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RESEARCH ARTICLE

Developmental emergence of holistic processing in word recognition

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Abstract

Holistic processing (HP) of faces refers to the obligatory, simultaneous processing of the parts and their relations, and it emerges over the course of development. HP is manifest in a decrement in the perception of inverted versus upright faces and a reduction in face processing ability when the relations between parts are perturbed. Here, adopting the HP framework for faces, we examined the developmental emergence of HP in another domain for which human adults have expertise, namely, visual word processing. Children, adolescents, and adults performed a lexical decision task and we used two established signatures of HP for faces: the advantage in perception of upright over inverted words and nonwords and the reduced sensitivity to increasing parts (word length). Relative to the other groups, children showed less of an advantage for upright versus inverted trials and lexical decision was more affected by increasing word length. Performance on these HP indices was strongly associated with age and with reading proficiency. Also, the emergence of HP for word perception was not simply a result of improved visual perception over the course of development as no group differences were observed on an object decision task. These results reveal the developmental emergence of HP for orthographic input, and reflect a further instance of experience-dependent tuning of visual perception. These results also add to existing findings on the commonalities of mechanisms of word and face recognition.

KEYWORDS
developmental trajectory, holistic processing, reading, word recognition

Research Highlights

- Children showed less of an advantage for upright versus inverted trials compared to adolescents and adults.
- Relative to the other groups, lexical decision in children was more affected by increasing word length.
- Performance on holistic processing (HP) indices was strongly associated with age and with reading proficiency.

- HP emergence for word perception was not due to improved visual perception over development as there were no group differences on an object decision task.

1 | INTRODUCTION

Holistic processing (HP) of a visual object such as a face refers to the enhanced attention to and/or simultaneous processing of the parts and relations between the parts (Mondloch et al., 2002; Richler & Gauthier, 2014). The output of HP is not an undifferentiated template; rather, the face parts are encoded and represented independently, and HP arises from the obligatory encoding of all object parts and their configural relations. HP is generally attributed to an observer's increased experience in processing faces and it emerges over the course of development (Maurer et al., 2002; Mondloch et al., 2003).

Although HP can manifest for uncommon or novel visual categories after explicit training, for example, of fingerprints (Vogelsang et al., 2017) or of Greebles (Gauthier & Tarr, 1997), HP is an incidental consequence of increased experience with faces over development. One well-established perceptual advantage afforded by HP is the "inversion effect" with better performance for upright over inverted faces and a configural effect for faces whose parts and relations are intact versus altered (for meta-analysis, see [Richler & Gauthier, 2014]). The inversion effect has been documented in infants and toddlers (Cashon & Holt, 2015) and is likely a consequence of the greater frequency for upright (87%) than for inverted (13%) faces in their "face diet". HP also continues to improve over development at least until 12 years of age (de Heering et al., 2012).

An obvious question, then, is whether the emergence of HP during word recognition shares similar mechanisms with HP documented during face recognition. We already know that, in adults, better readers engage HP more than poorer readers (Ventura et al., 2020; Wong et al., 2012; Wong et al., 2011; Wong et al., 2019). Also, HP is evident to a greater extent for native-language versus second-language readers and for known words than nonwords, as revealed by the word composite task (akin to the gold-standard face composite task of HP) (Wong et al., 2011). HP for reading is not accomplished based on global shape or a word envelope, a hypothesis that has long been discredited (Paap et al., 1984), nor does it implicate a template in which access to the letters is precluded. Rather, HP for words appears to mirror that for faces: the parts and their relations are obligatorily processed, and the parts, in this case the letters, are still represented.

In contrast with the development of HP for face perception (e.g., see [Mondloch et al., 2003]) and the adult profile of HP for word recognition, we know rather little about the nature and time course of the emergence of HP and its role in beginning versus mature readers. Unlike the acquisition of face perception competence, which starts in early stages of life, the acquisition of word perception is typically acquired by explicit and targeted training around ages 5 and 6 years, and, thus, may be more akin to the acquisition of trained expertise of fingerprints, Greebles or birds (Busey & Parada, 2010; Gauthier et al., 2000).

1.1 | Measures for documenting emerging HP

To elucidate the profile of HP for written words over development, we adopted two measures to characterize word recognition in a between-subjects design with three groups: children, adolescents, and adults. Selecting measures to index HP is notoriously complex. Paradigms for HP in face perception, for example, the inversion effect and the composite task, have different developmental trajectories, differential sensitivity to experimental manipulations (e.g., Richler & Gauthier, 2014), and are not obviously correlated with each other (Rezlescu et al., 2017) (also [Konar et al., 2010; Ventura, Tse, et al., 2022]). In the current study, we chose two measures of HP, inversion and length effects, as both have been used successfully in studies of HP in adult word reading.

In one example of the use of inversion to index HP of word stimuli (Koriat & Norman, 1985, 1989), participants made lexical decisions on words 2–5 letters in length which were misoriented at different angular rotations from upright through 300 degrees. Performance was significantly adversely impacted with misorientation, and, moreover, this was disproportionately the case for longer than shorter words. Hirshorn and colleagues replicated this misorientation or inversion sensitivity and argued that the stronger the inversion sensitivity (higher HP), the greater the reliance on more holistic lexical, rather than sublexical, information (Hirshorn et al., 2020). Moreover, using functional MRI, they proposed that the left hemisphere lateralization of the Visual Word Form Area, the pre-eminent neural region for word-selectivity, reflects the bias or preference for HP (Ben-Yehudah et al., 2019; Carlos et al., 2019).

