Development of the mirror-image sensitivity for different object categories—Evidence from the mirror costs of object images in children and adults

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Object recognition relies on a multitude of factors, including size, orientation, and so on. Mirrored orientation, particularly due to children's mirror confusion in reading, holds special significance among various object orientations. Brain imaging studies suggest that the visual ventral and dorsal streams

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exhibit distinct orientation sensitivity across diverse object categories. Yet, it remains unclear whether mirror orientation sensitivity also varies among these categories during development at the behavioral level. Here, we explored the mirror sensitivity of children and adults across five distinct categories, which encompass tools that activate both the visual ventral stream for function information and the dorsal stream for manipulation information, and animals and faces that mainly activate the ventral stream. Two types of symbols, letters and Chinese characters, were also included. Mirror sensitivity was assessed through mirror costs—that is, the additional reaction time or error rate in the mirrored versus the same orientation condition when judging the identity of object pairs. The mirror costs in reaction times and error rates consistently revealed that children exhibited null mirror costs for tools, and the mirror costs for tools in adults were minimal, if any, and were smaller than those for letters and characters. The mirror costs reflected in absolute reaction time and error rate were similar across adults and children, but when the overall difference in reaction times was considered, adults showed a larger mirror cost than children. Overall, our investigation unveils categorical distinctions and development in mirror sensitivity of object recognition across the ventral and dorsal streams.

Introduction

Object recognition is one of the most important functions of visual system. The recognition of objects depends on a myriad of attributes, encompassing dimensions such as size, orientation, position, and viewpoint, among others. Previous studies have extensively examined the sensitivity of these features behaviorally or physiologically with single-unit recording and brain imaging techniques (Ashbridge, Perrett, Oram, & Jellema, 2000; Dehaene, Cohen, Sigman, & Vinckier, 2005; James, Humphrey, Gati, Menon, & Goodale, 2002; Konen & Kastner, 2008; Kravitz, Vinson, & Baker, 2008; Niebauer & Christman, 1998; Tarr, Williams, Hayward, & Gauthier, 1998; Verma & Brysbaert, 2011). Generally, it has been commonly recognized that object recognition is principally modulated by higher level attributes, such as viewpoint and identity, in contradistinction to lower level features such as size and illumination conditions (Andresen, Vinberg, & Grill-Spector, 2009; DiCarlo & Cox, 2007; Tarr et al., 1998; Valyear, Culham, Sharif, Westwood, & Goodale, 2006; Wallis & Rolls, 1997).

Among the orientations of objects, mirrored orientation is a focal point of interest. Conventionally, objects in the natural world maintain their identity under mirror-image transformations, except in cases of mirror-oriented letters and characters such as “b” and “d” (Corballis & Beale, 1993; Fischer & Luxembourger, 2022; Resque et al., 2023). Mirror confusion in reading and writing regardless of languages, often observed in young children, compels an exploration of the impact of mirrored orientation on object recognition. By assessing the reaction times of judging whether two objects are identical when presented in the same or mirrored orientations, mirror cost was defined as the additional response time when the orientations were mirrored versus when they were the same. This analytical metric has been employed to assess the impact of mirrored orientation on object recognition (Corballis, Miller, & Morgan, 1971; De Heering, Collignon, & Kolinsky, 2018; De Heering & Kolinsky, 2019; Pegado, Nakamura, et al., 2014). Similarly, the additional error rate in mirrored orientations compared to identical orientations serves as another approach to measuring mirror cost (De Heering & Kolinsky, 2019; Dehaene et al., 2010).

Researchers have tested the mirror costs of strings, false fonts, and pictures of different object categories with behavioral approaches (Ahr, Houdé, & Borst, 2016; Borst, Ahr, Roell, & Houdé, 2015; Gregory & McCloskey, 2010; Kolinsky & Fernandes, 2013; Kolinsky & Fernandes, 2014; Pederson, 2003; Pegado, Nakamura, et al., 2014; Pegado, Nakamura, Cohen, & Dehaene, 2011) and tested the mirror sensitivity with brain imaging approaches (Dehaene et al., 2010; Dilks, Julian, Kubilius, Spelke, & Kanwisher, 2011; Pegado et al., 2011). For example, the study by Dilks et al. (2011) revealed a stronger mirror-image sensitivity during the initial phases of object processing compared with the later stages, for both objects and scenes. Andresen et al. (2009) demonstrated that people are more sensitive to the orientation of vehicles than animals. However, there remains a gap in investigating mirror sensitivity across object categories other than vehicles and animals, limiting our understanding of the factors that drive the distinctions in mirror sensitivity across categories of objects.

According to the two-visual-stream theory, the visual system consists of two streams: the ventral stream projecting from the primary visual cortex to the temporal cortex mediating the perception and recognition of objects (vision for perception), and the dorsal visual stream projecting from the primary visual cortex to the parietal cortex mediating the visually guided action (vision for action) (Goodale & Milner, 1992). Previous studies suggest that the ventral and dorsal visual streams have different sensitivities to the orientation of different categories of objects (James et al., 2002; Valyear et al., 2006). Unlike animals, faces, letters, and Chinese characters mainly involved in the ventral stream (note that Chinese characters also activate broader areas of the frontal and parietal areas for processing of phonological and semantic information; see below), tools are closely correlated to specific actions and are represented in both the ventral and dorsal stream, corresponding to the functional and manipulation information about object-related actions, respectively (Buxbaum & Saffran, 2002; Buxbaum, Veramontil, & Schwartz, 2000; Johnson-Frey, 2004). The dorsal stream is exclusively sensitive to the orientation of graspable objects (Rice, Valyear, Goodale, Milner, & Culham, 2007), which also suggests that the orientation sensitivity in the dorsal stream depends on the action-related properties of objects. However, these findings originate from brain imaging investigations. It is still unclear at the behavioral level whether or not people also show proficiency in making judgments of the orientation of action-related objects compared with other categories of objects such as animals and faces that are represented in the visual ventral stream (Grill-Spector, Knouf, & Kanwisher, 2004; Kanwisher, McDermott, & Chun, 1997). Therefore, the first purpose of our study was to compare the mirror orientation sensitivity of tools, an object category that is action related and is represented in both the ventral and dorsal streams (Johnson-Frey, 2004; Lewis, 2006), with the mirror sensitivity of other objects that are represented in the ventral streams, including animals, faces, letters, and Chinese characters.

