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The development of visual attention to the Ebbinghaus illusion across two cultures

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Selective attention typically becomes more refined with age, improving significantly from early to middle childhood. However, under certain conditions, such as the Ebbinghaus illusion task, younger children may display more focused selective attention than older children and adults. Cross-cultural differences have also been documented, with North American participants tending to focus selectively on central targets, while East Asian participants attending holistically and showing greater susceptibility to the illusion. Despite these findings, the physiological mechanisms underlying these age-related and cultural differences remain unclear. Specifically, does susceptibility to the illusion align with what we attend to? The present study investigated age-related and culture-related changes in susceptibility to the Ebbinghaus illusion among 3- to 8-year-old children in Japan and the U.S. using eye-tracking methods. The results revealed that older children and Japanese children were more susceptible to the Ebbinghaus illusion than younger children. Importantly, behavioral susceptibility was linked to gaze fixation patterns. In both cultures, the proportion of total fixation time on the correct target area, including target and distractor circles, rather than selective attention to targets alone, predicted susceptibility to the Ebbinghaus illusion. These findings highlight the role of gaze fixation in shaping perceptual experiences across developmental and cultural contexts.

The human brain continuously processes a vast influx of visual information rapidly through attentional mechanisms to interpret and navigate the surrounding environment. Selective attention, the ability to focus on relevant stimuli while ignoring distractions, is a fundamental cognitive skill that develops throughout the lifespan and plays a crucial role in both childhood and adulthood (e.g.,[1–3]). Over the past two decades, cross-cultural research has shown that visual attention and perception are shaped by cultural contexts. Specifically, studies have revealed significant differences in how adults from Western and Eastern cultures allocate selective attention to objects versus backgrounds (for a review, see[4]). These findings challenge the previously held assumption that visual attentional processes are universal, suggesting instead that attentional biases may be shaped by cultural backgrounds gradually emerging from early to middle childhood, rather than being innate to human nature.

The study of visual illusions provides an effective approach to investigating the influence of culture and development on visual attention. Visual illusions have long been valuable tools in psychological research, offering insights into cognitive systems and attentional processes (for reviews, see[5,6]). Visual illusions take various forms, creating discrepancies between perception and reality. Traditionally, visual illusions have been studied as manifestations of the visual system shaped by evolution, with research focusing on identifying universal patterns. However, recent studies suggest that there is little evidence supporting a general theory or common factor across different visual illusions[7]. Additionally, susceptibility to visual illusions appears to vary across the lifespan (e.g.,[8–10]) and cultural backgrounds (e.g.,[11,12]). Weak and non-significant correlations among various illusion tasks indicate that individual differences in susceptibility are likely shaped by genetic, experiential, and developmental factors rather than being explained by a unified theory for illusions.

Cross-cultural differences in visual attention and perception are explained by the analytic versus holistic cognitive model[13,14]. According to this model, people from Western cultures (e.g., Canada, the U.K., and the U.S.) tend to exhibit analytic cognition, characterized by selective and context-independent attention to main objects, while individuals from East Asian cultures (e.g., China, Japan, and Korea) display holistic cognition, marked by dispersed and context-sensitive attention to both objects and backgrounds. For example, in the Michigan Fish study, Masuda and Nisbett[15] found that U.S.-American participants focused on attributes of the main fish, whereas Japanese participants incorporated contextual elements, such as water color and background details. Similarly, Senzaki, Masuda, and Ishii[16] used eye-tracking to show that Canadian participants' gazes concentrated on the main fish, while Japanese participants exhibited broader, context-sensitive gaze patterns. Their findings

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further revealed strong correlations between eye movements and behavioral responses. These investigations highlight how cultural norms shape attentional processes, resulting in distinct styles across cultures.

Among various visual illusions, the Ebbinghaus illusion (Fig. 1), also known as Titchener circles, has been widely used in cross-cultural and developmental research. In this illusion, participants compare the sizes of two target circles surrounded by context circles. The illusion occurs when a target circle appears larger when surrounded by smaller context circles and smaller when surrounded by larger context circles. In a cross-cultural study with adults from Japan and UK[11], Japanese participants demonstrated greater susceptibility than their British counterparts. These differences are attributed to culturally influenced attention biases: East Asians exhibit more holistic and context-sensitive attention, while Westerners display more analytic and context-independent attention.

