Original Article

QJEP

Quarterly Journal of Experimental Psychology
2019, Vol. 72(7) 1682–1691

DOI: 10.1177/1747021818805063
qjep.sagepub.com
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Comparing length and frequency effects in children across modalities

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Abstract

Although it is well established that beginning readers rely heavily on phonological decoding, the overlap of the phonological pathways used in visual and auditory word recognition is not clear. Especially in transparent languages, phonological reading could use the same pathways as spoken word processing. In the present study, we report a direct comparison of lexical decision performance in the visual and auditory modality in beginning readers of a transparent language. Using lexical decision, we examine how marker effects of length and frequency differ in the two modalities and how these differences are modulated by reading ability. The results show that both frequency and length effects are stronger in the visual modality, and the differences in length effects between modalities are more pronounced for poorer readers than for better readers. This suggests that visual word recognition in beginning readers of a transparent language initially is based on phonological decoding and subsequent matching in the phonological lexicon, especially for poor readers. However, some orthographic processing seems to be involved already. We claim that the relative contribution of the phonological and orthographic route in beginning readers can be measured by the differences in marker effects between auditory and visual lexical decision.

Keywords

Reading development; visual word recognition; auditory word recognition; cross-modal

Received: 15 May 2017; revised: 12 September 2018; accepted: 14 September 2018

Models of visual word reading do agree not only that phonological information is activated during processing (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Diependaele, Ziegler, & Grainger, 2010; Grainger & Ferrand, 1994; Harm & Seidenberg, 2004) but also that phonological mediation is the key to reading acquisition. Beginning readers decode a written word by translating the letters into sounds and activating the word's phonological representation (e.g., Grainger, Lété, Bertand, Dufau, & Ziegler, 2012; Share, 1995). Hence, beginning readers rely heavily on phonological processing, prompting the question to which extent visual and auditory word recognition overlap in beginning readers. However, research in the visual and auditory domain has developed separately and has only recently been investigated jointly in adults (Ferrand et al., 2018) and never in children. To elucidate the differences and similarities between the two modalities, we investigated how length and frequency effects vary as a function of modality in beginning readers.

Models of the development of visual word recognition largely agree that beginning readers use phonological decoding: They translate each letter into its corresponding sound and assemble the sounds to obtain the whole word's phonology and meaning (Grainger et al., 2012; Share, 1995). Children in the early stages of reading acquisition sound out the words to themselves while reading and draw on their phonological lexicon already established from the spoken domain. Simplistically, reading in beginners can be conceptualised as decoding plus access to the phonological lexicon. Models of reading development further assume that with increasing reading ability, children rely more on orthographic

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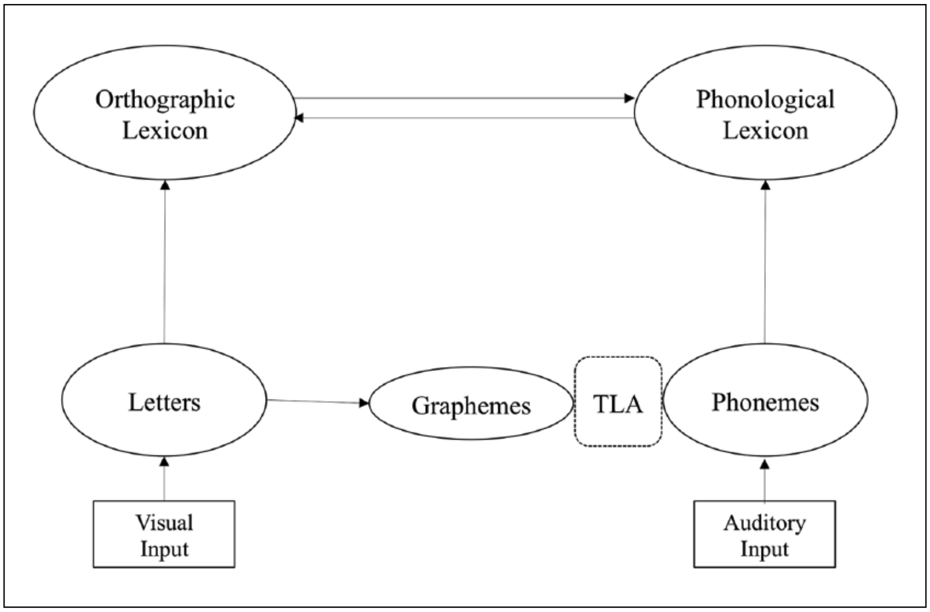

Figure 1. Schematic depiction of the BIAM, adapted from Diependaele et al. (2010), illustrating the phonological pathway shared by the visual and auditory modality.

information to directly retrieve meaning without consulting phonological representations (e.g., Grainger et al., 2012; Share, 2008). In dual- or multiple-route models, this is associated with the buildup of an orthographic lexicon and use of the orthographic route (e.g., Grainger & Ziegler, 2011); in connectionist models, it is associated with growing involvement of a direct orthography-to-semantics route in addition to the indirect orthography-to-phonology-to-semantics route (Seidenberg & McClelland, 1989).