In skilled readers, increasing word length has a negligible effect on reading (provided that the word fits into foveal vision and no saccade is needed) (Aghababian & Nazir, 2000). Word length of misoriented (including inverted) words incrementally affects performance adversely arguably because the word is no longer read holistically and, instead, the letters are processed in a piecemeal, part-by-part fashion. This interaction of misorientation and increasing length has been well captured in a study in which adults viewed upright and perceptually transformed text (inverted, but also mirrored or backwards) of different lengths (Björnström et al., 2014). The word length effect, calculated as the slope of reaction time across length, was significantly smaller when words were normally configured but increased significantly for transformations that were less familiar such as a mirrored rotation or backward words. As with acquired expertise, increased exposure to inverted words in adults can lead to a reduction of the word-length effect in this condition (Ahlén et al., 2014).

1.2 | Inversion sensitivity and word length over development

Both inversion and word length effects have been used in some relevant studies with children. For example, one study demonstrated sensitivity to inverted versus upright compound Chinese characters in 4-year-old children, whereas 6-year-olds were sensitive to mirrored compound characters (Zhang et al., 2021). Word length effects also differed across age with second-graders revealing a steep slope as a function of length (approximately 50 ms/letter), and college students showing a negligible effect of word length (Samuels et al., 1978). This was true even when words were presented upright and in the standard configuration (Bijeljac-Babic et al., 2004; Zoccolotti et al., 2005). Aside from a few such studies, there does not seem to be a systematic investigation of the developmental trajectory of HP and orthographic perception and, so, many different predictions can be generated. One obvious prediction is that inversion sensitivity might increase and word length effects might decrease across age and these two factors might interact. A different prediction is that the slope across increasing word length might be equivalent for upright and inverted words (but potentially an intercept change), especially in children who are attending sequentially to just one or a few letters. A third more counterintuitive possibility is that younger children might show an advantage for inverted over upright words relative to older readers. This last prediction derives from the finding that individuals with prosopagnosia, a deficit in face recognition, sometimes perform better than controls in processing inverted faces (Behrmann et al., 2005; Farah et al., 1995). The explanation offered for the prosopagnosic individuals (Van Belle et al., 2011) is that they are impaired at HP and typically recognize faces in a piecemeal, featural fashion when words are upright or inverted.

1.3 | The current study

In sum, the current study was designed to address several questions: what is the emerging profile of HP in word recognition from childhood to adulthood? Is this trajectory evident in and correlated across effects of word inversion and of word-length? Is the emergence of HP related to age and/or to reading competence? And, last, is this emerging sensitivity specific to orthographic input or a result of generally increased perceptual fluency in visual recognition?

To answer these questions, we characterized the orientation sensitivity for upright and inverted words across age using an established index, "inversion sensitivity" (IS), which is calculated for reaction time (RT) as "(median RT inverted words and nonwords)/(upright words and nonwords)", and, for accuracy, as "(accuracy inverted words and nonwords)/(upright words and nonwords)" (Carlos et al., 2019). We then determined whether age and/or reading competence was the relevant explanatory variable, with the latter assessed on a standardized reading test.

We then addressed one final question concerning the origin of the HP profile. One account of the emergence of HP favors an experience-dependent mechanism, with parts of the visual object becoming more holistic with experience (Chua & Gauthier, 2020). An alternative account is that, over development, perceptual efficiency increases across-the board and should thus facilitate the perception of many, if not all, classes of visual objects (Albonico et al., 2018). To adjudicate between these alternatives, we used an object decision task ("is this object real or not?") with upright and inverted common objects for which humans do not have expertise. We used black-and-white line drawings of objects which constitute a rough match to words in image statistics and also activate the pre-eminent word-selective area in adult visual cortex, the Visual Word Form Area (Baker et al., 2007). An overall increase in HP over age for both words and objects would favor a general increase in visual proficiency whereas a more specific account of increased exposure to written words would predict age-related effects for words but not objects.

2 | METHODS

2.1 | Participants

Participants were right-handed, native English speakers all of whom were educated in a school with English as the language of instruction. All had normal or corrected-to-normal vision by self- or parental-report. The adult group consisted of 21 participants (12 females; mean (M) age = 21.7 years, range 20–25 years; Race: 12 Asian, five White, one Hispanic, two Black, one more than one race), the adolescent group consisted of 19 participants (10 females; mean (M) age = 13.6 years, range 10–17 years; Race: 11 White, six Asian, one Black, one more than one race), and the child group consisted of 19 participants (11 females; mean (M) age = 7.8 years, range 7–9 years; Race: 18 White, one Asian). The sample size was based on G*Power calculated for three groups, with a Type-I error rate of 0.05, indicating that a total of 54 individuals was required to detect a medium effect (Cohen's d = 0.5) (Faul, Erdfelder, Buchner, & Lang, 2009). All participants were compensated $10 per session (the adults completed one session, while the children and adolescents completed two sessions). Participants were recruited from a local elementary and middle school, from Carnegie Mellon University, or by word of mouth. Adult participants provided written informed consent, adolescents and children provided assent, and a parent provided consent to the protocol approved by the Institutional Review Board of Carnegie Mellon University.

Prior to the experiment, participants (or their guardians) completed the Edinburgh Handedness Form (scores above 40 indicate a right-handed bias with the highest score of 100) and a survey of demographic information about age, native language, sex, and ethnicity. Participants with a self-reported (or parent-reported) history of reading difficulty were excluded. The mean Edinburgh Handedness score did not differ across group on a one-way Analysis of Variance (ANOVA), $F(2,56) = 0.65$, $p = 0.5$), with scores of 81.8 for adults, 87.9 for adolescents, and 85.9 for children. Any ensuing group differences cannot, therefore, be obviously attributed to differences in handedness across the groups.

2.2 | Materials

All participants completed a lexical decision task and an object decision task, and the children and adolescents completed the Diagnostic Online Reading Assessment in a second session.

