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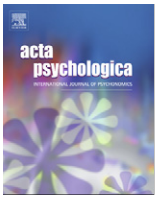

Letter-specific processing in children and adults matched for reading level

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Expert readers perform faster and more accurately during tasks that involve letters from the known language compared to tasks that involve unfamiliar letter-like forms (e.g., pseudoletters). Previous work with typically developing participants suggests that this letter-specific processing emerges as a consequence of increased reading ability, rather than increased age. In contrast, others have suggested that adults rely on visual information to a greater extent than children when reading, despite reading at similar less-than-expert levels, implying that adults may exhibit greater letter specificity than children. The present study aimed to discriminate between these possibilities by comparing the advantage for letters over pseudoletters in children and adults reading at the same less-than-expert (fourth grade) level. Results revealed greater letter specificity in adults than in children in both error rate and response time measures. Moreover, the magnitude of letter specificity did not vary with reading ability. Thus, results suggest that adults are more sensitive than children to the visual forms of letters, and that differences in letter specificity are not necessarily dependent on reading skill.

1. Introduction

A large body of research indicates that expert readers perform faster and more accurately during tasks that involve letters from the known language compared to tasks that involve unfamiliar letter-like forms (e.g., pseudoletters: Ambler & Proctor, 1976; Burgund, Lugar, Schlaggar, & Petersen, 2005; Burgund, Schlaggar, & Petersen, 2006; Jackson, 1980; Kim, 1996; LaBerge, 1973; Lachmann & van Leeuwen, 2004; van Leeuwen & Lachmann, 2004). This finding is not surprising given the frequent exposure to letters that individuals in literate cultures experience daily, and the immense social and economic importance of letters and words in the modern environment. Moreover, it is in line with theories of perceptual expertise that argue that skilled processing of certain classes of visual stimuli drives the tuning of perceptual mechanisms towards those forms (Gauthier, Skudlarski, Gore, & Anderson, 2000; McCandliss, Cohen, & Dehaene, 2003; Tanaka & Curran, 2001; Tarr & Gauthier, 2000), and with evidence that neural regions within the left occipito-temporal cortex respond preferentially to real letters compared to non-letter forms, such as pseudoletters (Price, Wise, & Frackowiak, 1996), unfamiliar characters (James, James, Jobard, Wong, & Gauthier, 2005; Pernet, Celsis, & Démonet, 2005), and faces (Puce, Allison, Asgari, Gore, & McCarthy, 1996).

Although the majority of evidence supporting behavioral and neural specialization for letters compared to non-letter forms comes from studies of adult populations (e.g., college undergraduates), recent results from a developing sample (6–19-year olds) suggest that letter-specific processing emerges with increased reading ability rather than with development per se (Burgund et al., 2006). In this study, participants decided whether pairs of letters or pairs of pseudoletters were the same (e.g., AA) or different (e.g., AB). Not surprisingly, participants were faster at matching real letters than matching pseudoletters. Critically however, when participants were equated in terms of reading ability, the advantage for letters compared to pseudoletters did not differ between older and younger participant groups. In contrast, when participants were equated in terms of age, high-ability readers exhibited a greater advantage for letters compared to pseudoletters than low-ability readers. Based on these results, Burgund et al. concluded that skilled processing, rather than maturation per se, drives the specialization of perceptual mechanisms for letters.

One prediction that stems directly from this conclusion is that adults who read at a less-than-expert level (i.e., illiterate or semi-literate adults) should exhibit differences between letters and pseudoletters that are similar to those exhibited by children reading at the same less-than-expert level. That is, if the advantage for letters over pseudoletters emerges entirely as a function of increased reading ability, and not as a function of increased age, individuals who read at the same level should exhibit similar amounts of letter-specific processing, regardless of their age. Indirect

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support for this prediction comes from studies in which illiterate adults and pre-literate children (3–5-years old) could not detect letter inaccuracies within highly familiar environmental signs (e.g., *McDonald's, Coca-Cola*: Cardoso-Martins, Rodrigues, & Ehri, 2003; Masonheimer, Drum, & Ehri, 1984). For example, despite being able to accurately identify familiar signs, neither children (Masonheimer et al., 1984) nor adults (Cardoso-Martins et al., 2003) were able to reliably detect incorrect letters within the signs (e.g., *'L'* in *Loca-Cola*), even when instructed explicitly to do so. Thus, even though illiterate adults had gained more exposure than children to environmental print throughout life, they did not attend to individual letters to a greater extent. In line with predictions from Burgund et al. (2006), this suggests that visual processing mechanisms do not become sensitive to the visual forms of letters until actual reading skills have been acquired.