The reliance on phonological versus orthographic reading strategies has been suggested to vary as a function of reading ability (e.g., Ziegler, Bertrand, Lété, & Grainger, 2014) and language transparency (Frost, Katz, & Bentin, 1987; Katz & Frost, 1992; Schmalz, Marinus, Coltheart, & Castles, 2015). Poor readers rely more heavily on phonological strategies, because building an orthographic lexicon is challenging and slow for them (Share, 1995). In transparent languages, phonological decoding leads to the correct outcome for the majority of words, and poor reading ability manifests through slow reading pace (Frith, Wimmer, & Landerl, 1998; Landerl, Wimmer, & Frith, 1997; Wimmer & Goswami, 1994). Given the high degree of regularity between letters and sounds in transparent languages and the importance of phonological decoding, the comparison between visual and auditory processing appears useful.

The most prominent models of auditory word recognition are arguably the cohort model (Marslen-Wilson, 1973, 1987) and the TRACE model (McClelland & Elman, 1986). They assume that during spoken word recognition, each speech segment activates all possible candidates sharing the same sound sequence. As the word in speech unfolds over time, the number of candidates in the phonological lexicon is narrowed down until only one match is left and unequivocal word identification is possible, called the *uniqueness point*. However, doubt about the word identity can remain after this point, because input rendering the stimuli a nonword might still follow (Ernestus & Cutler, 2015). Therefore, listeners have to wait for silence to be sure the stimulus has ended (Ernestus & Cutler, 2015; Ferrand et al., 2018), which allows other lexical characteristics, such as frequency, to influence auditory word recognition beyond the uniqueness point (Ernestus & Cutler, 2015; Taft & Hambly, 1986; Turner, Valentine, & Ellis, 1998). However, the temporal differences between auditory (unfolding over time) and visual word recognition (present as a whole at once) need to be kept in mind when comparing the shared mechanisms of the two modalities.

The Bimodal Interactive Activation Model (BIAM; Diependaele et al., 2010; Grainger & Ferrand, 1994) explicitly assumes a connection between the processing of input from the two modalities, as depicted in Figure 1. At the sublexical level, the BIAM encompasses an orthographic and a phonological layer with nodes for phonemes and letters, respectively, which are connected via representations for grapheme-to-phoneme translations. Letters and phonemes feed activation forward to the lexical level to an interconnected orthographic and a phonological lexicon. Consequently, visual word recognition can be achieved via a route that draws on the same structure as auditory word recognition plus a letter-to-phoneme translation stage. From the assumption that beginning readers rely on phonological decoding, it follows that visual word processing shares pathways with auditory word processing in reading and its acquisition. The BIAM provides a useful framework to investigate this hypothesis.

In a recent megastudy comparing auditory and visual lexical decision in adults, Ferrand et al. (2018) looked at the influence of different lexical variables on performance in both modalities. They found frequency to explain most variance in visual lexical decision and duration to explain most variance in auditory lexical decision. Frequency effects were present in both modalities, but more pronounced in the visual one. The effect of length (in letters) was the only effect that did not differ across modalities. This study is exemplary for how the direct comparison of processing across modalities allows investigating the extent to which effects of length and frequency are modality (un)specific.

Visual and auditory word recognition in children is usually not studied jointly. Visual word recognition studies in transparent languages typically report length effects as a marker for phonological decoding in beginning readers (Martens & de Jong, 2006; Spinelli et al., 2005; Van den Boer, de Jong, & Haentjens-van Meeteren, 2012, 2013; Zoccolotti et al., 2005). Martens and de Jong (2006) found length effects in lexical decision in Dutch second graders to be strong and remarkably similar to length effects in reading aloud, whereas fourth graders showed diminished length effects, raising the possibility that young readers approach lexical decision tasks as naming tasks. The findings on length effects fit very well with the idea that children initially decode words phonologically and make lexical decisions based on their phonological lexicon. Similarly, Burani, Marcolini, and Stella (2002) found length and frequency effects in Italian third to fifth graders in both naming and lexical decision, which did not interact with grade, suggesting that both phonological and orthographic processing are in place early in reading acquisition and change little (see also Sulpizio & Colombo, 2013). Schmalz, Marinus, and Castles (2013), using regularity effects (instead of length effects) as a phonological marker in English (an opaque language), found involvement of both phonological and orthographic processes in third-graders' lexical decision. Only the former correlated with reading ability. Marinelli, Angelelli, Di Filippo, and Zoccolotti (2011) directly compared visual and auditory lexical decision in children, but with the specific goal to examine whether developmental dyslexia is modality-specific. Their results from Italian fourth graders show slower lexical decision in children with dyslexia than in the control group for the visual, but not for the auditory modality, indicating that dyslexics are selectively impaired in visual word processing. Moreover, frequency effects were stronger in the visual than in the auditory modality. Unfortunately, this finding is not further discussed by the authors.