Further studies have investigated the developmental trajectories of susceptibility to the Ebbinghaus illusion in early to middle childhood. A large-scale developmental study conducted in the UK assessed children aged 4 to 10 and adults using a rigorous double dissociation paradigm to evaluate perception with the Ebbinghaus illusion[8]. Although susceptibility continued to increase with age, 10-year-old children were still less susceptible than adults. Notably, children aged 4 to 5 performed similarly in both the deceiving and no-context conditions, indicating their perception was not yet influenced by the illusion.

Another study provides compelling evidence for the combined effects of culture and development on visual perception by testing 175 children aged 4 to 9 from the United States and Japan[17]. The results showed that Japanese children were more susceptible to the Ebbinghaus illusion than U.S.-American children, with this tendency becoming more pronounced in older age groups (6–7 and 8–9 years). Notably, younger children across both cultures exhibited more focused attention, which transitioned to greater context-sensitivity with age, highlighting developmental shifts in attentional styles influenced by cultural norms. These studies underscore the importance of examining both developmental and cultural factors in visual perception; however, the underlying attentional mechanisms remain unknown.

The eye-tracking paradigm is a valuable tool for understanding the role of visual attention in cognition. Neurophysiological studies demonstrate that information processing, visual attention, and eye movements are closely interconnected (e.g.,[18,19]). For example, longer eye-gaze fixations on specific objects facilitate quicker recognition and better memory retention[20]. However, visual attention is not solely dependent on eye fixation; we can attend to visual areas without directly looking at them. For instance, in a study using a magic trick[21], researchers found that while the location of eye-gazes did not directly affect participants' ability to detect the trick, those who successfully detected it shifted their gaze to the target location more quickly than those who did not. These findings highlight the dynamic and multifaceted nature of attentional mechanisms, emphasizing the interplay between eye movements and cognitive processing.

The cognitive mechanisms underlying visual attention, particularly those related to visual illusions, are more complex and nuanced than previously thought. Building on previous cross-cultural and developmental evidence, we hypothesized that the brain processes and prioritizes sensory information based on individual experiences, leading to culturally divergent attentional mechanisms across the lifespan. The present study examined developmental changes in visual attention from ages 3 to 8 and investigated cross-cultural differences in the Ebbinghaus illusion task between children in Japan and the U.S. using an eye-tracking paradigm. In this task, pairs of visual stimuli were presented side by side, and children indicated which target circle appeared larger by pressing an arrow key. Gaze fixation during the task was recorded as an index of visual attention, along with accuracy based on children's responses. We hypothesized that gaze fixation patterns would predict behavioral susceptibility to the illusion, susceptibility to Ebbinghaus illusions would increase from age 3 to 8 in both cultures, and that Japanese children would show greater susceptibility than U.S.-American children.

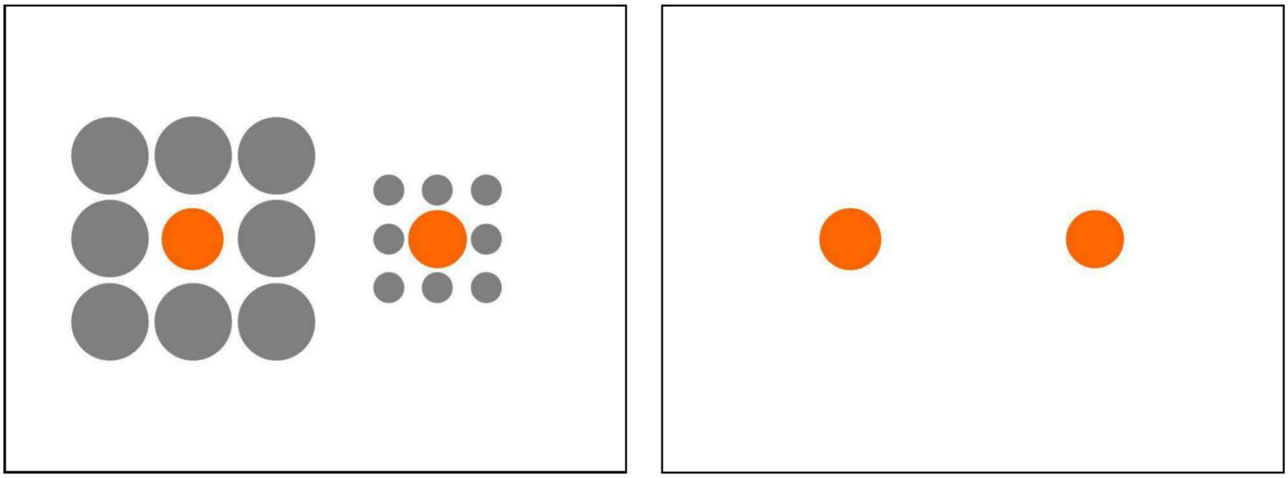

Fig. 1. An example of the Ebbinghaus illusion (**a**) with context and (**b**) without context. The target circles are in the sizes of 94 and 100 pixels, with the surrounding context circles that are at the size of 125% and 50% of the target circle.