In contrast to this perspective, others have emphasized differences in the ways that child and adult learners process written words (Hoffman, 1978; Perin, 1988). In particular, while child learners rely strongly on phonological information when reading, adult learners appear to rely more on visual/orthographic information (Greenberg, Ehri, & Perin, 1997, 2002; Thompkins & Binder, 2003). For example, in a direct comparison of children and adults determined to read at similar levels, adults were impaired relative to children at tasks demanding phonological processing (e.g., nonword reading), whereas children were impaired relative to adults at tasks demanding visual/orthographic processing (e.g., reading phonologically irregular words such as 'ocean' and 'iron'; Greenberg et al., 1997). This result suggests that, despite reading at equivalent levels, adults are more sensitive than children to visual information when reading. As such, adult learners may exhibit greater selectivity than child learners for letters compared to visually equivalent pseudoletters.

The present study was designed to discriminate between these possibilities. Accordingly, children and adults reading at similar less-than-expert levels, as assessed through the Word Identification subtest of the Woodcock Reading Mastery Test – Revised (WRMT-R; Woodcock, 1987), performed a letter and pseudoletter-matching task, similar to that used by Burgund et al. (2006). If the advantage for letters over pseudoletters emerges entirely as a function of increased reading ability, as hypothesized by Burgund et al., children and adults should exhibit similar amounts of letter specificity, and individual variation in this specificity should correlate positively with reading ability. In contrast, if adults rely on visual processing strategies to a greater extent than children, as argued by others (e.g., Greenberg et al., 1997, Greenberg, Ehri, & Perin, 2002; Thompkins & Binder, 2003), adults should exhibit greater letter specificity than children, despite the groups' equivalent reading abilities, and individual variation in letter specificity should not correlate with reading ability.

2. Method

2.1. Participants

Thirty adult participants were recruited from an adult literacy program in Houston, TX. Participants were between 18 and 60 years of age and were native speakers of English. Prior to participation, participants completed a detailed questionnaire assessing their medical history, and participants reporting any neurological or psychiatric problems, including stroke, epilepsy, closed head injury, severe depression, bi-polar disorder, and schizophrenia, were excluded from the sample. This screening reduced the sample size by one third. Thus, 20 adult participants were included in the present analysis. Half of the participants were male, and half were female. Their average age was 35 years (standard deviation = 13; range = 18–60). Adult participants gave informed consent in accordance with the guidelines and approval of the Rice University Institutional Review Board prior to participation.

Twenty-three child participants were recruited from the greater Houston area. Participants were between 6 and 12 years of age and were native speakers of English. Parents of child participants completed a detailed questionnaire assessing their medical history, and children with neurological or psychiatric problems were excluded from the sample. Only 1 participant was excluded based on this medical screening. Thus, 22 child participants were included in the present analysis. Of these, 9 were male, and 13 were female. Their average age was 9 years (standard deviation = 2; range = 6–12). Parents of child participants gave informed consent in accordance with the guidelines and approval of the Rice University Institutional Review Board prior to participation.

All participants were compensated $10 per hour of participation. The total amount paid to each participant ranged from $10–$20.