In this study, we compare visual and auditory word processing in beginning readers. German third graders from the whole range of reading ability completed two matched visual and auditory lexical decision tasks. We examine how length and frequency effects differ between modalities and whether they interact with reading skill. Based on the previous studies, we expect to find length and frequency effects in both modalities, which are also modulated by reading skill. In particular, if reading depends on phonological decoding as in poor readers, length effects should be more pronounced in the visual than in the auditory modality. By contrast, in good readers who rely more on direct orthographic activation, length effects should be similar in the two modalities.[1]

The expectations for the effects of frequency across the modalities are less clear. Assuming that increased reading ability is associated with more direct orthographic word recognition, one would expect stronger frequency effects in the visual modality for better readers as a result of their reliance on their orthographic lexicon. However, previous studies (Burani et al., 2002; Schmalz et al., 2013; Sulpizio & Colombo, 2013) have found that frequency effects do not change between modalities. This is in line with the BIAM, in which recourse to a frequency-dependent lexicon (either orthographic or phonological) is always necessary, regardless of the reading route. As both lexicons are sensitive to frequency, this suggests similar effects of frequency across modalities independent of reading ability.

Method

Participants

Data were acquired as part of a larger longitudinal project. In total, 114 third graders (61 girls, $M=8.48$, standard deviation [SD]$=0.52$, range$=8$-10) from four Berlin schools participated in the experiments. Signed informed consent was provided by the parents, and oral consent was given by the children prior to the start. All children had normal or corrected-to-normal vision and acquired German prior to school entry as their dominant language.

Children's reading ability was measured using the 1-min word reading test from the Salzburger Lese-Rechtschreibtest (SLRT) (Moll & Landerl, 2010).The scores were normally distributed ($M=68.14$, $SD=21.71$) and age-appropriate (norm sample: $M=63.82$, $SD=20.61$).

Materials

For the visual lexical decision task, 64 words were chosen from the childLex corpus (Schroeder, Würzner, Heister, & Geyken, 2014). Length in letters and written frequency were manipulated in a 2×2 design, such that half of the words were four letters long (monosyllabic) and the other half were eight letters long (bisyllabic), and half of the words were of high frequency (HF) and the other half were of low frequency (LF). Item characteristics are summarised in Table 1. In addition, 64 pronounceable pseudowords matched to the words on length, syllable structure, orthographic neighbours, and bigram frequency, all $ts < 2$, all

Table 1. Means of orthographic and phonological measures for words in the auditory and visual stimulus set (standard deviations in parentheses). LF and HF refer to low frequency and high frequency words, respectively. 4 and 8 refer to the number of letters.

	Auditory set				Visual set			
	LF 4	LF 8	HF 4	HF 8	LF 4	LF 8	HF 4	HF 8
Orthographic measures								
Length in letters	4 (0)	8 (0)	4 (0)	8 (0)	4 (0)	8 (0)	4 (0)	8 (0)
Normalised lemma frequency (written)	7.3 (3.8)	6.4 (3.7)	67.8 (38.1)	54.2 (40.5)	8.1 (3.9)	7.3 (4.1)	78.4 (54.6)	78.8 (85.9)
OLD20[a]	1.5 (0.3)	1.4 (0.3)	2.2 (0.4)	2.3 (0.4)	1.4 (0.3)	2.5 (0.6)	1.2 (0.3)	2.2 (0.5)
Phonological measures								
Length in phonemes	3.7 (0.6)	6.3 (0.9)	3.6 (0.6)	6.0 (0.6)	3.4 (0.7)	6.3 (0.9)	4.0 (0.5)	6.4 (1.0)
Normalised lemma frequency (spoken)	6.7 (4.2)	6.3 (4.0)	67.8 (38.4)	59.7 (47.1)	14.0 (21.0)	8.0 (5.0)	81.3 (56.3)	76.0 (65.3)
PLD20[b]	1.3 (0.3)	2.0 (0.4)	1.2 (0.3)	2.1 (0.3)	1.2 (0.3)	2.3 (0.5)	1.2 (0.3)	2.0 (0.4)
Phonological uniqueness point[c]	3.7 (0.6)	6.4 (1.0)	3.6 (0.6)	6.0 (0.6)	3.5 (0.7)	6.3 (0.9)	4.0 (0.5)	6.4 (1.0)

[a]Orthographic Leveshtein Distance 20
[b]Phonological Levenshtein Distance 20
[c]Note that the phonological uniqueness point in our stimuli corresponds to the length in phonemes. This is due to the productive German morphology that results in the existence of complex forms of most simple words.