Additionally, we anticipated that cross-cultural differences in attentional mechanisms would become more pronounced with age.

We further investigated how individual differences in gaze fixation influenced behavioral performance on the Ebbinghaus illusion task across cultures. Two competing hypotheses regarding gaze fixation patterns were tested. The first focused on selective gaze fixation, measuring the proportion of time spent looking at the central target relative to the surrounding distractors, irrespective of sizes of target and distractor circles. The second examined correct gaze fixation, assessing the proportion of time spent looking at the correct target area, including both target and distractor circles, relative to both correct and incorrect target areas (i.e., left vs. right). These analyses were designed to elucidate the role of gaze fixation in shaping cultural and developmental differences in susceptibility to the Ebbinghaus illusion.

Methods

Participants

This study protocol was approved by the University of Wisconsin–Green Bay Institutional Review Board (UWGB IRB), and all experiments were conducted in accordance with the guidelines and regulations provided by the UWGB IRB. A total of 230 children, aged 3 to 8 years, were recruited through outreach efforts at daycares, libraries, and community centers in Japan and the United States. Testing was conducted at local universities, and informed consent was obtained from the legal guardians of all participants prior to testing. For analysis, children were divided into three age groups: 3–4 years, 5–6 years, and 7–8 years. Detailed demographic information for each age group is presented in Table 1. Families received gift cards, and children were given a small prize as a token of appreciation for their participation. According to parental reports, the racial makeup of the U.S. children was as follows: 112 White, 5 Black or African American, 1 American Indian or Alaskan Native, 1 Asian, and 3 Hispanic or Latino. All U.S. children were born in the U.S. and spoke English as their first language. All Japanese children were born in Japan and spoke Japanese as their first language. Data from some participants were excluded from further analyses due to failure to complete the task (Japan: 3; U.S.: 7) or due to experimental/eye-tracker errors (Japan: 11; U.S.: 11).

Materials and procedure

The Ebbinghaus task used in this study was adapted from Imada et al.[17] and Doherty et al.[8] and followed a two-alternative forced-choice paradigm. The task consisted of two blocks: a no-context condition (10 trials) and a context condition (24 trials). In both conditions, two orange target circles were presented at 2.6 degrees from the center of the display. One of the target circles was 100 pixels in diameter, while the other was either 2, 6, 10, 14, or 18 pixels larger or smaller.

In the context condition, each target circle was surrounded by eight gray circles, either larger than the target circle (125% of the target size) or smaller (50% of the target size) (Fig. 1). The side of the larger target circle and the combinations of target and surrounding circles were counterbalanced across trials. The block order was consistent across participants, with the no-context condition presented first, while trials within each block were randomized. Participants were instructed to choose the larger circle by pressing the Z or M keys on a keyboard, which were covered with arrow labels for clarity. Following the procedure outlined by Imada et al.[17], trials with a 6% size difference in the no-context and context conditions were included in the analyses.

The same eye-tracking hardware and software were used in both countries. All instructions were translated and back-translated between English and Japanese to ensure accuracy. The Ebbinghaus illusion task was presented using E-Prime software with T-Prime extensions for Tobii Pro Lab on a 15.6-inch laptop with a display resolution of $1{,}920 \times 1{,}080$ pixels. Participants sat approximately 70 cm away from the screen.

Eye movements were recorded using a Tobii Pro Lab X3-120 eye tracker (Tobii Technology AB) with a sampling rate of 120 Hz. A five-point calibration was conducted at the start of the experiment. The Tobii I-VT gaze filter (fixation) was applied, using the average of both eyes without interpolation and employing moving median noise reduction at three samples. The fixation threshold was set at 30 degrees per second with a window length of 20 ms. Fixations within 0.5 degrees that occurred within 75 ms or less were merged, while fixations shorter than 60 ms were discarded.