The sensitivity to mirrored orientation exhibits temporal dynamism, evolving with age and reading experiences (Ahr et al., 2016; Kolinsky et al., 2011; Pederson, 2003; Pegado, Comerlato, et al., 2014; Pegado, Nakamura, et al., 2014; Zhang et al., 2023). In both children and adults, reading breaks mirror invariance and increases the orientation sensitivity of letters (Fernandes & Kolinsky, 2013; Kolinsky et al., 2011; Pegado, Nakamura, et al., 2014). However, researchers also found that the mirror invariance was never completely unlearned, and mirror cost persists even in adults (Borst et al., 2015). In addition, the mirror sensitivity was not equally improved across all object categories with reading (Pegado, Comerlato, et al., 2014). Therefore, the second purpose of the study was to compare the mirror orientation sensitivity between children and adults for different categories of objects.

To compare the mirror costs of categories in children and adults, five categories of objects (tools, animals, faces, letters, and Chinese characters) were selected as stimuli, and the mirror costs of all of these categories were evaluated in children between 6 and 7 years old and in adults. Tools were selected as stimuli due to their association with specific actions, engaging both the ventral stream mediating object recognition and the dorsal stream mediating action manipulation (Chen, Snow, Culham, & Goodale, 2018; Frey, 2007; Johnson-Frey, 2004; Lewis, 2006). In contrast, non-tool objects (such as animals and faces) mainly activate the visual ventral stream (Grill-Spector et al., 2004; Kanwisher et al., 1997). As such, animal pictures have commonly served as a contrast condition for the localization of tool-selective areas with brain imaging (Garcea & Mahon, 2014; Lewis, Brefczynski, Phinney, Janik, & DeYoe, 2005; Mahon, Kumar, & Almeida, 2013; Perani et al., 1995). Unlike pictures of tools, animals, and faces, symbols including letters and Chinese characters were included because children often show mirror confusion in letter and character recognition (Ahr, Houdé, & Borst, 2017; Dehaene et al., 2010; Pegado, Nakamura, et al., 2014). Perception of single letters has also been demonstrated to be selectively mediated by the fusiform area in the ventral visual stream (Flowers et al., 2004; James, James, Jobard, Wong, & Gauthier, 2005; Polk & Farah, 1998; Polk et al., 2002). The activation of Chinese characters is broadly distributed, including the visual ventral stream (lingual gyrus and the fusiform gyrus) for processing the visual properties of characters and the parietal and frontal areas for processing the phonological and semantic information (Tan, Laird, Li, & Fox, 2005; Tan et al., 2000), but there is no evidence showing that these activations are action related. Previous studies also used faces and words as controls to define the tool-selective network (Kersey, Clark, Lussier, Mahon, & Cantlon, 2015). In short, these five categories of objects cover a wide range of categories for object recognition. With these five categories of objects as stimuli, we expected to uncover the development of the mirror sensitivity across categories represented in the ventral and dorsal streams.

Given that 6- to 7-year-old children are at the onset of letter and character learning, children ages 6 to 7 years old (first-grade students) were recruited for this study. In contrast to letters and Chinese characters, they were exposed to tools, animals, and faces much earlier. Previous studies showed that, by age 7, low-level feature sensitivity such as retinotopic maps (Conner, Sharma, Lemieux, & Mendola, 2004) and contrast sensitivity (Ben-Shachar, Dougherty, Deutsch, & Wandell, 2007) can reach an adult-like state; high-level object recognition may well develop between 7 and 11 years of age, but the recognition of faces and places continues to develop gradually (Golarai et al., 2007). These findings also suggest that 6 to 7 years of age is critical, as it marks the watershed of visual recognition of low-level features and high-level features.

To sum up, by comparing the mirror costs of five categories in children and adults, we endeavored to uncover the development of orientation sensitivity, particularly the sensitivity to mirrored orientation between the ventral and dorsal stream and between object pictures and cultural symbols (Kolinsky & Fernandes, 2014).

Materials and methods

Participants

Thirty-eight children (15 females and 23 males; mean ± SD age, 6.54 ± 0.51 years) and 40 adults (16 females and 24 males; age, 21.71 ± 0.12 years) participated in the study. The data from one child were excluded because he failed to follow instructions in the experiment, which resulted in 37 participants in the children group. All participants had normal or corrected-to-normal vision. None of the participants reported any neurological, psychiatric, or other medical problems. Written informed consent was obtained from adult participants. For the child participants, consent was obtained from their parents. All participants received monetary compensation for their time. The study was approved by the Human Research Ethics Board at South China Normal University (SCNU), and the methods were in accordance with the tenets of the Declaration of Helsinki.

Apparatus

The experiment was carried out on a computer monitor (refresh rate, 60 Hz; resolution, 1366 × 768; Lenovo, Hong Kong). The presentation of stimuli was controlled by Psychtoolbox 3 (Brainard, 1997; Pelli, 1997) embedded in MATLAB 2019 (MathWorks, Natick, MA). The viewing distance was 34 cm.

Stimuli

The stimuli used in the experiment consisted of grayscale images of tools, animals, faces, letters, and Chinese characters. The maximum width and length of the images were 6.60° and 8.72°, respectively (see Figure 1 for the exemplars for each category of images).

The stimuli of each category included 14 exemplars. For each participant, four out of the 14 exemplars were randomly selected to be used in practice trials, and six out of the rest were randomly selected for the experiment session. The tool stimuli included brush, scoop, shovel, scraper, screwdriver, rake, toothbrush, wok, spatula, fork, clip, hammer, scissors, and knife. The animal stimuli included chicken, pig, rabbit, whale, alligator, hawk, bear, rhinoceros, ram, fox, elephant, dog, elk, and cow. The face stimuli included 14 neutral-emotion face images (AM10NEHR, AM21NEHR, AM34NEHR, BM12NEHR, BM16NEHR, BM23NEHR, BM28NEHR, AF06NEHR, AF08NEHR, AF18NEHR, AF24NEHR, AF25NEHR, AF34NEHR, and BF01NEHR) from the Karolinska Directed Emotional Faces (KDEF) gallery (Lundqvist, Flykt, & Öhman, 1998; Lundqvist & Litton, 1998). The letter stimuli included c, z, r, s, a, e, b, p, f, k, g, j, t, and h presented in Arial font. The stimuli of Chinese character included 云, 电, 耳, 鸟, 头, 白, 上, 小, 气, 书, 飞, 月, 少, and 升 (all in boldface). All participants could recognize the tools, animals, letters, and Chinese characters presented. They reported no difficulty in face recognition in everyday life despite their unfamiliarity with the Caucasian faces.

