (32.2%) than on control objects (19.6%). No main effect of age was detected (b = −0.05, 95% CI = [−0.14, 0.04], z = −1.14, p = .253). Moreover, the results revealed a significant interaction between age and condition (b = 0.18, 95% CI = [0.03, 0.33], z = 2.36, p = .019). Separate simple-slope analyses indicated that accuracy for control objects declined with age (b = −0.15, 95% CI = [−0.27, −0.02], z = −2.29, p = .022), whereas accuracy for embodied objects remained consistent with age (b = 0.03, 95% CI = [−0.07, 0.14], z = 0.64, p = .523).

Post-hoc Supplementary Analyses

After the first round of review, we conducted two post-hoc supplementary analyses. The first examined whether gender confounded the interaction between age and condition observed in the main analysis. As Yzerbyt et al. (2004) pointed out, a model with no interaction term between a covariate and an independent variable of interest would produce biased estimates. To address this issue, we conducted a GLMM analysis for the accuracy data with a new model consisting of age, condition, gender, and all possible interactions among them as fixed effects and participant as a random intercept effect. Since this model did not converge first, we used standardized values for age instead of centered ones. We then divided age-related estimates by the *SD* of age so that they can be interpreted as nonstandardized coefficients (as in the main analysis). We found a significant main effect of gender (b = 0.43, 95% CI = [0.02, 0.84], z = 2.06, p = .039) and condition (b = 0.81, 95% CI =

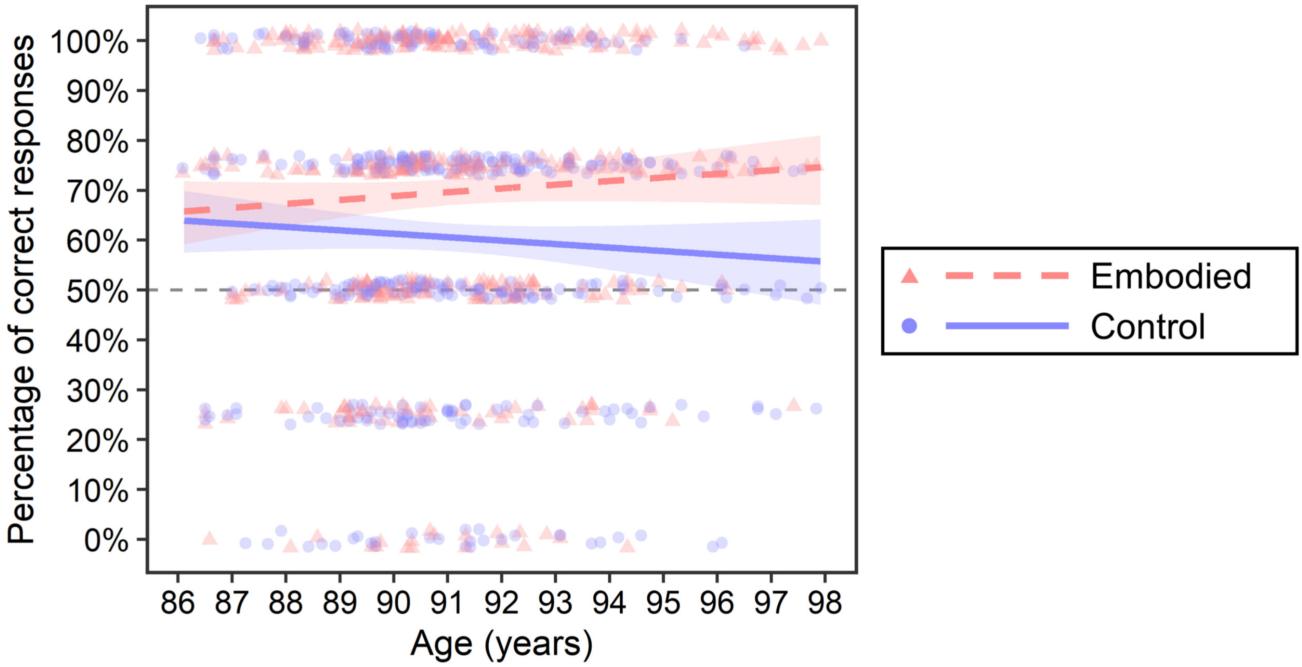

Figure 3. Accuracy of each participant based on the number of correct responses (both hits and correct rejections) and best-fitted logistic regression curves predicted by a generalized linear mixed model per embodiment condition.

Error bands represent 95% confidence intervals. A gray horizontal dashed line indicates a 50% chance level.