Statistical analyses

The Kolmogorov–Smirnov test was used to verify the distribution of continuous variables. Data are expressed as raw values, percentages, and medians (interquartile range). For continuous variables with a normal distribution, Student's t-test (for two groups) and ANOVA (for more than two groups) were applied; for continuous variables that deviated from a normal distribution, Wilcoxon–Mann–Whitney two-sample tests (for two groups) and Kruskal–Wallis tests (for more than two groups) were used. All tests were two-tailed. To account for multiple

	Japanese				US American			
Age group	Total	Girls	Boys	Mean Age (SD)	Total	Girls	Boys	Mean Age (SD)
3–4	33	14	19	48.30 (7.30)	44	21	23	47.82 (4.71)
5–6	43	21	22	70.81 (6.61)	43	20	23	70.22 (8.45)
7–8	32	16	16	95.57 (7.43)	35	19	16	95.27 (7.35)

Table 1. Demographic information of all participants, including the country of origin, gender distribution in each age group, and the mean ages and standard deviations in each age group in months.

Measure	Age group	Japan (M, SD)	US (M, SD)	*p*-value	95% CI Lower	95% CI Upper	Partial η²
Behavioral susceptibility	3–4	0.52 (.47)	0.14 (.48)	< .001	0.214	0.547	.085
	5–6	0.83 (.22)	0.68 (.42)	.048	0.001	0.313	.018
	7–8	0.94 (.14)	0.86 (.29)	.91	− 0.097	0.268	.004
Correct gaze score	3–4	0.55 (.28)	0.60 (.23)	.38	− 0.154	0.059	.004
	5–6	0.50 (.17)	0.46 (.21)	.36	− 0.059	0.14	.003
	7–8	0.58 (.24)	0.44 (.16)	.014	0.023	0.255	.029
Selective attention score	3–4	0.37 (.26)	0.35 (.24)	.78	− 0.118	0.158	0
	5–6	0.46 (.25)	0.32 (.24)	.016	0.02	0.27	.028
	7–8	0.41 (.31)	0.43 (.31)	.99	− 0.167	0.13	0

Table 2. Descriptive Statistics for behavioral susceptibility, correct gaze score, and selective attention score. Values represent means (M) and standard deviations (SD), CI = Confidence Interval, Partial η^2 represents effect size for each comparison.

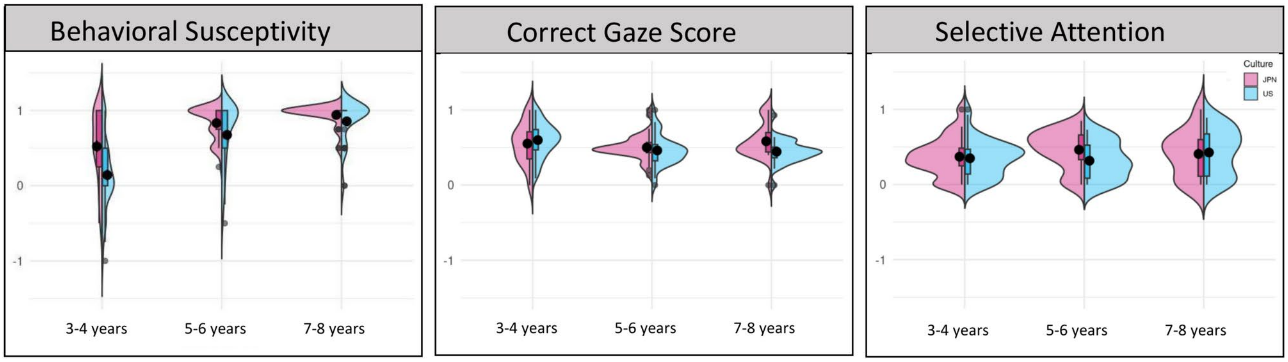

Fig. 2. (**a**) behavioral susceptibility in the Ebbinghaus illusion by subtracting the percentage of accuracy in the context condition from no-context condition, (**b**) the proportion of fixation duration on the correct target and its surrounding circles over the total fixation duration on both correct and incorrect target and surrounding circles (i.e., Correct Gaze Score), and (**c**) the proportion of fixation duration of the target circles over the surrounding context circles (i.e., Selective Attention Score) in Japan (red) and the U.S. (blue). Error bar indicates standard error. Violin plots indicate the raw data.

comparisons, we applied the Bonferroni adjustment, setting the α threshold at approximately 0.0056 per test to control for family-wise error. Statistical analyses were conducted in SPSS (IBM SPSS Statistics for Windows, Version 29.0.2.0), and graphs were generated using R (R Core Team, 2021).

Demographic and descriptive statistics were summarized for both cultural groups in Table 1. Age in months was tested using independent t-tests, and gender proportions were examined using Chi-square tests. The age distributions and gender proportions were similar between cultural groups, and gender was not significantly associated with dependent variables (see the supplemental document); therefore, it was excluded as an independent variable or covariate in subsequent analyses.