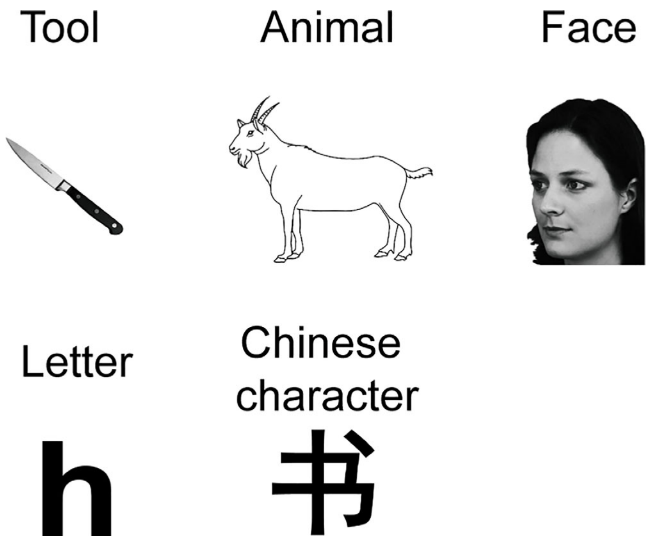

Figure 1. One exemplar for each of the five categories of stimuli. The face stimulus shown is BF01NEHL from the Karolinska Directed Emotional Faces (KDEF) gallery (Lundqvist et al., 1998; Lundqvist & Litton, 1998).

Design and procedure

Each trial started with a fixation cross for 300 ms. The first stimulus was then presented for 500 ms followed by another fixation cross for 300 ms. The second stimulus from the same category was then presented for 500 ms. The first and the second stimulus could be the same exemplar presented in the same direction (“SS”), the same exemplar but presented in mirrored directions (“SM”), a different exemplar presented in the same direction (“DS”), or a different exemplar presented in a mirrored direction (“DM”). Participants were asked to report whether or not the two stimuli were the same regardless of direction. In other words, participants were instructed to respond “same” in both SS and SM conditions and “different” in both DS and DM conditions. There was no time limit. The left arrow or the right arrow was pressed to indicate the participant’s response. The correspondence between the two keys and the two responses (i.e., “same” or “different”) was counterbalanced across participants.

There were five blocks in the experiment, one for each category of stimuli (i.e., tools, animals, faces, Chinese

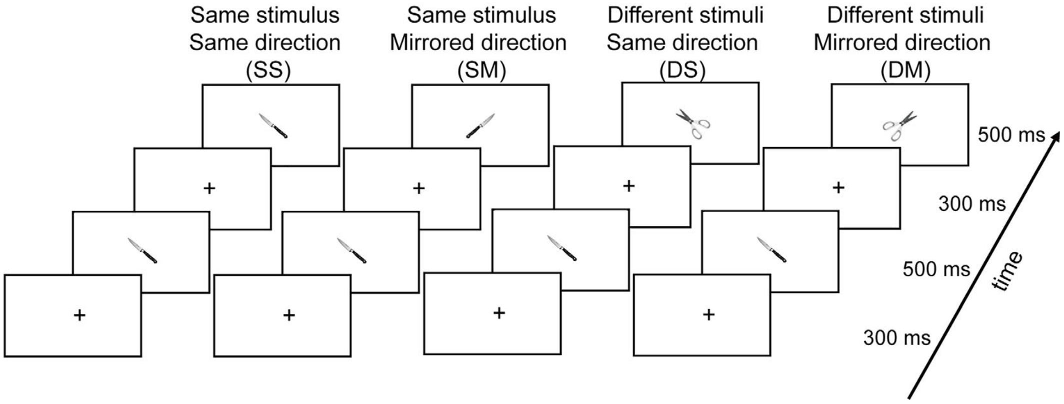

Figure 2. Schematic overview of the protocol of each condition. A fixation cross was presented for 300 ms, followed by a stimulus presented for another 500 ms. After 300 ms, a second stimulus was presented for 500 ms. The two stimuli could be the same stimuli presented in the same direction (SS) or a mirrored direction (SM), or the different stimuli could be presented in the same direction (DS) or a mirrored direction (DM). Participants were asked to press keys to report whether or not the two stimuli were the same objects regardless of directions.

characters, or letters). The order of the five blocks was randomized across participants. In each block, there were 24 trials, six trials for each of the four conditions (SS, SM, DS, or DM). Participants were given short breaks between blocks if needed.

Before the experiment, each participant completed 20 trials for practice, with four trials for each category. In the practice trials, participants received feedback if their response was incorrect or too slow (>3 seconds). The feedback was a sad face for children and the word "wrong" for adults.

Data analysis

Only conditions with the responses of "same" (i.e., SS and SM) (Figure 2) were included for analyses (Pegado, Nakamura, et al., 2014). In conditions with "different" responses (i.e., DS and DM), the two stimuli were different in identity anyway, regardless of the orientations. Therefore, the comparison between the same orientation and mirrored orientation on these "different" trials could not yield meaningful insights into the manifestation of mirror cost.

Reaction time and mirror costs reflected in reaction times

We first analyzed the reaction times (RTs) of trials in the SS and SM conditions. Trials with wrong responses and with RTs beyond ±3 standard deviations (*SD*) from the mean were removed from analyses. Among the remaining trials, only those exemplars for which both the SS and SM conditions remained were included for analyses. Two statistical methods were used: Three-way ANOVAs with group (children and adults) as a between-subject factor and category (tools, animals, faces, letters, and Chinese characters) and conditions (SS and SM) as within-subject factors were performed on RTs. Partial η^2 was reported to indicate the effect size of ANOVAs. Bonferroni correction was applied for multiple comparison correction.

In addition to the ANOVAs, we also used linear mixed modeling (LMM) with subjects and items as random factors, and group, categories, and conditions as the fixed factors, with comprehensive consideration of the interactions between each pair and all three of the fixed factors, to analyze the RT data because LMM can model both fixed factors (the factors we are interested in) and random factors (subjects and items). In addition, previous studies have suggested the use of LMM to analyze RT data because such data follow a skewed distribution rather than a normal distribution (Lo & Andrews, 2015; Whelan, 2008).