[0.44, 1.17], z = 4.36, p < .001). A main effect of age was not significant (b = −0.06, 95% CI = [−0.14, 0.03], z = −1.28, p = .202), while the two-way interaction between age and condition was significant (b = 0.18, 95% CI = [0.03, 0.33], z = 2.32, p = .020). These results were the same as in the original analysis. Importantly, the additional two- and three-way interactions including gender did not achieve significance (for age and gender, b = 0.13, 95% CI = [−0.04, 0.31], z = 1.53, p = .127; for condition and gender, b = 0.24, 95% CI = [−0.46, 0.95], z = 0.68, p = .500; and for age, condition, and gender, b = −0.06, 95% CI = [−0.36, 0.24], z = −0.37, p = .713). Thus, we observed that in the present sample, gender affected overall performance (i.e., intercept) but did not interact with age and condition. As in the main analysis, simple-slope analyses revealed an age-related decline in accuracy for control objects (b = −0.15, 95% CI = [−0.27, −0.02], z = −2.29, p = .022) but not for embodied ones (b = 0.03, 95% CI = [−0.07, 0.14], z = 0.64, p = .523).

Second, as a robustness check, we analyzed the number of correct responses. Our original analysis defined accuracy based on whether participants' answers were complete (i.e., choosing two correct figures and omitting the other two). However, we can also define accuracy based on the number of correct responses consisting of hits and correct rejections (the chance level is 50% for each of the four figures). Therefore, we conducted a binomial GLMM analysis for the number of correct responses (0–4), for which we entered age, condition, gender, and their possible interactions as fixed effects and participant as a random intercept effect. Figure 3 presents each participant's data and estimated logistic curves. We found significant main effects of gender (b = 0.36, 95% CI = [0.17, 0.55], z = 3.80, p < .001) and condition (b = 0.40, 95% CI = [0.25, 0.55], z = 5.34, p < .001) with the same sign as in the original analysis. Proportions of correct responses averaged across participants were 68.1% and 59.8% for the embodied and control objects, respectively, and 67.6% for men and 60.1% for women. No main effect of age was detected (b = 0.00, 95% CI = [−0.04, 0.04], z = 0.16, p = .877). The two-way interaction between age and condition was significant with the same sign as in the original analysis (b = 0.07, 95% CI = [0.01, 0.13], z = 2.20, p = .028). The two- and three-way interactions including gender were not confirmed (for age and gender, b = 0.03, 95% CI = [−0.05, 0.11], z = 0.81, p = .416; for condition and gender, b = 0.26, 95% CI = [−0.04, 0.55], z = 1.71, p = .088; for age, condition, and gender, b = −0.11, 95% CI = [−0.23, 0.02], z = −1.67, p = .094). These results were consistent with those of previous analyses. However, simple slopes did not achieve significance for both control (b = −0.03, 95% CI = [−0.08, 0.02], z = −1.23, p = .220) and embodied objects (b = 0.04, 95% CI = [−0.01, 0.09], z = 1.40, p = .160).

Discussion

Using a paper-and-pencil test comprising items on abstract and embodied objects, the present study demonstrated that the human-body analogy improved mental rotation accuracy in oldest-old adults. To the best of our knowledge, this is the first evidence to support that the body analogy effect, which has been observed in younger populations, also occurs in older populations. Furthermore, we found that the effect of age on mental rotation depended on how embodied the stimuli were. Consistent with previous studies comparing mental rotation performance among a wider range of age groups (Band & Kok, 2000; Berg et al., 1982; Borella et al., 2014; Briggs et al., 1999; Cerella et al., 1981; Dror et al., 2005; Dror & Kosslyn, 1994; Gondo et al., 1998; Hertzog et al., 1993; Hertzog & Rypma, 1991; Iachini et al., 2019; Kemps & Newson, 2005; Puglisi & Morrell, 1986; Zhao et al., 2019, 2020), mental rotation accuracy for abstract objects was demonstrated to decline with age, within the present population aged from 86 to 97 years (but our post-hoc analysis for the number of correct responses failed to detect age-related decline in accuracy for control objects). Comparatively, accuracy for embodied objects was more preserved with age, which supports our hypothesis that older adults assumed to have fewer cognitive resources can take advantage of the human-body analogy for mental rotation performance.

As the human-body advantage in an oldest-old population reported here is a qualitative replication of the human-body analogy effect previously observed in younger adults, we considered the mechanisms underlying improved mental rotation accuracy for embodied objects in the present study's participants. As described in the introduction, embodying to-be-rotated objects is considered to prompt a more efficient holistic rotation strategy, rather than a piecemeal rotation strategy, since human bodies are more familiar and thus more likely to be regarded as a whole (Alexander & Evardone, 2008; Amorim et al., 2006; Doyle & Voyer, 2018; Jansen et al., 2012; Krüger et al., 2014; Muto & Nagai, 2020; Voyer & Jansen, 2016). This is consistent with previous reports that older adults tended to use a piecemeal rotation strategy for abstract objects, because of a lack of cognitive resources (Zhao et al., 2020), but a holistic rotation strategy for familiar objects (Dror et al., 2005). The present findings regarding more advantageous effects in older participants assumed to have fewer cognitive resources and rely more on a piecemeal strategy also support this notion. Thus, a strategy shift from piecemeal to holistic rotation appears to be one persuasive explanation for the human-body advantage found in both older and younger adults.