Results

Behavioral susceptibility to the Ebbinghaus illusion

Table 2 and Fig. 2a show behavioral susceptibility scores for context-sensitive attention across three age groups (3–4, 5–6, and 7–8 years) in both cultures. Means and standard deviations for each age group by country are summarized in Table 2. Age- and culture-related changes were identified: (1) older children's performance was more influenced by contextual information, and (2) Japanese children were generally more influenced by contextual information. However, significant cross-cultural differences were observed only in the youngest age group (3–4 years). Analyses of accuracy in context vs. no-context conditions and response times are provided in the supplemental document.

Gaze fixation patterns during the Ebbinghaus illusion

Overall gaze fixation patterns were averaged across all trials. Average fixation duration was similar for Japanese (173.53 ms) and U.S.-American children (189.7 ms), $t = 0.39$, $p > 0.05$. However, U.S.-American children showed significantly longer total fixation durations (526.53 ms vs. 882.97 ms, $p < 0.01$) and more fixations (3.35 vs. 4.15), $z = 16.04$, $p < 0.01$. We then analyzed the proportion of looking at the central target circles relative to overall looking and compared it between the no-context and context conditions. U.S.-American children were more likely to focus on the central circles in the no-context condition than in the context condition (0.58 vs. 0.42,

Predictors		Δ R^2	B	β	SE	*p*	95% CI		VIF
Behavioral Susceptibility (N = 192)									
Step 1		0.126							
	Correct		− 0.668	− 0.319	0.149	< .001	− 0.962	− 0.374	1.06
	Context		0.161	0.097	0.119	0.176	-0.073	0.396	1.06
Step 2		0.319							
	Correct		− 0.604	− 0.276	0.121	< .001	− 0.816	− 0.34	1.08
	Context		0.06	0.028	0.096	0.625	− 0.143	0.237	1.08
	Culture		0.276	0.3	0.05	< .001	0.17	0.369	1.02
	Age-Group	0.267	0.48	0.032	< .001	0.211	0.337	1.02	

Table 3. Hierarchical regression models predicting behavioral susceptibility to the Ebbinghaus illusion task. Final R2 = 0.45 (p < .001); Final adjusted R2 = 0.43.

$p < 0.001$). In contrast, Japanese children's gaze patterns did not differ between the two conditions (0.42 vs. 0.42, *ns*). The effect of age group was not significant.

Table 2 and Fig. 2bc show the results for Correct Gaze Scores and Selective Attention Gaze Scores. After applying the Bonferroni correction, no significant differences in gaze patterns between the two cultural groups were found across the three age groups.

Association between gaze patterns and behavioral performance

Hierarchical regression analyses were conducted to evaluate the roles of gaze fixation patterns, cultural groups, and age groups on children's behavioral susceptibility to the Ebbinghaus illusion task. In the first step, Correct Gaze Score and Selective Attention Gaze Score (continuous variables) were centered and included as predictors. In the second step, cultural and age groups were added as between-subject factors. Behavioral accuracy in context trials with a 6% size difference served as the outcome variable. Interaction terms were excluded from the final model due to multicollinearity (VIFs ≥ 10).

The results showed that only the Correct Gaze Score significantly predicted behavioral susceptibility, while the Selective Attention Gaze Score did not (Table 3). When cultural and age groups were added, Correct Gaze Score remained a significant predictor. Cultural and age group factors also played a significant role in explaining susceptibility. Longer fixation times on the correct target area were associated with increased accuracy and reduced susceptibility to the illusion, whereas fixation duration on target and surrounding circles was not statistically related to behavioral performance in Japanese and U.S.-American children.

Discussion

This study aimed to explore the mechanisms driving developmental and cross-cultural differences in susceptibility to the Ebbinghaus illusion among 3- to 8-year-old children in Japan and the U.S. through the use of eye-tracking technology. While developmental research generally indicates more refined selective attention emerging from early to middle childhood, prior studies with the Ebbinghaus illusion task revealed that older children and adults were more influenced by contextual and irrelevant stimuli compared to younger children[8]. Additionally, cross-cultural research has highlighted differences in behavioral susceptibility to the Ebbinghaus illusion between Japanese and U.S.-American adults[11].