For the *lexical decision task*, two lists of words were drawn up, one for adults and adolescents using words appropriate for fourth grade, and one for children, using words appropriate for first grade. In each list, forty words of three, five, and seven letters in length were included. The average frequencies for each length were 3077.2, 122.8, and 29.54 per million, respectively, for adolescents/adults, and 3056.8, 180.4, and 33.1 per million, respectively, for children (see Appendix 1 for list). There were no differences in the frequencies for the two lists. An ANOVA with Grade as a between-subjects factor, Length as a within-subjects variable and Frequency as the dependent measure revealed a main effect of Length, $p < 0.001$, with seven letters words being least frequent, but no interaction of Grade × Frequency, $F < 0.9$. Pronounceable nonwords were matched to each word by changing a single letter (usually vowel) of the words.

Because the number of orthographic neighbors varies as a function of word length (Yarkoni, Balota, & Yap, 2008), we also analyzed the neighborhood values for the two Grade lists as a function of word length. As above, we conducted an ANOVA with Grade as a between-subjects factor, Length as a within-subjects variable and Neighborhood count as the dependent measure (derived from Wall Street Journal Corpus; https://doi.org/10.35111/ewkm-cg47). There was a significant main effect of Length, $F(2,2) = 860.8$, $p < 0.001$, but not of Grade ($p > 0.5$), and no interaction of Grade × Length, $F(2,2) = 2.65$, $p > 0.07$. We also ensured that the items on the two Grade lists were comparable in morphological complexity. Because, to our knowledge, there is no agreed-upon corpus specifying morphological complexity of words, we asked a psycholinguist to rate the words for us as morphologically complex or not (binary judgement). The rating of 1 was assigned to plurals, past tense, agentive, and compound words. A 2 × 3 X^2 analysis of Grade × Complexity score showed no significant interaction, $X^2 = 0.947$, $p = 0.623$.

Last, we examined the distribution of symmetrical lowercase letters in upright and inverted orientation across the two Grade lists. Any difference in the frequency of symmetrical letters might affect performance. For the lowercase letters (x, o, c, l), the total was 127/600 (22.8%) for the 1st and 109/600 (18.2%) for the 4th grade lists and we compared the counts across the 2 Grade lists for each length. These counts did not differ from one another at any length (three letters: $X^2(1) = 0.52$, $p = 0.47$, five letters: $X^2(1) = 1.75$, $p = 0.18$; seven letters $X^2(1) = 1.7$, $p = 0.18$).

In sum, there were no confounds of frequency, neighborhood, morphological complexity or number of symmetrical letters for the 1st and 4th grade word lists, and, as such, any group effects or group × length interactions across age groups is not attributable to any of these factors.

An image of each lowercase word and nonword, in black Arial 18 point font against a grey background, was created in Adobe Photoshop. The images were resized to 640 × 480 pixels. The inverted stimuli were the same word and nonword images but rotated 180°. The upright and inverted lexical decision tasks were presented in separate blocks, with the upright task always presented first.

To ensure that no participant saw the same word twice (e.g., once upright and once inverted), we developed two experimental lists, A and B, with one list containing the upright version of the word and the second list containing its inverted counterpart. Similarly, to ensure that no participant viewed a word and its matched nonword (e.g., "bus" and "bes"), the corresponding nonwords of list A were placed in list B and vice versa. The stimuli were randomized within block for each participant. This resulted in 60 experimental trials for each of the upright and inverted blocks, reflecting the orthogonal crossing of lexical status (word/nonword) and length (3, 5, 7 letters) for a total of 120 trials. For both the upright and inverted tasks, twelve practice trials were presented first, with two trials of each length × word/nonword in randomized order (none of which are included in experimental items).

In the *object decision task*, the stimuli were black and white line drawings (Gerlach, Law, Gade, & Paulson, 1999; Gerlach & Poirel, 2018; Snodgrass & Vanderwart, 1980), half of which were manmade and half natural objects. Each non-object was formed by pairing two halves of two different real objects (e.g., the head of a mule with the back end of a fox). The images were presented on a white background and resized to 640 × 480 pixels. The inverted objects were the same images but rotated 180°. As with the lexical decision task, the matched real and non-object were assigned to different lists so that no participant saw both versions of the same item. For each of the upright and inverted object decision tasks, there were 44 experimental trials with 11 trials of each type of object (real/non-real × natural/ manmade), for a total of 88 trials. The stimuli were randomized within block for each participant. Twelve practice trials, with three trials of each type of object, were presented first, followed by the experimental trials.

For both the lexical and object decision tasks, if a participant's mean RT fell more than 2SDs from the mean of the cell of the age group, it was replaced with the smallest or largest value closest to it from that cell. Winsorized data occurred roughly equally in all groups, and, together, accounted for 6.7% of trials.

The *Diagnostic Online Reading Assessment* (DORA), a standardized reading test, was used to characterize the reading ability of the participants (shop.letsgolearn.com/shop/store/product/dora-diagnostic-online-reading-assessment). The test consists of tasks such as typing words read aloud by the program[1], and choosing pictures corresponding to the meanings of words. The DORA has been benchmarked against the SBAC English Language Arts (ELA) for third graders and has been shown to not only match the SBAC ELA but to provide

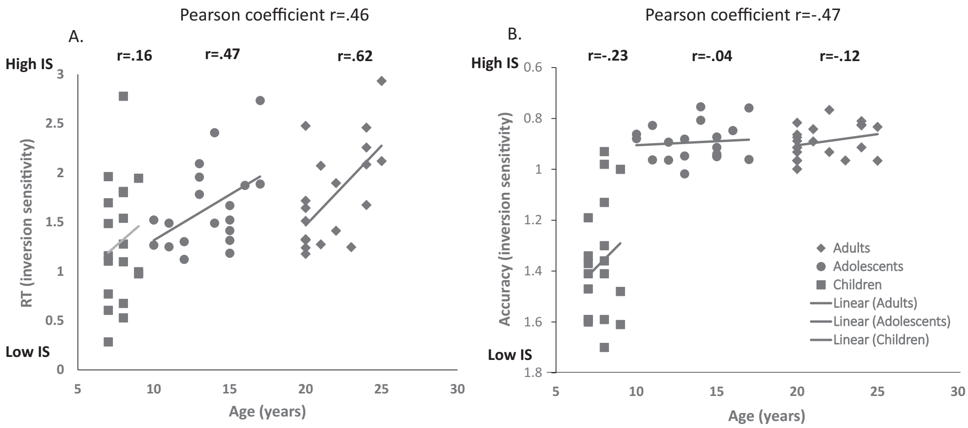

FIGURE 1 Scatterplot of inversion sensitivity (y-axis) in lexical decision as a function of age (x-axis) separately for adults, adolescents and children with the linear fit plotted per group. (a). Inversion sensitivity in RT. (b). Inversion sensitivity in accuracy (note reversed scale).