Two methods were used to calculate mirror costs based on the RT data. One was the absolute difference in RT between SM and SS, denoted as AbsoluteMirrorCost-RT. We first performed one-sample *t*-tests to see if the mirror cost in any condition was significantly different from 0. Results of the *t*-tests were subjected to Bonferroni correction for multiple comparisons. Subsequently, ANOVA and LMM were employed to reveal the effect of group and category on mirror costs.

Given the non-normal distribution of the RT data, as noted in many studies (De Heering et al., 2018; De Heering & Kolinsky, 2019; Kolinsky & Fernandes, 2014; Pegado, Nakamura, et al., 2014), we applied a natural logarithm to the RT and then utilized $\text{logRT}_{SM} - \text{logRT}_{SS}$ to assess the mirror cost of "same" responses. This transformation of RT data ensured that the data did not violate the assumption of normalization for statistical analysis. Considering the substantial variation in RT between children and adults (the RT of

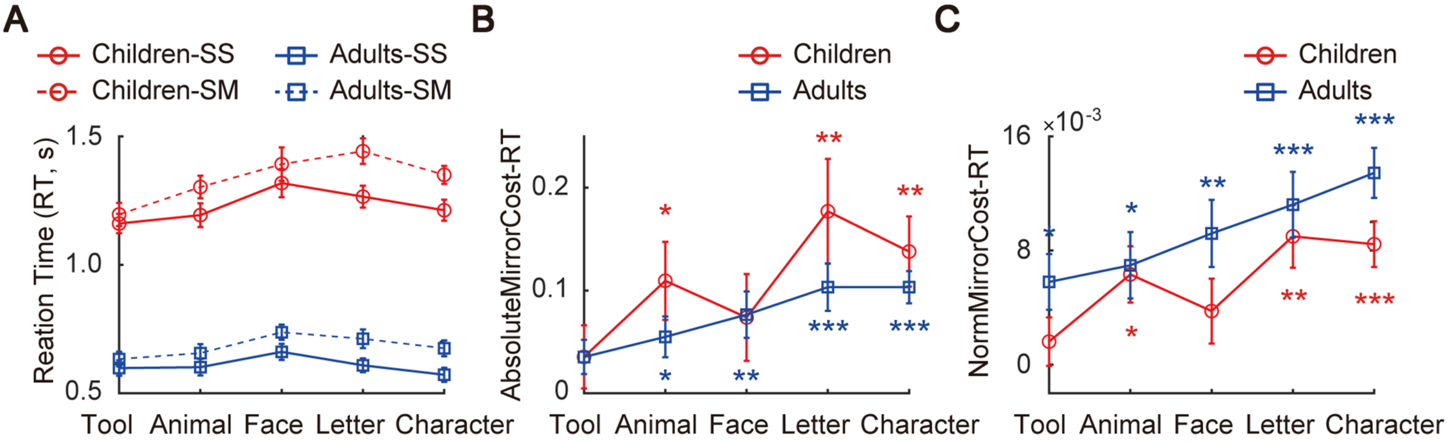

Figure 3. Results of RTs and mirror costs for trials with the "same" response. (**A**) RTs in adult and child participants under the SS and SM conditions. (**B**) The mirror cost (AbsoluteMirrorCost-RT) was defined as $RT_{SM} - RT_{SS}$ in children and adults for all categories of images. (**C**) The normalized mirror cost (i.e., NormMirrorCost-RT) was defined as $(\log RT_{SM} - \log RT_{SS})/(\log RT_{SM} + \log RT_{SS})$ in children and adults for all categories of images. Error bars indicate 1 *SE*. In (**B**) and (**C**), one-sample *t*-tests were performed to test whether a mirror cost was significantly different from zero. $^*p_{corr} < 0.05$, $^{**}p_{corr} < 0.01$, $^{***}p_{corr} < 0.001$, with Bonferroni correction.

children was close to double that of adults) (Figure 3A), a normalization step was undertaken to account for this global disparity and enable a meaningful cross-group comparison of mirror costs. Specifically, the mirror cost was then normalized by the summation of log-transformed RT values for both SM and SS conditions for each participant ($\log RT_{SM} + \log RT_{SS}$). In other words, the normalized mirror cost (denoted as NormMirrorCost-RT) was defined as ($\log RT_{SM} - \log RT_{SS})/(\log RT_{SM} + \log RT_{SS}$). This approach was also employed in previous studies to define mirror cost (De Heering et al., 2018; De Heering & Kolinsky, 2019; Kolinsky & Fernandes, 2014; Pegado, Nakamura, et al., 2014). The statistical analyses (one-sample *t*-test, ANOVA, and LMM) were similar to those for AbsoluteMirrorCost-RT as addressed above.

It should be noted that, although some researchers have suggested transforming RT to logRT or 1/RT for statistical analyses, such transformations undoubtedly bring distortion to the raw data (Lo & Andrews, 2015). Therefore, it is still worthwhile to look at the raw RT data and the mirror costs calculated based on raw RTs (i.e., AbsoluteMirrorCost-RT) in addition to the normalized mirror costs (NormMirrorCost-RT). This approach ensures a comprehensive evaluation of the outcomes.

Error rates and mirror costs reflected in error rates

In addition to RT, we also analyzed the error rates (ERs) of the SS and SM conditions to uncover the effect of mirrored orientation on the accuracy of recognition. Three-way ANOVA with group as a between-subject factor and category and conditions as within-subject factors was performed on ER. Partial η^2 is reported to indicate the effect size of ANOVAs. Bonferroni correction was applied for multiple comparison correction.

The mirror cost reflected in the ER was defined as the additional ER in the mirrored orientation (SM) compared to the same orientation condition (SS) (denoted as AbsoluteMirrorCost-ER) (De Heering & Kolinsky, 2019; Dehaene et al., 2010). Because the ERs were not substantially different between children and adults (10% at most, in contrast to the doubled RT of children as compared to adults) (Figure 4A), we did not do the normalization step for ER. For statistical analysis, we first performed one-sample *t*-tests to see if the mirror cost in any condition was significantly different from 0. Results of the *t*-tests were subjected to Bonferroni correction for multiple comparisons. Three-way ANOVA with group (children vs. adults) as a between-subject factor and category and conditions as within-subject factors was performed on the ER. A LMM was also performed with group, category, and condition as fixed factors and with subjects and items as random factors. Moreover, two-way ANOVA with group as a between-subject factor and category as a within-subject factor was performed to examine the effect of these factors on error-rate-based mirror costs (AbsoluteMirrorCost-ER). Similar to the RT results, LMM was also employed to reveal the effect of group and category on mirror costs with subjects and items as random factors.