Alternative Explanations

Although our findings confirmed the hypothesis that the human-body analogy facilitates older adults' use of holistic rotation, we cannot rule out alternative explanations. We will discuss two alternatives that highlight the roles of bodily projection and emotion.

Amorim et al.'s (2006) pioneering study proposed the notion that one's projection of their own body axis onto stimuli leads to the human-body analogy effect (i.e., "spatial embodiment"), which several researchers have accepted (Jansen et al., 2012; Muto, 2021; Muto & Nagai, 2020; Voyer & Jansen, 2016). For example, Muto (2021) showed that spatial perspective-taking, which entails a bodily projection process, was more strongly correlated with response time for embodied objects than for control objects. Because people can perform bodily projection even for abstract objects with two or more orthogonal axes (Muto et al., 2019), adding intrinsic axes (e.g., front–back, left–right, and top–bottom) to stimuli might be sufficient to induce facilitation effects.

The potential role of emotion in improving mental rotation performance could also be considered because our embodied stimuli have a smiley face. A smile has been consistently observed to induce positive emotion and evoke approach motivation (e.g., Nittono, 2016). Thus, positive emotion evoked by a smile may improve general motivation or mental rotation per se. However, the role played by positive emotion in mental rotation performance remains unknown, while fear was shown to facilitate mental rotation performance (Borst, 2013; Kaltner & Jansen, 2014). Furthermore, studies on young adults using stimuli with neutral facial expressions have observed the human-body analogy effect (e.g., Amorim et al., 2006; Makinae et al., 2015; Makinae & Kasai, 2017). Nevertheless, emotion could play a crucial role in or at least facilitate the human-body analogy effect in older adults.

Because these two explanations as well as the holistic rotation account do not contradict the present findings, future studies must test the alternatives by manipulating the features of embodied stimuli (e.g., intrinsic axes or facial expression). Nonetheless, it is noteworthy that our findings could not be explained by low-level visual features such as luminance contrast, contour, smoothness, or availability of location cues as we used control and embodied stimuli with as minimal differences as possible.

Potential Mediating Variables

This section discusses four possible mediators of the human-body analogy effect. The first candidate is the cognitive resource. In the present study, we hypothesized that the human-body analogy would facilitate a holistic rotation strategy by reducing cognitive demand on older adults with fewer cognitive resources. However, we did not directly investigate the association between a smaller amount of available cognitive resources and increased benefits from the human-body analogy. To address this issue, it is helpful to measure participants' working memory capacities or employ a dual-task paradigm.

Second, motor functions may modulate the human-body analogy effect. This hypothesis can be derived from the notion that the human-body analogy effect is subserved by the mental emulation of the embodied object's observed posture, which Amorim et al. (2006) called "motoric embodiment." Consistent with this, Jansen et al. (2012) used chronometric mental rotation task and demonstrated that athletes (i.e., male soccer players) took greater advantage of human bodies than nonathletes. Given that the co-occurrence of physical and cognitive declines is a central topic in embodied cognition research on aging (e.g., Kuehn et al., 2018; Muto et al., 2022), examining the role of motor functions in the human-body analogy effect can be considered as a promising approach.

Third, gender differences could be observed in the size of the human-body analogy effect. Since women are more likely than men to adopt an inefficient piecemeal rotation strategy (e.g., Heil & Jansen-Osmann, 2008), they may benefit more from the human-body analogy effect. So far, this has been tested by both chronometric (e.g., Makinae & Kasai, 2017; Voyer & Jansen, 2016) and psychometric (e.g., Alexander & Evardone, 2008; Doyle & Voyer, 2018) studies involving young adults, but results were mixed and remain unclear. In addition, our post-hoc analyses failed to detect gender differences in both the human-body analogy effect per se and age-related change in the effect. Hence, future studies should clarify the conditions under which gender modulates the human-body analogy effect and synthesize them with gender differences in embodiment effects found in other spatial cognition domains (e.g., Kessler et al., 2014; Kessler & Wang, 2012; Muto et al., 2021).