2.2. Materials

Stimuli were pairs of letters and pairs of unfamiliar pseudoletters. Eleven letters (D, E, F, G, K, M, P, Q, S, T, and Y) were selected from the Roman alphabet. Letters were presented in Geneva font, and only upper-case versions were used. Pseudoletters were created from letters by moving one or two lines to a different location. For example, as illustrated in Fig. 1, the pseudoletter for the letter 'D' was created by moving one line to a different location, and the pseudoletter for the letter 'E' was created by moving two lines to different locations. Thus, stimuli were 11 letters and their 11 pseudoletter counterparts (see Fig. 1). Paired *t*-tests comparing

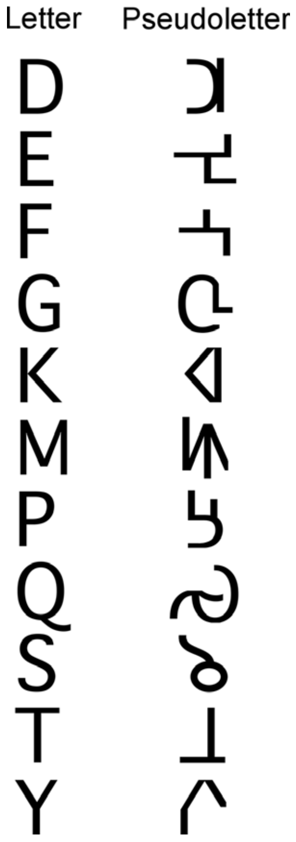

Fig. 1. Letters and their pseudoletter counterparts. Pseudoletters were created from letters by moving one or two lines to a different location (see text for details). For example, the pseudoletter for 'D' was created by moving one line; the pseudoletter for 'E' was created by moving two lines.

letters and pseudoletters in terms of numbers of lines, line junctions, and enclosed spaces did not reveal significant differences between the stimulus types (all *ps* >.340); thus letters and pseudoletters were similar in visual complexity. All pairs were presented centrally, in white against a black background. Individual letters and pseudoletters subtended approximately 1.5° × 1.5° of visual angle. Letter and pseudoletter pairs subtended approximately 1.5° × 3.5° of visual angle in the vertical and horizontal dimensions, respectively. Presentations and response time measurement were controlled by the PsyScope software package (Cohen, MacWhinney, Flatt, & Provost, 1993; http://psy.ck.sissa.it).

The letter/pseudoletter-matching task was divided into two blocks of trials with a short break (~ 1 minute) in between. Each block contained 44 trials, half of which were letter pairs, and half of which were pseudoletter pairs. Within each type of trial, half were the "same" (e.g., D D), and half were "different" (e.g., D F). All possible "same" pairs were presented in each block. Different pairings were used for the "different" pairs in each block. "Different" pairs were created arbitrarily with the constraints that (1) all letters were used across all pairs for each subject, (2) each letter participated in eight different pairings across subjects (e.g., 'D' was paired with 'F', 'G', 'K', 'M', 'P', 'Q', 'S', and 'T'; see Appendix), and (3) all pairings had relatively low visual similarity ratings (less than 350 on a 100–500 scale), as determined from the values provided by Boles and Clifford (1989). To ensure that pairs had comparable levels of similarity in letter and pseudoletter conditions, the same pairings of letters and pseudoletters were used across subjects. For example, the "different" pair 'D F' was presented in its letter form for one subject and in its pseudoletter form for another subject. Trials were randomly intermixed with the constraint that no more than 3 of the same type (letter/pseudoletter or "same"/"different") appeared in a row.

2.3. Procedure

Participants were tested individually in a single session lasting 1–2 h. At the beginning of the session, participants performed the letter/pseudoletter-matching task. Each trial began with the presentation of a fixation cross (+) for 1 s. Immediately after, a letter or pseudoletter pair was presented for 250 ms and followed by another cross, which remained on the screen until a response was recorded. For each stimulus pair, participants were instructed to decide whether items within the pair were the same or different, and to indicate their response as quickly and accurately as possible by pushing a key on the keyboard. Participants pushed the 'p' key (or 'q' key) with the index finger of their right (or left) hand to indicate a "same" response, and the 'q' key (or 'p' key) with the index finger of their left (or right) hand, to indicate a "different" response. The hand (left vs. right) used to indicate a "same" response was counterbalanced across participants. Participants engaged in 10 practice trials before beginning the task to ensure that they understood the instructions.