For all ANOVAs performed in this study, Mauchly's sphericity test was used to validate ANOVAs for within-subject factors. If Mauchly's test indicated that the assumption of sphericity had been violated, Greenhouse–Geisser correction was performed and the results after correction were reported. Significant

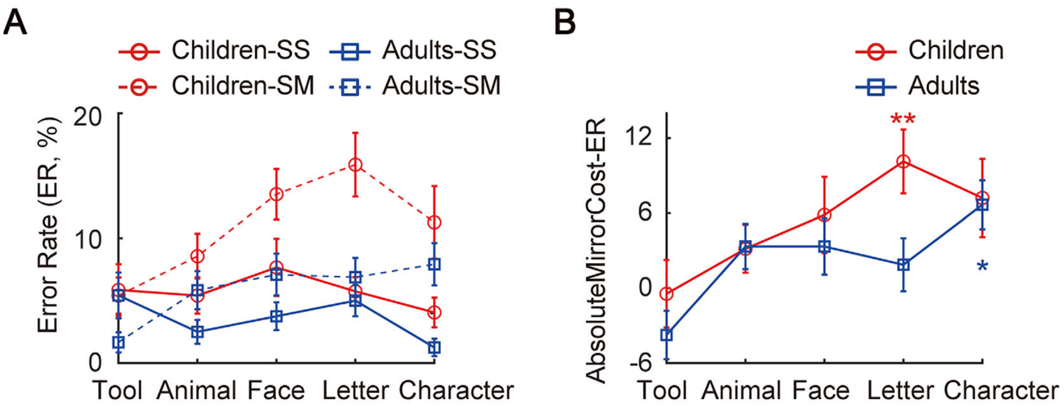

Figure 4. Results of ER and the mirror cost reflected in ER (MirrorCost-ER). (**A**) ER results for trials with the response of "same." (**B**) The mirror cost reflected in ER (MirrorCost-ER = ER_{SM}-ER_{SS}). Error bars indicate 1 *SE*. *$p_{corr} < 0.05$, **$p_{corr} < 0.01$, with Bonferroni correction.

interactions were further analyzed using Tukey's honestly significant difference (HSD) post hoc tests to reveal distinctions among condition pairs. Bonferroni correction was applied for multiple comparison correction. Partial eta squared (η^2_p) indicates the effect size for ANOVAs. Values of partial eta squared of 0.0099, 0.0588, and 0.1379 corresponded to small, medium, and large effects, respectively (Richardson, 2011).

Correlation between behavioral performance and mirror costs

To examine whether discrepancies in mirror costs across categories were due to the stimulus complexity that affected the task difficulty, we calculated the Pearson correlation between the averaged accuracy and averaged mirror cost reflected in RT (AbsoluteMirrorCost-RT and NormMirrorCost-RT, respectively), and the correlation between the averaged RT and the mirror cost reflected in the ER (AbsoluteMirrorCost-ER). In all correlation analyses, one data point was obtained from each participant by averaging the RT or ER of all trials and averaging the mirror cost indices of all conditions. This approach allowed us to reveal a general and unbiased relationship between accuracy or RT and mirror costs.

All the analyses were performed with MATLAB and SPSS Statistics 24 (IBM Corporation, Chicago, IL).

Results

Reaction time

In the SS and SM conditions, participants had to report "same." The raw RT results of the SS and SM conditions are shown in Figure 3A. The three-way ANOVA (group [2 levels: children and adults] × category [5 levels: tools, animals, faces, letters, and Chinese characters] × condition [2 levels: SS and SM]) revealed significant main effects of group, category, and condition (all $p < 0.001$, $\eta^2_p > 0.128$, Greenhouse–Geisser correction). Children were overall slower than adults ($p < 0.001$). In addition, as expected, the response was faster on SS trials than on SM trials ($p < 0.001$), which demonstrated an evident mirror cost effect (Corballis et al., 1971). Responses to tools were faster than those to faces, letters, and Chinese characters (all $p_{corr} < 0.026$), responses to animals were faster than those to faces and letters (both $p_{corr} < 0.017$), and responses to faces were faster than those to Chinese characters ($p_{corr} = 0.048$).

The interaction between condition and category, $F(3.483, 261.214) = 3.652$, $p = 0.009$, $\eta^2_p = 0.046$, Greenhouse–Geisser correction, was also significant. Post hoc analysis revealed that the difference in RT between the SS and SM conditions was just statistically detectable for tools ($p_{corr} = 0.043$) but was strongly significant in all of the other four categories (all $p_{corr} < 0.002$), suggesting a weak mirror cost for tools but a strong mirror cost for other categories of stimuli.

Although ANOVA has been commonly used to analyze RT data for decades, researchers have recently suggested using LMM to analyze RT data because LMM can model both fixed factors (the factors of interest) and random factors (subjects and items) and works even when the variable does not follow a normal distribution. Therefore, we also performed LMM to reveal the effect of group, condition, and category and their interactions on RT. The results from LMM were generally consistent with those of ANOVA, with significant main effects of group, category, and condition (all $p < 0.001$) and significant interactions between group and category ($p = 0.001$) and between condition and category ($p = 0.005$).

The only difference between the LMM and ANOVA results is that LMM also revealed a significant interaction between group and category ($F = 4.823$, $p = 0.001$). Post hoc analysis revealed that the response was faster for tools compared to the other four categories in children (all $p_{corr} < 0.038$), whereas in adults the response for tools was only faster than that for faces ($p_{corr} = 0.007$).

Mirror costs reflected in reaction time

To quantify the impact of mirrored orientation on RTs for the various categories of stimuli, we calculated the mirror costs in all conditions. The mirror cost was calculated based on either the raw RT, where AbsoluteMirrorCost-RT = $\mathrm{RT}_{\mathrm{SM}} - \mathrm{RT}_{\mathrm{SS}}$ (Figure 3B), or the log-transformed and then normalized RT, where NormMirrorCost-RT = $(\log\mathrm{RT}_{\mathrm{SM}} - \log\mathrm{RT}_{\mathrm{SS}})/(\log\mathrm{RT}_{\mathrm{SM}} + \log\mathrm{RT}_{\mathrm{SS}})$ (Figure 3C).