a more nuanced view based on the collection of its subtests. We used six of the 11 subtests which provide numeric scores, including high frequency word (HF), word recognition (WR), phonics (PH), spelling (SP), word meaning (VO), and silent reading (CO). A Weighted Score (WS) of the subtests was used as a summary score.

2.3 | Procedure

The consent and assent forms were signed prior to start of the experimental session. The experiments, using the Tellab platform (https://lab.tellab.org/), and the DORA were presented remotely and the experimenter remained present on Zoom throughout the session, providing instruction and encouragement as needed. If needed, the parent/guardian was present initially to assist with seating, adjusting screen position as necessary, comprehending instructions, and assisting completion of practice trials if needed.

For children and adolescents, the order of the DORA and the lexical and object decision tasks was counterbalanced. Participants were assigned to list A or list B for both the lexical and object decision tasks with counterbalancing such that half completed the object decision task first (upright followed by the inverted version) whereas the other half completed the lexical decision task first (upright followed by the inverted version). Participants were instructed to determine, as quickly and as accurately as possible, whether or not the presented letter string or picture was a real word or a real object, respectively. Half of the participants pressed "r" and "n" on the keyboard with the left and right index fingers, respectively, while the other half used the reverse mapping. Participants were told not to tilt their heads in the inverted experiments–this was monitored by the experimenter and participants were reminded of this during the experiment.

The lexical and object decision blocks were preceded by practice trials. No feedback was offered during the experimental blocks but coaching, as needed, and feedback was provided during the practice trials.

2.4 | Results

First, we compare the results of the lexical decision task across groups and confirm this result in a further analysis with age as a continuous variable. We then explore the effect of length for words and nonwords, both upright and inverted, and examine correlations with reading proficiency. Last, we report accuracy and RT in object decision, and correlate performance with that of lexical decision.

2.4.1 | Inversion sensitivity: Lexical decision

Inversion sensitivity over age

This first analysis used inversion sensitivity (IS) (Carlos et al., 2019) as the dependent measure, calculated from RT and then from accuracy (see Figure 1a and b). Note that, for RT, *larger* numbers reflect higher inversion sensitivity (either because inverted trials are responded to more slowly or upright trials are responded to more quickly), whereas, for accuracy, *lower* scores indicate higher inversion sensitivity (either because inverted trials are responded to less accurately or upright trials are responded to more accurately). For ease of comparison, we have reversed the y-axis on Figure 1(b) (IS accuracy) so that, in both the RT and accuracy graphs, higher IS is shown towards the top of the graph and lower IS towards the bottom of the graph.

With RT as the dependent measure, a one-way ANOVA revealed a significant difference across groups, $F(2,56) = 4.02$, $p = 0.02$, $\eta^2{}_p = 0.13$, with a mean IS of 1.74 in Adults, 1.65 in Adolescents and 1.29 in Children (see Figure 1a). On subsequent pairwise tests, whereas there was no significant difference between Adults and Adolescents, $F < 0.1$, there was a significant difference between Adults and Children, $F(1,38) = 6.4$, $p = 0.016$, $\eta^2{}_p = 0.144$, and between Adolescents and Children, $F(1,36) = 4.3$, $p = 0.05$, $\eta^2{}_p = 0.10$. The results were replicated using accuracy (see Figure 1b with reversed scale): there was a significant difference across groups, $F(2,56) = 16.9$, $p < 0.001$, $\eta^2{}_p = 0.38$, with IS scores of 1.14, 1.13 and 1.37 for Adults, Adolescents

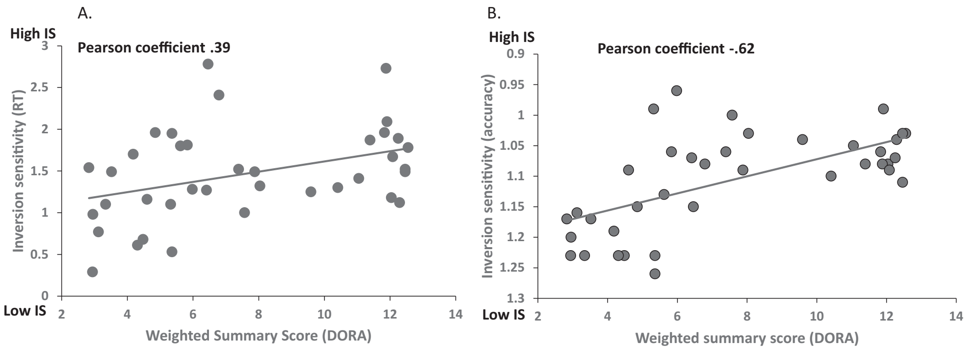

FIGURE 2 (a). Scatterplot and linear fit of the correlation between RT inversion sensitivity scores and the Weighted Summary Score of the Diagnostic Online Reading Assessment (DORA). (b). Scatterplot and linear fit of the correlation between accuracy inversion sensitivity scores and the Weighted Summary Score of the DORA (shown here as *positive* on the reversed y-axis to match the figure in a).

and Children, respectively. Whereas the difference between Adults and Adolescents was not significant, F < 0.1, both groups differed from children: Adults and Children, F(1,34) = 18.9, $p = 0.001$, $\eta^2_p = 0.33$, and Adolescents and Children, F(1,36) = 18.4, $p < 0.001$, $\eta^2_p = 0.34$.