Fourth, because all our participants were Japanese, cultural background must be considered. In an intriguing study, Kessler et al. (2014) demonstrated that East Asian young adults showed stronger other-oriented bias than young adult Westerners when judging another person's visual perspective. For example, East Asians preferred an embodiment strategy to imagine another person's view more than Westerners even in a condition under which they could respond based on their egocentric view. Thus, future research must investigate whether the observed clear improvement in accuracy by humanizing objects could be attributed to cultural bias (e.g., approach tendencies for human bodies).

Limitations

Although we confirmed that the use of embodied objects improved mental rotation accuracy among the oldest-old group, its underlying processes should be cautiously examined by considering this study's limitations. The first limitation pertains to the use of a paper-and-pencil psychometric test, whose scores are rougher and more difficult to interpret as measures of mental rotation performance than response times of a chronometric task. Indeed, previous studies have repeatedly reported that psychometric test scores reflect processes other than mental rotation per se, such as test-specific strategies (e.g., Boone & Hegarty, 2017; Hirnstein et al., 2009; Moè, 2016). In contrast, chronometric measures could differentiate three subprocesses at least to some degree (Just & Carpenter, 1976, 1985). For example, chronometric studies using behavioral and physiological measures revealed that age-related decline occurs simultaneously in (1) the perceptual encoding of stimuli (Briggs et al., 1999; Zhao et al., 2019), (2) mental rotation (Band & Kok, 2000; Berg et al., 1982; Briggs et al., 1999; Cerella et al., 1981; Dror et al., 2005; Gondo et al., 1998; Hertzog et al., 1993; Hertzog & Rypma, 1991; Kemps & Newson, 2005; Puglisi & Morrell, 1986; Zhao et al., 2019, 2020), and (3) response selection and execution (Falkenstein et al., 2006; Roggeveen et al., 2007). To determine the process or strategy facilitated by the human-body analogy, using chronometric mental rotation tasks in behavioral and psychophysiological experiments could be helpful.

The second limitation was that our test only had two items, which aimed to alleviate the burden on our oldest-old participants. This made it difficult to identify whether each participant was a guesser, while the average accuracy (proportion of completely answered items) across participants was beyond the chance level of 6.25% or 3.33% (19.6% and 32.2% for control and embodied items, respectively). Our post-hoc supplementary analysis for the number of correct responses provided some suggestions. This analysis showed again that overall accuracy averaged across participants was beyond the 50% chance level (59.8% and 68.1% for control and embodied items, respectively). Since all participants provided eight responses (4 figures × 2 items), we could calculate the number of correct responses (0–8) per participant by collapsing across embodiment conditions. Therefore, 15.6% of participants correctly responded to 0–3 figures (below chance), 23.2% to 4 figures (chance), and 61.2% to 5–8 figures (above chance). This aggregation does not necessarily imply that participants in each category actually performed below or above chance because of probability errors, meaning we cannot precisely identify guessers. Thus, our findings should be interpreted as coming from a sample that includes guessers. Future studies could overcome this limitation by developing a sophisticated test with more items, which involve using a tablet-based form that randomizes the item sequence and conducting a direct comparison of different age groups. Nonetheless, one must consider that a certain percentage of guessers may be "representative" of the oldest-old population. It should also be noted that if the human-body analogy changes a guesser into a nonguesser, then that would be an important finding at least in practical applications.

Because of these limitations, we can say little about the detailed processes of the human-body analogy effect in the oldest-old group. Simply put, the human-body analogy, rather than a mental rotation process per se, may have improved participants' comprehension of test items' meanings. Nevertheless, our findings are important in that they suggest a way to improve the performance of older adults on spatial cognition as well as facilitate future aging studies on the human-body analogy effect.

Conclusion

The present study demonstrated that the human-body analogy improved mental rotation performance in older adults. More specifically, a simple and minimal manipulation of stimuli's resemblance to the human body (i.e., adding a pattern similar to a human head or an abstract pattern to cubes) was demonstrated to be sufficient to increase oldest-old participants' response accuracy for mental rotation performance. Despite questions remaining regarding underlying mechanisms, the present findings raise the possibility that age-related decline in spatial abilities could be compensated for by using a familiar pattern, such as a human body.

Author Contributions

Contributed to conception and design: HM

Contributed to acquisition of data: HM, YG, HI, YM, TN, MO, WO, YI, KN, SY

Contributed to analysis and interpretation of data: HM

Drafted and/or revised the article: HM, YG, HI, TN, MO, WO, YI, SY

Approved the submitted version for publication: HM, YG, HI, YM, TN, MO, WO, YI, KN, SY

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Competing Interests

The authors declare no competing financial interests.

Data Accessibility Statement

The raw data, analysis script, and study materials are available on OSF: https://doi.org/10.17605/osf.io/gt76v.

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Supplementary Materials

Review Responses

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