For AbsoluteMirrorCost-RT (Figure 3B), the one-sample *t*-tests revealed that both children and adults exhibited a null mirror cost for tools (children, $p_{corr} = 0.258$; adults, $p_{corr} = 0.122$). Children also exhibited a null mirror cost for faces ($p_{corr} = 0.180$), but positive mirror costs for the remaining three categories: animals, letters, and Chinese characters (all $p_{corr} < 0.033$). Adults exhibited positive mirror costs for all four categories of objects, including animals, faces, letters, and Chinese characters (all $p_{corr} < 0.036$).

ANOVA with group as a between-subject factor and category as a within-subject factor revealed a significant main effect of category, $F(3.483, 261.214) = 3.483$, $p = 0.009$, $\eta^2_p = 0.045$, Greenhouse–Geisser correction, and a non-significant main effect of group, $F(1, 75) = 2.447$, $p = 0.122$, $\eta^2_p = 0.032$) on AbsoluteMirrorCost-RT. The main effect of category manifested as a smaller mirror cost of tools than letters ($p_{corr} = 0.017$) and Chinese characters ($p_{corr} = 0.019$). The LMM with subjects and items as random factors and with group and category with fixed factors confirmed the above ANOVA results and also revealed a significant main effect of category ($F = 2.971$, $p = 0.039$) but not group ($F = 2.607$, $p = 0.111$). The interaction between category and group was not significant in either ANOVA or LMM (both $p > 0.633$).

For the normalized mirror cost (NormMirrorCost-RT), again, children showed null mirror costs for both tools and faces (both $p_{corr} > 0.215$), but positive mirror costs for the other three categories (all $p_{corr} < 0.014$). In contrast, adults showed positive mirror costs for all categories of objects (all $p_{corr} < 0.019$) (Figure 3C). ANOVA with group as a between-subject factor and category as a within-subject factor revealed a significant main effect of category, $F(4, 300) = 4.434$, $p = 0.002$, $\eta^2_p = 0.056$, and group, $F(1, 75) = 5.312$, $p = 0.024$, $\eta^2_p = 0.066$, on the normalized mirror cost. The interaction between category and group was not significant, $F(4, 300) = 0.519$, $p = 0.722$, $\eta^2_p = 0.007$. Similar to AbsoluteMirrorCost-RT, the main effect of category was manifested as a smaller mirror cost for tools than for letters ($p_{corr} = 0.01$) and Chinese characters ($p_{corr} = 0.002$). The main effect of group was manifested as a larger mirror cost for adults than children, which is different from the results of the unnormalized mirror cost (AbsoluteMirrorCost-RT). We will discuss this further in the Discussion section.

As above, we also performed LMM to test the effect of group and category. LMM also showed a significant fixed effect of category ($F = 4.229$, $p = 0.008$) and group ($F = 4.637$, $p = 0.034$) but no significant interaction between category and group ($F = 0.453$, $p = 0.77$).

Error rates

We also examined the effects of category, group, and conditions on the ER of responses with ANOVA. For trials with the "same" response, the three-way ANOVA (group [2 levels] × category [5 levels] × condition [2 levels, SS and SM]) revealed significant main effects of category, $F(4, 300) = 3.993$, $p = 0.004$, $\eta^2_p = 0.051$; group, $F(1, 75) = 18.801$, $p < 0.001$, $\eta^2_p = 0.2$; and condition, $F(1, 75) = 20.455$, $p < 0.001$, $\eta^2_p = 0.214$ (Figure 4A). The significant main effect of category was manifested as a lower ER for tools than for faces ($p_{corr} = 0.02$) and letters ($p_{corr} = 0.006$). The significant main effect of group was manifested as a lower ER for adults than children ($p_{corr} < 0.001$). The significant main effect of condition was manifested as a lower ER on SS than SM trials ($p_{corr} < 0.001$). The results of ERs revealed effects essentially parallel to the RT analysis, indicating that there was no speed-accuracy trade-off.

The interaction between category and condition, $F(3.577, 268.262) = 4.772$, $p = 0.002$, $\eta^2_p = 0.06$, Greenhouse–Geisser correction, was also significant. Post hoc analysis showed that, for other categories but not tools, the ER for SM trials was larger than for SS trials (tools, $p_{corr} = 0.205$; animals, $p_{corr} = 0.016$; faces, $p_{corr} = 0.016$; letters, $p_{corr} = 0.001$; Chinese characters, $p_{corr} < 0.001$), suggesting a null mirror cost for tools but positive mirror cost for other categories of objects.

The above results were also confirmed by LMM; that is, there were significant main effects of group ($F = 18.020$, $p < 0.001$) and condition ($F = 28.607$, $p < 0.001$) and significant interactions between group and condition ($F = 4.275$, $p = 0.039$) and between category and condition ($F = 5.067$, $p < 0.001$).

Mirror costs reflected in error rates

The difference in ERs between trials with the same identity but mirrored orientation (SM) and trials with the same identity and same orientation (SS) also reflected the cost of mirrored orientation (De Heering & Kolinsky, 2019; Dehaene et al., 2010). Therefore, we also calculated the difference between ERs on SM trials and SS trials (MirrorCost-ER = ER$_{SM}$ – ER$_{SS}$).

One-sample *t*-tests indicated again null mirror costs for tools in both children and adults. Similarly, they also exhibited null mirror costs for animals and faces. Children only exhibited significant mirror costs in letters condition ($p_{corr} = 0.003$), and adults only exhibited significant mirror costs in the Chinese characters condition ($p_{corr} = 0.014$) (Figure 4B). The mirror cost in ER seems smaller than the mirror cost reflected in RTs because the latter showed a positive mirror cost for three out of the five stimulus categories, suggesting that the mirror cost predominantly manifests in RT rather than in ER. Nevertheless, we did observe a positive mirror cost for letters in children and a positive mirror cost for Chinese in adults, aligning with the results of the mirror cost reflected in RT.