To explore the effect of age further, a regression analysis with age as a continuous variable and RT as the dependent measure revealed a Pearson correlation of = 0.46 ($p < 0.05$). Note also that, within each of the three age groups (see linear fit for each group in Figure 1), there was also a significant positive relationship between RT and age except in the group of Children whose age range was more narrow than the other groups, spanning only ages 7–9 years (Pearson correlation: Children = 0.16, Adolescents = 0.47, Adults = 0.62). This result also held using accuracy as the dependent measure with a Pearson correlation of = −0.47 ($p < 0.001$), although the within-group indices revealed no statistically significant correlation of age and IS within any of the age groups (all > $p = 0.1$) (see Figure 1b).

Inversion sensitivity and reading competence

If HP is a product of experience and proficiency in word recognition, rather than age per se (Ventura et al., 2020a; Wong et al., 2011; Wong et al., 2019), then we might expect a correlation between IS and scores on a test of reading competence. Adolescents and Children (n = 38) completed the DORA, a standardized test designed for readers in grades K-12. We derived scores from six subtests for which values are available, as well as a weighted score across these subtests. Both the RT and Accuracy IS score were significantly correlated with the Weighted Summary Score ($p < 0.03$ for RT; $p < 0.002$ for accuracy) as shown in Figure 2(a) and (b) (note again that, for accuracy, IS is shown on a reverse scale to match the RT figure). These correlations indicate that the higher the RT IS and/or the lower the Accuracy IS, the better the reader, reflecting a strong association between IS and reading competence. Also, the IS in RT and accuracy were correlated with most subtests, as shown in Table 1. The significance of the correlation values reflects subtests that survive a family-wise Bonferroni correction, generally indicating a strong association between reading proficiency and IS.

Effects of word length across age group

Thus far, we have shown that HP, measured using IS in lexical decision is associated with age and with reading skill. Here, across the three groups, we assess another index of HP, namely, the impact of word length on lexical decision (Björnström et al., 2014). For this analysis, the RT and accuracy of lexical decision for each of three, five and seven letter strings were calculated per participant for upright and inverted words and nonwords. Then, a repeated measures ANOVA was conducted with Length (three, five, seven), Orientation (upright, inverted) and Stimulus (word, nonword) as within-subjects measures and Group as a between-subject measure. Because our central interest concerns differences across Groups and the effect of Length, we focus on these factors and on any interaction with these factors (for the complete within-subjects ANOVA F-tables, see Appendix 2).

The four-way ANOVA with RT revealed a significant main effect of Group (F(2,56) = 18.6, $p < 0.001$, $\eta^2_p = 0.4$), and a significant effect of Length (F(2,112) = 43.9, $p < 0.001$, $\eta^2_p = 0.44$), but no other interaction of Group × Length or any higher-order interactions with these variables (all $p > 0.05$). The same analysis, with accuracy as the dependent measure, revealed an effect of Group (F(2,55) = 26.8, $p < 0.001$, $\eta^2_p = 0.49$) and of Length (F(2,4) = 8.5, $p < 0.001$, $\eta^2_p = 0.363$), which were qualified in a Group × Length interaction (F(4,110) = 7.71, $p < 0.001$, $\eta^2_p = 0.22$) (see Figure 3). As shown in Figure 3, there was no difference in the mean slope for the Adults and Adolescents (Slope: Adults = 0.0046; Adolescents = 0.013) but both groups differed from the mean of the Children who had the steepest downward slope (0.027; $p < 0.05$). There was also a trend towards an interaction of Group × Length × Stimulus, (F(2,55) = 2.1, $p < 0.08$, $\eta^2_p = 0.07$). We were unable to assess whether this Group × Length interaction was mediated by reading competence as the DORA standardized test was not designed for Adult readers (but see below for related data). Note that there was also a significant interaction of Group × Stimulus × Orientation, (F(2,55) = 9.6, $p < 0.001$, $\eta^2_p = 0.26$), but this is already captured above in the IS measure.

TABLE 1 Correlation values (and *p* value) between inversion sensitivity and subtests and summary score of the DORA.

	High frequency word (HF)	Word recognition (WR)	Phonics, word analysis (PH)	Phonemics awareness (PA)	Word meaning (VO)	Silent reading (CO)
RT inversion sensitivity	0.45[a]	0.48[a]	0.38[b]	0.36[b]	0.35	0.43[a]
Accuracy inversion sensitivity	−0.29	−0.67[a]	−0.50[a]	−0.69[a]	−0.49[a]	−0.60[a]

[a]Significant with Bonferroni correction.
[b]Marginally significant with Bonferroni correction.

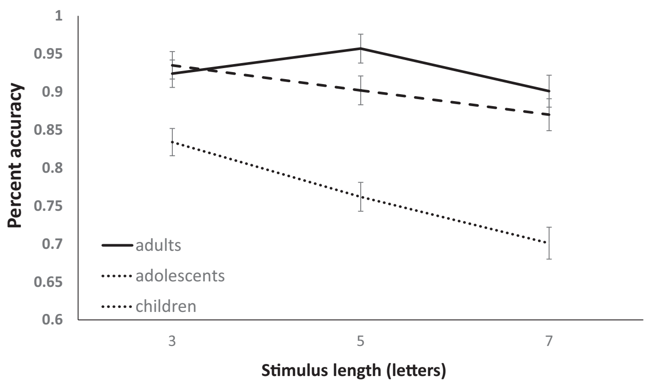

FIGURE 3 Mean percentage accuracy (and 1SE) on lexical decision for the three age groups as a function of the length of the stimulus.

Correlation of inversion sensitivity and word length

This analysis examines specifically whether HP, defined using IS of lexical decision (in RT and/or accuracy), is associated with the effect of string length on performance. If so, this provides additional evidence for HP in word perception. Here, we correlated IS with the slope calculated for words and nonwords in each of upright and inverted orientations over length (3, 5 and 7 letters), with high IS for the accuracy again plotted upwards in the graph to mirror the pattern in RT.