The results revealed that Japanese children exhibited greater overall susceptibility to the Ebbinghaus illusion in their behavioral performance. Additionally, susceptibility to the illusion increased with age in both cultural groups. However, contrary to our prediction, cultural differences in attention were more pronounced in younger children than in older children. This discrepancy between the present findings and those of Imada et al.[19] may be attributed to differences in statistical approaches. In the current study, behavioral performance data were not normally distributed, leading us to use Wilcoxon–Mann–Whitney non-parametric tests to compare cultural differences. Furthermore, the age group distributions in our study differed slightly, as Imada et al. compared children aged 4–5, 6–7, and 8–9 years. Although the cross-cultural differences in older children in the present study were not statistically significant, the mean values observed in the present study were consistent with those reported by Imada et al.

Using an eye-tracking paradigm, our study revealed both similarities and differences in attention and gaze fixation patterns across cultures. First, U.S.-American children demonstrated a greater ability to focus on the target circles when presented without distractor circles in the Ebbinghaus illusion task. In contrast, Japanese children's gaze patterns in the no-context condition were similar to those in the context condition with distractors. It is notable that the cultural differences in gaze patterns emerged in the no-context condition without distractors but not in the context condition with distractors. Children from both cultures exhibited generally similar patterns across two gaze fixation analyses: selective gaze fixation and correct gaze fixation. Selective gaze fixation was defined as the proportion of fixations on the central target circles relative to the surrounding distractor circles, regardless of the size of the target circles, to assess whether participants could filter out distractors and focus on the target circles. Correct gaze fixation, in contrast, measured the proportion of fixations on the correct target area, including both target and distractor circles, by comparing left versus right areas to capture gaze distribution over the broader correct target area.

Critically, the proportion of gaze fixation on the correct target area relative to the total gaze fixation, rather than selective attention to filter out distractors, significantly predicted behavioral susceptibility to the Ebbinghaus illusion in children. A previous study using a magic trick[21] found that gaze location did not directly influence participants' ability to detect the trick. Similarly, our results suggest that selectively attending to the central target circle while ignoring surrounding distractors was not related to behavioral performance. Instead, behavioral performance was better predicted by the overall time spent fixating on the correct target area compared to the incorrect area. This finding suggest that broad attentional strategies over narrowly focused selective attention may be more important in determining susceptibility to Ebbinghaus illusion.

The behavioral results from the present study align with previous research testing early to middle childhood[8,19,22–24], showing that 5- to 6 and 7- to 8-year-old children were more susceptible to the Ebbinghaus illusion than 3- to 4-year-old children. In contrast, studies on older adults have reported reduced susceptibility to the Ebbinghaus illusion with age[9,10]. Particularly, 6- to 18-year-old were more susceptible to the Ebbinghaus illusion than those aged 18–60 and 60–81. Together, these findings suggest that susceptibility to the Ebbinghaus illusion may follow an inverted U-shaped developmental trajectory, peaking in adolescence or early adulthood and declining in later adulthood. Future studies should investigate the developmental trajectory of Ebbinghaus illusion perception across the lifespan.

In the present study, gaze fixation patterns of children from both cultures showed that they spent approximately 50% of their time looking at target stimuli. These results align with findings from a recent eye-tracking study investigating perception–action dissociation in the Ebbinghaus illusion task with adults[25]. In that study, researchers replicated the classic dissociation in the Ebbinghaus illusion, showing that grasping actions were less affected by the illusion compared to perceptual judgments. Furthermore, their findings indicated that differences in visual attention, as measured by gaze fixations, did not account for the discrepancy between how people perceive the illusion and how they physically interact with it. These results suggest that distinct neural mechanisms underlie visual judgments and goal-directed actions. Our findings provide additional evidence that the function of visual cognition in the Ebbinghaus illusion task is influenced by factors beyond gaze fixation patterns on targets versus surroundings.

This study has several limitations. First, cultural tendencies in other psychological factors, such as independent-interdependent self-construals[26], were not examined. These self-construals have been proposed as potential mediators of cultural differences in cognitive styles, but this theory was beyond the scope of our study. Additionally, recent studies using neurophysiological methods, such as eye-tracking and EEG, have produced mixed findings regarding cultural differences in attention. For instance, research has shown that children and adults from East Asian and Western cultures exhibit similar attentional patterns (e.g.,[27–29]). Future studies could explore the interplay between social orientation and cognitive styles more thoroughly to address these discrepancies.

Another important avenue for future research is conducting longitudinal studies to map the developmental trajectories of cross-cultural differences in attention. For example, Li et al.[30] conducted longitudinal research tracking attentional development in children from diverse cultural backgrounds, providing valuable insights into how cultural factors influence attentional processes during critical developmental periods. Finally, our study involved a relatively small sample of 230 children from only two countries. Future research with larger sample sizes and greater representation of countries could uncover additional nuances in cultural differences in the development of visual attention, offering a more comprehensive understanding of these processes.