After the matching task, participants completed the reading ability assessment. Following Greenberg et al. (1997, 2002), reading ability was measured via the Word Identification subtest of the WRMT-R (Woodcock, 1987). In addition, a measure of intelligence (full IQ) was obtained for each participant via four subtests from the Weschler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999).

3. Results

3.1. Ability assessments

Child and adult participant groups were first compared via unpaired *t*-tests in terms of reading ability and full IQ. Critically, children and adults did not differ in terms of reading ability, $t(40) = .175$, $p = .862$, with both groups reading at the fourth-grade level (children: mean = 490; standard deviation = 37; adults: mean = 491; standard deviation = 25). Despite similar reading abilities however, children and adults differed dramatically in terms of full IQ, with adults scoring much lower (mean = 74; standard deviation = 11) than children (mean = 118; standard deviation = 14), $t(40) = 11.06$, $p < .0001$.

3.2. Matching performance

Prior to analysis, responses were pruned to exclude those that exceeded three standard deviations from the mean response time. This criterion excluded responses with times longer than 2748 ms and eliminated less than 2% of all trials.

3.3. Error rates

Error rates were analyzed in a 2-way, repeated-measures analysis of variance (ANOVA) with Stimulus Type (letter vs. pseudoletter) as a within-participants variable, and Group (adult vs. child) as a between-participants variable. Results from this analysis are shown in Fig. 2A. Overall, participants made more errors on pseudoletter pairs (10%) than on letter pairs (6%), $F(1,40) = 17.44$, $p = .0002$, for the main effect of Stimulus Type. Most important however, the interaction of Stimulus Type X Group was significant, $F(1,40) = 4.83$, $p = .034$. Tests of the simple effects revealed greater errors for pseudoletters (12%) than letters (5%) in adults, $t(19) = 3.79$, $p = .001$, but no difference between pseudoletters (8%) and letters (6%) in children, $t(21) = 1.73$, $p = .098$. No main effect of Group was observed, $F < 1$. It should be noted that the difference between groups was not significant when letters or pseudoletters were tested independently (both *ps* >.224). Thus, it was the opposing difference in errors for the two types of stimuli that lead to the interaction effect, rather than an independent difference in one or the other stimulus type.

To assess the extent to which the difference between letters and pseudoletters might vary as a function of reading ability, the difference between letters and pseudoletters was computed for each participant and correlated with reading ability. No relationship between the two variables was observed, $r = -.069$, $p = .660$.

3.4. Reaction times

Reaction times for correct responses were analyzed in a two-way, repeated-measures ANOVA with Stimulus Type (letter vs. pseudoletter) as a within-participants variable, and Group (adult vs. child) as a between-participants variable. Results from this analysis are shown in Fig. 2B. Similar to results from the analysis of error rates, reaction times were longer for pseudoletter pairs (889 ms) than for letter pairs (843 ms), $F(1,40) = 16.87$, $p = .0002$, for the main effect of Stimulus Type. Unlike results from the analysis of error rates however, the interaction of Stimulus Type X Group did not approach significance, $F < 1$, potentially undermining the error rate finding. Nonetheless, the opportunity to observe this interaction may have been precluded by a difference in overall response times between participant groups (see Chapman & Chapman, 1973; Chapman, Chapman, Curran, & Miller, 1994). Indeed, children took much longer (1005 ms) than adults (713 ms) to respond correctly, $F(1,40) = 19.68$, $p < .0001$, for the main effect of Group. Thus, the potential difference between children and adults in letter-specific processing was re-assessed using proportionalized difference scores as the dependent variable. These scores were computed by subtracting the letter response time from the pseudoletter response time and dividing by the pseudoletter response time ([pseudoletter – letter]/pseudoletter) for each participant. Results from the analysis of proportionalized difference scores are shown in Fig. 2C. Critically, the difference between children and adults was significant, $t(40) = 2.39$, $p = .022$, with adults exhibiting a greater advantage for letters over pseudoletters (.11) than children (.04).

To assess the extent to which the difference between letters and pseudoletters might vary as a function of reading ability, the proportionalized difference scores were correlated with reading ability. Similar to the analysis of error rates, no relationship between the two variables was observed, $r = .183$, $p = .240$.