Because of the number of correlation tests, we used a familywise correction ($p < 0.005$) to determine significance. With age partialled out (to permit more specific correlation of the indices) and RT as the dependent measure, there was a significant association between inversion sensitivity and slope across length for inverted words (0.55, $p < 0.001$) revealing that the better the reader, the steeper the slope (see Figure 4). No association survived correction with accuracy as the dependent measure. When the DORA weighted summary score was partialled out, the significant association of IS in RT with the slope across length for inverted words also held (0.53, $p < 0.001$) and no association survived correction with accuracy as the dependent measure. Results indicate that HP is well captured not only by the IS index but also by speed of lexical decision across string length (RT) and that the two metrics are reliably associated with each other even after partialling out age or reading competence.

Summary of lexical decision

Several findings emerge from the lexical decision task: (1) inversion sensitivity increases both when age is considered as a discrete and as a continuous variable; (2) inversion sensitivity and reading proficiency on a standardized reading test are correlated; (3) in Children primarily, word length has a statistically significant effect on performance; and (4) inversion sensitivity is associated with the slope of string length on RT for inverted words – the better the reader, the steeper the slope. Together, these results characterize the developmental trajectory of HP of orthographic stimuli.

2.5 | Inversion sensitivity: Object decision

Inversion sensitivity as a function of age

The final question is whether the pattern of inversion (IS) is specific to the perception of orthographic strings or results from more general visual maturation or increased experience (Chua & Gauthier, 2020; Richler et al., 2017). A one-way ANOVA was conducted with IS calculated from the object decision task (using the same metric as in Carlos et al., 2019, and in lexical decision above) and Group as the between-subjects factor. This was done first with RT and then with Accuracy as the dependent measure. There were no significant differences as a function of Group for either RT or accuracy measure $p > 0.05$ (see Figure 5a and b), suggesting that higher IS as a function of age is specific to words and not a product of generalized maturation of the visual system or of a domain-general visual ability (McGugin et al., 2012; McGugin et al., 2022).

To pit the object decision results directly against the lexical decision results, an ANOVA was conducted with task as a within-subject measure (see Figure 5). With RT IS as the dependent measure, there was a significant interaction of Task, ($F(1,56) = 62.8$, $p < 0.001$, $\eta^2_p = 0.53$), a marginal effect of Group, ($F(2,56) = 4.0$, $p < 0.05$, $\eta^2_p = 0.082$) and an interaction of these variables ($F(2,56) = 3.6$, $p < 0.035$, $\eta^2_p = 0.159$). With accuracy of IS as the dependent measure, there was a significant effect of Task ($F(1,56) = 179.1$, $p < 0.001$, $\eta^2_p = 0.76$), but not of Group, ($F > 1$), and their Interaction ($F(2,56) = 5.8$, $p < 0.01$, $\eta^2_p = 0.174$). The presence of a dissociation in performance in the two tasks indicates that specific, rather than general, experience likely accounts for the age (and proficiency-related) effects in the emerging HP for words recognition.

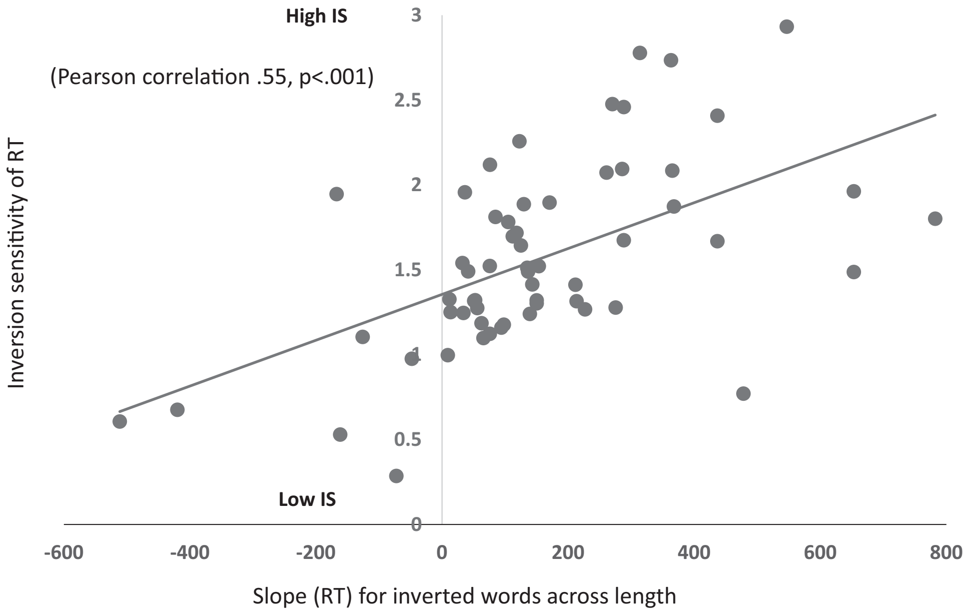

FIGURE 4 Scatterplot and linear fit of the correlation between inversion sensitivity for RT and slope across length in RT for inverted words. The influence of age was partialled out of this correlation.