Two-way ANOVA with category as a within-subject factor and group as a between-subject factor unveiled a significant main effect of category, $F(3.577, 268.262) = 4.772$; $p = 0.002$, $\eta^2_p = 0.060$, Greenhouse–Geisser correction, on MirrorCost-ER. Consistent with the mirror costs reflected in RTs (i.e., AbsoluteMirrorCost-RT and NormMirrorCost-RT), the main effect of category on mirror costs manifested as a significantly smaller mirror cost for tools compared to letters ($p_{corr} = 0.011$) and Chinese characters ($p_{corr} = 0.003$). The main effect of group was not significant, $F(1, 75) = 3.057$, $p = 0.084$, $\eta_p^2 = 0.039$). The interaction between Group and Category was not significant (F(3.577, 268.262) = 1.043; p = 0.385, $\eta^2_p = 0.014$, Greenhouse–Geisser correction. LMM, however, did not reveal any significant fixed factors (group, $F = 2.959$, $p = 0.089$; category, $F = 2.163$, $p = 0.100$; interaction between group and category, $F = 1.349$, $p = 0.249$), suggesting that the modulation of category on mirror costs calculated based on ERs is not a solid result, consistent with the above results that the mirror cost predominantly manifests in RT rather than in ER.

Overall, children consistently exhibited null mirror costs for tools across all three indices of mirror cost. Adults exhibited minimal, if any, mirror cost for tools. Also, both ANOVA and LMM revealed a significant main effect of category on the mirror cost indices, suggesting that mirror costs do vary with object categories. With respect to the effect of group, the absolute and normalized mirror costs yielded different results. Without considering the overall variation in RTs, children and adults showed comparable mirror costs. However, after normalization by the overall RTs, adults exhibited larger mirror costs than those of the children.

Correlation between task performance and mirror cost

For all three types of mirror cost indices, we observed null mirror costs for tools in children and minimal, if any, mirror costs for tools in adults. We also observed a significant main effect of category on the amount of mirror costs, and the main effect manifested as a smaller mirror cost for tools than the costs for letters and Chinese characters. Although not significant, visual inspection of the mirror cost indices (Figures 3B, 3C, and Figure 4B) revealed a trend of smaller mirror costs for tools than for animals and faces. In other

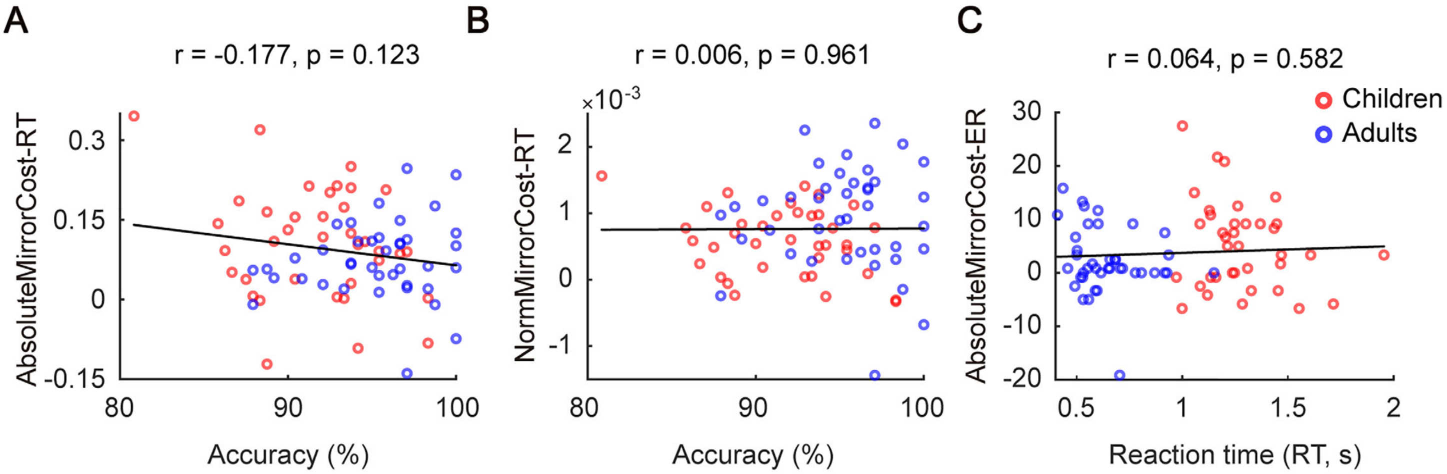

Figure 5. The correlation between behavioral performance (accuracy and RT) and mirror cost indices. (**A**) Correlation between accuracy and AbsoluteMirrorCost-RT. (**B**) Correlation between accuracy and NormMirrorCost-RT. (**C**) Correlation between RT and MirrorCost-ER.

words, tools seem to exhibit the smallest mirror cost among the five tested stimulus categories. However, one may argue that the main effect of category on mirror cost may simply reflect the differences in low-level features. Compared to other categories of stimuli, tools possess relatively simple visual features. This is corroborated by the overall shorter RTs and lower ERs. Unfortunately, we could not completely rule out the potential contribution of differences in low-level features to the mirror costs because these differences are tied to the appearance of the stimuli. For example, tools typically feature elongated handles but faces are characterized by rounded shapes with complicated details.

To explore whether the variance in mirror costs across categories of objects could be attributed solely to differences in visual complexity and consequent task difficulty, we calculated the correlation between accuracy and the mirror costs reflected in RTs (Figures 5A and 5B), as well as between RT and the mirror cost reflected in ER (Figure 5C). Each data point represents the averaged results for individual participant. Notably, none of these correlations was statistically significant (Pearson correlation, all absolute value of $r < 0.177$, all $p > 0.123$) (Figure 5), suggesting that mirror costs remain independent of accuracy or RTs. Thus, the main effect of category on mirror cost cannot be merely explained by the stimulus complexity and ensuing task difficulty.

Discussion

Our study delved into the intriguing phenomenon of mirror sensitivity across different age groups within the realm of visual object recognition. We explored how children and adults respond to diverse stimulus categories, including tool images that activate both the visual ventral and dorsal streams, as well as animal and face images that primarily activate the ventral stream, together with two kinds of symbols (letters and Chinese characters). The mirror costs in RTs and ERs consistently revealed that the mirror cost for tools only existed for adults and was comparatively smaller than that for letters and characters. The mirror costs reflected in absolute RTs and ERs were similar across adults and children, but when the overall difference in RTs was considered (i.e., NormMirrorCost-RT), adults showed larger mirror costs than those of the children. Our results revealed disparities in mirror sensitivity across various visual categories and help us to understand the development of mirror sensitivity.

Unlike the other four categories, tools exhibited null mirror costs in children and negligible mirror costs or, at most, minimal effects in adults. Particularly, the mirror cost for tools was significantly less than that for letters and Chinese characters. This observation suggests that the cognitive system, when encountering tools, is proficient in processing orientation of tools, rendering additional processing time unnecessary.