4. Discussion

Previous work examining letter-specific processing in a typically developing sample suggests that reading ability is an important factor in determining the magnitude of advantage for letters compared to pseudoletters (Burgund et al., 2006). In contrast, other evidence indicates that adult learners rely on visual information to a greater extent than children when reading (Greenberg et al., 1997, 2002; Thompkins & Binder, 2003), thereby suggesting that adults may exhibit greater letter specificity than children, regardless of reading skill. The present study aimed to discriminate between these possibilities by comparing the advantage for letters over pseudoletters in children and adults reading at the same less-than-expert (fourth grade) level. Results revealed greater letter specificity in adults than in children in both error rate and response time measures. Moreover, the magnitude of letter specificity did not vary with reading ability. Thus, results suggest that adults are more sensitive than children to the visual forms of letters, and that differences in letter specificity are not necessarily dependent on reading skill. Critically, this conclusion contrasts directly with the conclusion drawn by Burgund et al. (2006), as well as with conclusions drawn by others regarding the role of expertise in stimulus-specific tuning (e.g., Gauthier et al., 2000; McCandliss et al., 2003; Tanaka & Curran, 2001; Tarr & Gauthier, 2000). As such, it is important to consider differences between the present study and that of Burgund et al., as well as the implications of the present work for theories of visual form processing.

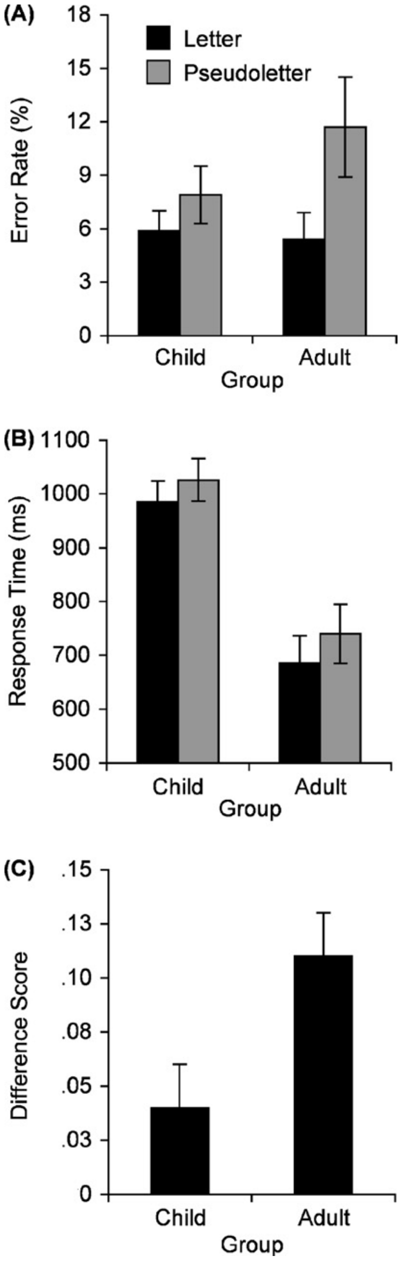

Fig. 2. Error rates (A) and response times (B) displayed as a function of Stimulus Type (letter vs. pseudoletter) and Group (child vs. adult). Difference scores (C) are based on response times (see text for details) and displayed as a function of Group. Vertical lines indicate the standard error from the mean.

Although the present study was intended to be very similar to the study by Burgund et al. (2006), it differed in several important ways. For one, participants in the Burgund et al. study had a much wider range of reading abilities than participants in the present study. Indeed, testing participants with similar reading abilities was one of the main goals of the present study; nonetheless, the narrower range of abilities included may have limited our capacity to observe a relationship between letter-specific processing and reading ability. In addition, it should be noted that adults in the present study scored well below average on our assessment of intelligence, while children scored somewhat above average. Unfortunately, correlations between letter specificity and intelligence were prohibited by the non-normal distribution of intelligence scores across the entire sample. However, post hoc correlations between letter specificity measures and intelligence scores were not significant when computed separately for adults and children (all *ps* > .316). Thus, differences in intelligence cannot explain the effect of group on letter-specific processing in the present experiment. Accordingly, we conclude that the effect of group in the present study emerged due to a greater reliance on visual information by adult learners than by children, in line with the proposals of Greenberg et al. (1997, 2002) and Thompkins and Binder (2003), and that reading ability does not always play a role in the emergence of letter-specific processing.