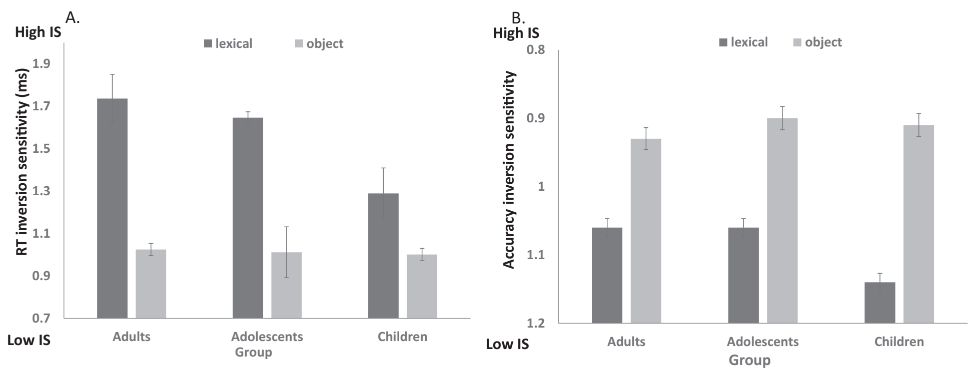

FIGURE 5 (a): RT inversion sensitivity (and 1SE) for lexical and object decision as a function of Group. (b): Accuracy inversion sensitivity (and 1SE) for lexical and object decision as a function of Group.

3 | GENERAL DISCUSSION

Although the emergence of holistic processing (HP) over development has been well documented in the context of face recognition (Mondloch et al., 2003, 2002), whether a similar trajectory applies in the context of word recognition is not known. The results of the current study suggest that this is the case and that expertise, either attained incidentally (for faces) or generally acquired through explicit training (for words), manifest the same characteristics.

We have characterized the emergence of HP for word processing from childhood to adulthood using two established measures of HP, one assessing the relative advantage for reading upright over inverted words and nonwords, and the other is revealed by the effect of word length on lexical decision performance. The developmental trajectory was correlated both with age but also with reading proficiency, independent of age. Last, this HP developmental profile was specific to orthographic perception as there was neither an effect of age on object decision nor a correlation between performance on the lexical decision and on object decision tasks. Together, these findings reinforce the claim that HP is increasingly engaged with greater experience with a class of visual stimuli and is not merely a function of enhanced visual perception with increasing age.

3.1 | HP in orthographic processing

Our findings using inversion sensitivity and word length in lexical decision mirror those of the studies that have been done with adults. In one such study, readers who learned to read in Chinese (which requires HP) showed a bias for holistic or lexical coding when reading upright versus inverted words in English, while those who learned to read in Korean (does not require HP) showed a bias towards adopting more analytic or sublexical procedures. The key outcome was that the Chinese readers took longer than the Korean readers to read inverted words while the groups performed comparably on the upright words (Ben-Yehudah et al., 2019). The possible interference of HP on inverted word reading parallels the results reported in this paper. Similarly, a correlation was found between configural sensitivity and fluency for written words in a group of exchange students learning Chinese (Wong et al., 2019).

The data from the word length effect, with lower accuracy across length on Children, are also consistent with the findings of substantial word-length effects in second-graders but a negligible effect in college students (Samuels et al., 1978). This differential impact of length across age is, however, modulated by the stimulus (word versus nonword) which is also manifest in the relationship between IS (in RT) and slope — the higher the IS (better reader), the steeper the slope across length (see Figure 4). Such a result might seem counterintuitive given that older individuals show less of an effect of length on their reading. The key finding here is that the better the reader, the steeper the slope for inverted nonwords. This finding is similar to that observed during inverted face recognition:increasing expertise along with the bias for HP interferes with the recognition of inverted faces which do not benefit from HP, and are typically processed in a more sequential or piecemeal fashion (but see (Meinhardt-Injac et al., 2014) for some controversy about these claims). A similar account can be offered here:better readers with a stronger bias to HP are adversely affected to a greater degree than less proficient readers for inverted stimuli (Van Belle et al., 2011).

Our results are seemingly at odds with findings that HP follows a non-monotonic U-shaped function. As has been documented, when children learn Chinese character recognition (Tso et al., 2022), younger, but not older, children perceive a small number of Chinese characters holistically (Tso, Au, & Hsiao, 2014) and attend to all input equally at the onset of reading (Hsiao & Cottrell, 2009). A similar inverted-U trend has also been proposed to apply in the case of face recognition (Hsiao & Galmar, 2016). Then, once children learn to write, they begin to appreciate the orthographic structure of the Chinese characters, enabling them to process the characters more sequentially or componentially (Tso et al., 2022). An account that resembles this has also been offered for English word reading (which is alphabetic) with early readers engaging in logographic reading and recognizing a limited number of familiar words with no awareness of grapheme-phoneme correspondences. Following this, readers begin to develop alphabetic skills and phoneme awareness and, last, the mature reader is able to recognize many words and does so automatically and quickly (Frith, 1985). These U-shape functions suggest that learners need to know enough items (words) in order to work out or bootstrap the statistics of how parts behave (for example, bigrams or trigrams or even whole words).

Although a U-shaped function seems eminently explainable, it is not easy to reconcile the “first more holistic, then more analytic processing” with our findings. Both the IS and word length measures are not clearly compatible with a discrete staged account. One way to reconcile these views is to acknowledge that both HP and the local parts or elements play a role (Bartlett & Searcy, 1993; Burton et al., 2015), perhaps with differential weighting at different ages. On this last view, global holistic and local featural approaches may both play a crucial but complementary role; for example, using a Garner interference paradigm, both configural and featural information in face perception can be uncovered (Kimchi et al., 2012) and perhaps a similar paradigm might be exploited to evaluate the simultaneous adoption of HP and featural processing in the context of word perception and its trajectory over development. Also, adopting an approach that allows one to evaluate compositionality, both behaviorally and neurally, by designing many objects from predefined components, might uncover the nature of computations for both words and faces (Arun, 2022).

3.2 | Same holistic mechanism across visual classes?

HP in face perception has been documented in hundreds of studies in both children and adults (Richler et al., 2011; Richler & Gauthier, 2014). To complement the few studies on HP and word perception in adult participants (Ventura et al., 2019), we document the trajectory of acquisition across development, and the findings are highly compatible with existing data on the developmental emergence of HP in face perception (Mondloch et al., 2003; Sun et al., 2020). This consistency is interesting given the differences in the way expertise or proficiency is acquired, with faces acquired incidentally and words (usually) by explicit instruction. Both routes apparently lead to expertise. Mere occasional exposure, however, may not suffice as we do not see comparable inversion effects for black-and-white drawings of common objects.