Previous studies have suggested that the representation of tools, which closely corresponds to actions, encompasses two distinct components: function and manipulation (Buxbaum & Saffran, 2002; Buxbaum et al., 2000; Johnson-Frey, 2004). The former is mediated by the middle temporal gyrus (MTG) in the ventral stream (Chao, Haxby, & Martin, 1999; Martin, Wiggs, Ungerleider, & Haxby, 1996), whereas the latter is mediated by the posterior parietal cortex (PPC) and premotor cortex in the dorsal stream (Gallivan & Culham, 2015; Gallivan, McLean, Valyear, & Culham, 2013). A recent study reported a fascinating distinction in children's and adults' responses to manipulation priming versus function priming. Specifically, they found that children at age 8 only showed manipulation priming and function priming was not observed until adulthood (Collette, Bonnotte, Jacquemont, Kalénine, & Bartolo, 2016). Given that all participants in the children's group were younger than 8 years old, it is plausible that they primarily extracted the manipulation-related but not the function-related information of tools. As such, the null mirror costs for tools in children observed here should be related to the manipulation information mediated in the dorsal stream. The high manipulability of the tool category likely contributes to its efficient processing in the dorsal stream (Kalénine & Bonthoux, 2008).

One may argue that it is the simple shapes linked to manipulative information of tools that lead participants to respond more rapidly to mirrored orientation images of tools compared to other categories, yielding a relatively smaller mirror cost. However, our correlation analyses cast doubt upon this idea. Specifically, our correlation findings revealed no significant correlation between mirror cost and accuracy or RT. Consequently, there is reason to believe that it is the action-related properties or manipulability of tools that made their orientation be processed proficiently and quickly in the dorsal stream, avoiding any additional processing time for mirrored orientations.

Conversely, unlike tools, positive mirror costs were evident for animals, letters, and Chinese characters in both children and adults, all of which predominantly engaged in the visual ventral stream (Grill-Spector et al., 2004; Kanwisher et al., 1997). Previous studies have shown that the ventral stream is generally less sensitive to object orientation or viewpoint, compared with the dorsal stream (James et al., 2002). In addition, unlike pictures of tools, animals, and faces, the mirror costs for symbols of letters (Harrison & Strother, 2018) and Chinese characters (Yang et al., 2019) could be attributed to the prolonged learning curve. Because these symbols are explicitly taught as distinct entities, participants took a longer time (i.e., incurred a larger mirror cost) to judge the mirrored image of these symbols as the "same."

Faces, also being mediated by the visual ventral stream, exhibited similar patterns as the animals, letters, and Chinese characters—that is, positive mean mirror costs in both children and adults, although not significant in children due to big variance (see the large error bar in Figure 3B). One reason why children did not show consistent positive mirror costs could be that children were unfamiliar with the Caucasian faces and therefore it was difficult for them to recognize the faces in both the SS and SM conditions, a notion that is supported by the longer RTs for faces than other categories of objects even in the SS condition (Figure 3A). As such, the additional amount of RTs in the mirrored orientation compared with the same orientation condition was not evident.

Second, our study unveiled intriguing findings related to age differences. Although we expected to see differences in mirror costs between children and adults, the mirror costs in absolute RTs and ERs did not yield a significant main effect of group. This suggests that the additional cognitive effort required for mentally flipping and matching the mirrored images remains relatively constant regardless of age, which means that the mirror cost of objects may never be unlearned even in adults, except perhaps for tools. However, just as shown in the results of normalized mirror cost, where NormMirrorCost-RT $= (\log RT_{SM} - \log RT_{SS})/(\log RT_{SM} + \log RT_{SS})$, the additional RT accounts for a significantly larger proportion of the overall RT in adults than in children because adults have much shorter overall RTs than children. In other words, even though adults become faster in making responses generally, the temporal requirement for mentally flipping mirrored images remains unaltered, which means that the speed of mental flipping of mirrored images does not increase with age. This result is in contrast with the results of mental rotation, such that the speed of mental rotation increased with development (Frick, Hansen, & Newcombe, 2013; Kail, Pellegrino, & Carter, 1980). This contrast may suggest that mental flipping for mirrored images is qualitatively different from mental rotation.

Third, our main findings, which underscore the minimal mirror costs for tools in contrast to those for letters and Chinese characters, cannot be exclusively ascribed to disparities in stimulus complexity or task difficulty across categories of objects. The shorter RTs and lower ERs both suggest that tools are easier to recognize. This is in line with the previous finding that tools are easier than other categories for children to recognize, possibly due to their inherent manipulability (Kalénine & Bonthoux, 2008). However, our correlation results revealed that none of the three mirror cost indices bore a significant correlation with the RTs or accuracy of task. Moreover, adults exhibited positive mirror costs in animals, faces, letters, and Chinese characters, despite their faster response times compared with children. This underscores that task difficulty does not seem to be a pivotal determinant of mirror cost, casting additional light on this phenomenon.

Finally, one may argue that our main findings stem from the differences in low-level features inherent to distinct categories of objects. Unfortunately, given that low-level features, such as shape and texture, are adherent to different categories of objects, we cannot completely rule out the contribution of low-level features to the distinctions in mirror sensitivity. Nevertheless, previous studies have suggested that object recognition in the ventral stream is not sensitive to features such as size and illumination conditions (Andresen et al., 2009; Cho & He, 2019; DiCarlo & Cox, 2007; Lee, Matsumiya, & Wilson, 2006; Tarr et al., 1998; Valyear et al., 2006; Wallis & Rolls, 1997). Thus, differences in low-level features are unlikely to be the primary driving force behind variations in mirror sensitivity across categories. However, it is likely that the middle-level visual features such as the elongated shape of tools and symmetrical shape of faces have contributed to the mirror sensitivity. The elongated shape has been shown to play a critical role in tool manipulation (Almeida et al., 2014; Chen et al., 2018). Moreover, familiarity with the stimulus may also play a role (Weisberg, Van Turennout, & Martin, 2007).

In conclusion, our findings shed new light on mirror sensitivity in visual object recognition across age groups. The distinctive mirror cost patterns observed, particularly minimal mirror costs associated with tools potentially stemming from its manipulability, offer valuable insights into human object recognition across the ventral stream and dorsal stream. Furthermore, our investigation elucidated age-related consistency, as well as distinction of mirror sensitivity, across various object categories, thus enriching our understanding of the field of object recognition during development.

Keywords: children, mirror cost, tool, animal, face, letters, Chinese characters, mirrored image, object recognition, development

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