As noted above, this conclusion contrasts with theories of visual-form recognition that emphasize the role of expertise in the tuning of representations for certain classes of stimuli (e.g., Burgund et al., 2006; Gauthier et al., 2000; McCandliss et al., 2003; Tanaka & Curran, 2001; Tarr & Gauthier, 2000). However, support for the role of expertise in previous studies has been obtained from typically developing or developed samples, while results from the present study were obtained from adults that did not learn to read in the "normal" context (i.e., as children at home or in school). Adults who do not learn to read as children, but who mature in literate cultures where the ability to read has immense social and economic value, and where letters and words are pervasive throughout the environment, may develop somewhat unique strategies to cope with or mask their disability. For example, these individuals may memorize the visual structures of certain words, such as 'NAME/name' or 'SIGNATURE/signature', in order to complete common forms without assistance, and this memorization may support some tuning or specialization for words and letterforms. Interestingly, this specialization for letters may only occur in individuals living in literate cultures, as adults maturing in pervasively illiterate environments (e.g., rural Brazil) do not appear to have developed specialized representations for letterforms. Indeed, as described in the Introduction, illiterate adults from rural Brazil could not detect letter inaccuracies in highly familiar signs that they were nonetheless able to pronounce correctly (Cardoso-Martins et al., 2003). Thus, the emergence of letter-specific processing may not come simply through frequent exposure to letters, but may depend on compensatory strategies developed to function with moderate success in a literate culture.

Although adults in the present study exhibited letter-specific processing similar to that observed in expert readers in the Burgund et al. (2006) study, despite their less-than-expert reading skills, it is unclear whether similar brain regions support this specialization. Greater neural activity for letters than non-letters has been observed in expert readers in the left occipito-temporal cortex in several studies (e.g., James et al., 2005; Pernet et al., 2005; Price et al., 1996; Puce et al., 1996), leading some to label this region a ‘visual word form area’ (Cohen & Dehaene, 2004; Cohen et al., 2000, 2002; Dehaene et al., 2001), and activity in this area has been related to increased reading expertise (Shaywitz et al., 1998, 2002; Simos, Breier, Fletcher, Bergman, & Papanicolaou, 2000). However, given that letter-specific processing in the present study was not related to reading skill, it seems more likely that other neural regions may support this specialization in non-expert adult readers. Indeed, results from a brain imaging study of literate and illiterate adults suggest that these groups recruit different sets of neural regions when performing the same word and pseudoword repetition tasks (Castro-Caldas, Petersson, Reis, Stone-Elander, & Ingvar, 1998).

In conclusion, results from the present study indicate that letter-specific processing does not necessarily emerge as a consequence of increased reading ability. Rather, letter specificity may emerge with compensatory, visual memorization strategies that are developed in order to cope with pressures from a pervasively literate environment. Although questions regarding the nature of these strategies remain, this study provides the groundwork for future investigations into perceptual tuning during adulthood, the importance of skilled processing for such tuning, and the role of this tuning in skill acquisition beyond childhood.

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Appendix

See Table 1.

Table 1
Pairs presented in “different” trials

Letter	Pair 1	Pair 2	Pair 3	Pair 4	Pair 5	Pair 6	Pair 7	Pair 8
D	F	G	K	M	P	Q	S	T
E	G	K	M	P	Q	S	T	Y
F	D	K	M	P	Q	S	T	Y
G	D	E	M	P	Q	S	T	Y
K	D	E	F	P	Q	S	T	Y
M	D	E	F	G	Q	S	T	Y
P	D	E	F	G	K	S	T	Y
Q	D	E	F	G	K	M	T	Y
S	D	E	F	G	K	M	P	Y
T	D	E	F	G	K	M	P	Q
Y	E	F	G	K	M	P	Q	S

Note. The same pairings were used for letter and pseudoletter trials.

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