There are now many demonstrations of HP with expertise for other classes of visual objects. Aside from fingerprints and Greebles, as indicated above, expertise for several other classes has been reported, for example, for mammogram inspection, cars, dogs (McGugin et al., 2012; Richler et al., 2017) and even chessboard configurations (Boggan et al., 2012). The profiles of expertise for these different classes also evince the same traits:poorer perception with inversion and a decrement in processing following some alteration of the parts (such as reconfiguring the arrangement of parts). Word perception may well fall into the same set of visual classes with the additional constraints that the instruction is offered to large swaths of the population (albeit not to everyone) and the exposure starts relatively early in life (typically school-going age).

3.3 | Same mechanism/s for faces and words?

Recently, the argument has been made that face and word recognition share the same computational principles. We have shown here that this, at least at first glance, appears to be the case, and that this may apply to the neural mechanisms, as well. This finding is consistent with the claim that, in contrast with many classical studies in neuropsychology reporting highly selective deficits in word or face recognition, unilateral damage to posterior visual cortex often results in an impairment in both face and word perception (Behrmann & Plaut, 2014; Rice et al., 2021), implicating more neural overlap than considered previously (but see (Robotham & Starrfelt, 2017)). Also, individuals with "congenital prosopagnosia", a lifelong deficit in face perception in the absence of neural damage, also appear to have an impairment in word reading (Collins et al., 2017), and the converse holds for those with developmental dyslexia (Sigurdardottir et al., 2015).

A further source of support for the overlap in HP for words and faces comes from a host of ERP studies. Previously, HP for faces has been ascribed to the derivation of holistic information at an early phase of visual perception as reflected in the early N170 evoked response potential component (Jacques & Rossion, 2009). More recently, a similar early signature has been demonstrated for Chinese character recognition (Chen et al., 2013), also indicating the representation of HP in early perceptual processing (Ventura et al., 2022). Taken together, these findings suggest at least some commonalities between the acquisition of face and word perception and the engagement of HP in both cases, although data comparing the acquisition of face and word representations and the emerging HP should be characterized in the same participants longitudinally (for cross-sectional examples, see (Dundas et al., 2013, 2014)) for further confirmation of the overlap across classes within-individual.

One account that may explain the similarities as well as the difference is that in which, prior to the acquisition of literacy at around age 5 or 6 years for most children, both the right and left hemisphere posterior cortex is tuned to represent faces. Once literacy is acquired, however, the left hemisphere becomes increasingly optimized to connect visual regions and language areas (with language being left lateralized in the majority of the population). As the left hemisphere attains superiority (but not exclusively so) for representing words, so, by virtue of competition, the right hemisphere is increasingly optimized for the representation faces of (Behrmann & Plaut, 2020; Blauch et al., 2022).

But one observation offers a reason for pause. If face and word perception both rely on HP and both share at least some aspects of the underlying neural mechanism, one might have predicted that HP might generalize from the incidental learning of faces to the more labored acquisition of word perception. This observation suggests that there are distinctions between HP for different stimulus types and just as we do not see any association between inversion sensitivity in lexical decision and object decision, HP for face and word perception seem not to be fully generalizable.

3.4 | Limitations and future considerations

Needless to say, there are some clear limitations of the current study and implications for future studies. One possibility is that the variability we have identified across individuals might be a product of the way the data were acquired–because of the Covid-19 pandemic, the data were collected remotely, although the data for all the experiments were collected on the same equipment within each participant. Nevertheless, differences in screens, size of stimuli and distance from the screen, among other factors, might have had some effect on performance (and potentially even, artifactually between groups). A replication of the experiments with more standard data collection procedures might be warranted. Future studies might also focus directly on differences in the developmental trajectory of children learning to read more logographic versus more alphabetic languages, which might have a different developmental cascade and a different weighting of holistic versus more elemental processing. In a similar fashion, examining featural/letter and configural/holistic information would provide insight into the separability versus integrality of this information using a task like Garner's speeded classification (Kimchi et al., 2012) and perhaps the differential balance of these abilities over age. While we have focused on inversion in these experiments, all of which occurs across the horizontal plane, understanding the relationship between different transformations such as inversion across the vertical domain might shed light on mirror reversals (reading "dog" as "bog" or even as "god") and particular atypical reading profiles, especially in younger children. Last, evaluating further whether the behavioral and neural profile that underlies face and word recognition are similar or different would be of interest as well, and further exploration of differences in the neural code of the two hemispheres over development would be valuable (Carlos et al., 2019).

4 | CONCLUSION

In order to document the detailed trajectory of the emergence of holistic word processing (HP) over development, we examined inversion sensitivity in lexical decision in adults, adolescents and children. Not only did we observe an increment in HP with age, but also with reading proficiency, highly suggestive of an experienced-based or expertise effect. There was no correlation between IS in lexical decision and common object decision, suggesting that the observed emergence of HP is likely an outcome of specific experience rather than of a general refinement of visual perception over time. We interpret the findings in the context of the generalizability of HP and the overlap between mechanisms of word recognition and face recognition given that both appear to follow the same trend of emergence. We conclude that direct evaluation between different classes of visual stimuli, ideally in within-subject longitudinal studies, will advance our understanding of the psychological and neural mechanisms that support complex visual pattern recognition.

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CONFLICT OF INTEREST

The authors have no conflicts to report.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available upon reasonable request from the corresponding author.

ETHICS STATEMENT

The protocol adopted was approved by the Institutional Review Board at Carnegie Mellon University.

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ENDNOTE

[1] Note that the children were all receiving schooling on-line and typing their schoolwork. Additionally, their typing scores were consistent with other non-typed scores and so typing was not a complicating aspect of the study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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