In sum, the present study provides both theoretical and practical insights into children's attentional development across cultures, emphasizing the dynamic nature of attentional mechanisms. The findings support the theoretical claim that young children may have a unique ability to selectively focus on specific features of an image, showing lower susceptibility to distractors compared to adults when exposed to the Ebbinghaus illusion[11]. Additionally, the results revealed that behavioral susceptibility to the illusion was significantly influenced by gaze fixations on correct versus incorrect areas, rather than by selective gaze patterns on targets versus distractors. Older children and Japanese children were more susceptible to the illusion, with their behavioral performance more affected by surrounding distractors. These findings suggest that the underlying neurophysiological mechanisms of the Ebbinghaus illusion involve a complex interplay between visual attention and cognition. Practically, this research aligns with the ongoing shift in psychological science to explore visual attention as a means to better understand and support individuals with diverse cognitive styles. Future studies should thoroughly examine the mechanisms underlying the developmental trajectories of visual attention and perception of the Ebbinghaus illusion across different cultures.

Data availability

The datasets generated during the current study are available from the corresponding author on reasonable request.

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References

1. Checa, P. & Rueda, M. R. Behavioral and brain measures of executive attention and school competence in late childhood. *Dev. Neuropsychol.* **3**, 1–15 (2011).
2. Stevens, C. & Bavelier, D. The role of selective attention on academic foundations: A cognitive neuroscience perspective. *Dev. Cogn. Neurosci.* **2**, S30–S48. https://doi.org/10.1016/j.dcn.2011.11.001 (2012).
3. Stipek, D. & Valentino, R. A. Early childhood memory and attention as predictors of academic growth trajectories. *J. Educ. Psychol.* **107**, 771–788. https://doi.org/10.1037/edu0000004 (2015).

4. Masuda, T. Culture and attention: Recent empirical findings and new directions in cultural psychology. *Soc. Pers. Psychol. Compass* **11**, e12363. https://doi.org/10.1111/spc3.12363 (2017).
5. Eagleman, D. M. Visual illusions and neurobiology. *Nat. Rev. Neurosci.* **2**, 920–926. https://doi.org/10.1038/35104092 (2001).
6. Gori, S., Molteni, M. & Facoetti, A. Visual illusions: An interesting tool to investigate developmental dyslexia and autism spectrum disorder. *Front. Human Neurosci.* **10**, 175. https://doi.org/10.3389/fnhum.2016.00175 (2016).
7. Cretenoud, A. F. et al. Factors underlying visual illusions are illusion-specific but not feature-specific. *J. Vis.* https://doi.org/10.1167/19.14.12 (2019).
8. Doherty, M., Campbell, N., Tsuji, H. & William, P. The Ebbinghaus illusion deceives adults but not children. *Dev. Sci.* **13**, 714–721. https://doi.org/10.1111/j.1467-7687.2009.00931.x (2010).
9. Grzeczkowski, L., Clarke, A. M., Francis, G., Mast, F. W. & Herzog, M. H. About individual differences in vision. *Vis. Res.* **141**, 282–292. https://doi.org/10.1016/j.visres.2016.10.006 (2017).
10. Mazuz, Y., Kessler, Y. & Ganel, T. Age-related changes in the susceptibility to visual illusions of size. *Sci. Rep.* **14**, 14583. https://doi.org/10.1038/s41598-024-65405-6 (2024).
11. Doherty, M. J., Tsuji, H. & Phillips, W. A. The context sensitivity of visual size perception varies across cultures. *Perception* **37**, 1426–1433. https://doi.org/10.1068/p5946 (2008).
12. McCauler, R. N. & Henrich, J. Susceptibility to the Müller-Lyer illusion, theory-neutral observation, and the diachronic penetrability of the visual input system. *Philos. Psychol.* **19**, 1–23. https://doi.org/10.1080/09515080500462347 (2006).
13. Nisbett, R. E. & Masuda, T. Culture and point of view. *Proc. Nat. Acad. Sci. United States Am.* **100**(19), 11163–11170. https://doi.org/10.1073/pnas.1934527100 (2003).
14. Nisbett, R. E., Peng, K., Choi, I. & Norenzayan, A. Culture and systems of thought: Holistic versus analytic cognition. *Psychol. Rev.* **108**, 291–310. https://doi.org/10.1037/0033-295X.108.2.291 (2001).
15. Masuda, T. & Nisbett, R. E. Attending holistically versus analytically: Comparing the context sensitivity of Japanese and Americans. *J. Personal. Soc Psychol.* **81**, 922–934. https://doi.org/10.1037/0022-3514.81.5.922 (2001).
16. Senzaki, S., Masuda, T. & Ishii, K. When is perception top-down and when is it not? Culture, narrative, and attention. *Cognit. Sci.* **38**, 1493–1506. https://doi.org/10.1111/cogs.12118 (2014).
17. Imada, T., Carlson, S. M. & Itakura, S. East-West cultural differences in context-sensitivity are evident in early childhood. *Dev. Sci.* **16**, 198–208. https://doi.org/10.1111/desc.12016 (2013).
18. Astafiev, S. V. et al. Functional organization of human intraparietal and frontal cortex for attending looking, and pointing. *J. Neurosci.* **23**, 4689–4699. https://doi.org/10.1523/JNEUROSCI.23-11-04689.2003 (2003).
19. Corbetta, M. et al. A common network of functional areas for attention and eye movements. *Neuron* **21**, 761–773. https://doi.org/10.1016/s0896-6273(00)80593-0 (1998).
20. Olejarczyk, J. H., Luke, S. G. & Henderson, J. M. Incidental memory for parts of scenes from eye movements. *Vis. Cognition* **22**, 975–995. https://doi.org/10.1080/13506285.2014.941433 (2014).
21. Kuhn, G., Tatler, B. W., Findlay, J. M. & Cole, G. G. Misdirection in magic: Implications for the relationship between eye gaze and attention. *Vis. Cognition* **16**, 391–405. https://doi.org/10.1080/13506280701479750 (2008).
22. Bremner, A. J. et al. Effects of culture and the urban environment on the development of the Ebbinghaus illusion. *Child Dev* **87**, 962–981. https://doi.org/10.1111/cdev.12511 (2016).
23. Duemmler, T., Franz, V. H., Jovanovic, B. & Schwarzer, G. Effects of the Ebbinghaus illusion on children's perception and grasping. *Exp. Brain Res.* **186**, 249–260. https://doi.org/10.1007/s00221-007-1229-0 (2008).
24. Wincza, R., Hartley, C., Fenton-Romdhani, J., Linkenauger, S. & Crawford, T. The development of susceptibility to geometric visual illusions in children – A systematic review. *Cognitive Dev.* **69**, 101410. https://doi.org/10.1016/j.cogdev.2023.101410 (2024).
25. Whitwell, R. L., Garach, M. A., Goodale, M. A. & Sperandiom, I. Looking at the Ebbinghaus illusion: differences in neurocomputational requirements, not gaze-mediated attention, explain a classic perception-action dissociation. *Phil. Trans. R. Soc. B* **378**, 20210459. https://doi.org/10.1098/rstb.2021.0459 (2022).
26. Markus, H. R. & Kitayama, S. Culture and the self: Implications for cognition, emotion, and motivation. *Psychol. Rev.* **98**, 224–253. https://doi.org/10.1037/0033-295X.98.2.224 (1991).
27. Köster, M., Itakura, S., Yovsi, R. & Kärtner, J. Visual attention in 5-year-olds from three different cultures. *PloS one* **13**, e0200239. https://doi.org/10.1371/journal.pone.0200239 (2018).
28. Evans, K., Rotello, C. M., Li, X. & Rayner, K. Scene perception and memory revealed by eye movements and receiver-operating characteristic analyses: Does a cultural difference truly exist?. *Q. J. Exper. Psychol.* **62**, 276–285. https://doi.org/10.1080/17470210802373720 (2009).
29. Weigl, M. et al. Not so different after all An event-related potential study on item and source memory for object-scene pairs in German and Chinese young adults. *Front. Human Neurosci.* https://doi.org/10.3389/fnhum.2023.1233594 (2023).
30. Li, C., Hart, E. R., Duncan, R. J. & Watts, T. W. Bi-directional relations between behavioral problems and executive function: Assessing the longitudinal development of self-regulation. *Dev. Sci.* **26**, e13331. https://doi.org/10.1111/desc.13331 (2023).

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Author contributions

Senzaki was responsible for the conception and design of the work, acquisition, analyses, and interpretation of data, and have drafted the work. Shimizu was responsible for acquisition and interpretation of data. Ibe was responsible for acquisition, analyses, and interpretation of data, and have drafted the work.

Declarations

Competing interests

We declare that there are no competing financial and/or non-financial interests in relation to the work described.

Additional information

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