*p*s > .05, were taken from the Developmental Lexicon Project (Schröter & Schroeder, 2017).

For the auditory lexical decision task, a parallel stimulus set was created by choosing 64 new words from the childLex corpus. The auditory stimuli were matched to the visual stimuli on the same orthographic measures (length in letters, written frequency, neighbourhood size, bigram frequencies). The focus in matching was on the written lexical characteristics to maximise comparability of the variables that are most important with regard to *reading*, but spoken lexical characteristics were also matched closely (cf. Table 1), making the sets analogous with regard to both dimensions (see Table 1). Pseudowords were created by changing one to three letters of the word stimuli. The changes never affected onsets to ensure that lexical decision could not be made based on the onset. Words and pseudowords in the auditory set were matched on length, syllable structure, orthographic neighbours, and bigram frequency, all *t*s < 2, all *p*s > .05.

The stimuli for the auditory task were recorded by a native speaker (female, 23 years) in a soundproof cabin. The speaker was instructed to articulate the words and pseudowords clear, but as naturally as possible. The software Audacity was used for recording and editing volume and intensity where needed to minimise differences between items. The mean stimulus duration was 493.7 ms (*SD* = 66.5, range = 336-638) for short words and 708.1 ms (*SD* = 119.7, range = 509-963) for long words.

Procedure

The children were tested in individual sessions in a quiet room in their schools. The experiments were run on a 15″ laptop monitor. In the visual lexical decision task, the stimuli were presented in the centre of the screen in white 20-point Courier New font on black background. Each trial started with a 500-ms fixation cross, followed by the presentation of a word or pseudoword, which remained on the screen until a response was made by the participant. In the auditory lexical decision task, the stimuli were presented via headphones. Each trial started with a 500-ms fixation cross, followed by the auditory presentation of a word or pseudoword, while the screen remained black. In both tasks, participants were instructed to decide as quickly and accurately as possible whether the presented stimulus was an existing German word or not. Responses were made by pressing D or K on a standard keyboard, marked red and green. Accuracy and response time (RT) were recorded; the latter was measured from the stimulus onset until key press. Eight practice trials with feedback were given prior to the experimental trials. After half of the items, the participants had a break timed by the experimenter. The order of the tasks was varied across participants.

Results

Data analysis was carried out using linear-mixed effects models with the lme4 package (Bates, Mächler, Bolker, & Walker, 2015) in the software R. Data from the visual and the auditory task were analysed together to directly compare the two tasks. Descriptive statistics are provided in Table 2. Words and pseudowords were analysed separately as the pseudoword analysis cannot include frequency by definition. For words, a generalised linear-mixed effects model was conducted for the accuracy data including length (4 vs. 8), frequency (HF vs. LF), modality (visual vs. auditory), and reading ability (as a centred continuous variable) as fixed effects. Furthermore, phonological uniqueness point (as a centred continuous variable) was included as a covariate in the word analysis. Participant and Item were included as random effects. For pseudowords, a similar model was specified, but without frequency and phonological uniqueness point. The same model structures were used to analyse the RT data with linear-mixed effects models. Results for the

Table 2. Mean error rates (in %) and response times (in ms) to words and pseudowords in the auditory task and the visual task as predicted by the mixed effects models. LF and HF refer to low frequency and high frequency words, respectively. 4 and 8 refer to the number of letters.

	Auditory task		Visual task	
	Error rates	Response times	Error rates	Response times
Words				
LF 4	15.94 (3.46)	1,150 (39)	11.13 (2.68)	1,272 (45)
LF 8	30.15 (5.72)	1,280 (44)	10.13 (2.37)	1,721 (56)
HF 4	6.81 (1.64)	1,121 (38)	4.03 (0.96)	1,133 (36)
HF 8	18.41 (33.75)	1,283 (41)	6.66 (1.67)	1,619 (55)
Pseudowords				
4	10.78 (1.45)	1,280 (27)	8.07 (1.15)	1,614 (34)
8	8.58 (1.22)	1,381 (30)	7.03 (1.04)	2,476 (54)

Standard errors are given in parentheses.

Table 3. Results from mixed effects models for words and pseudowords with length, frequency (for words only), modality, and reading fluency, and phonological uniqueness point (for words only) as fixed effects, and participant and item as random intercepts.

	χ^2			
	Words		Pseudowords	
	Errors	RTs	Errors	RTs
Fixed effects				
Intercept	432*	198,260*	580*	171,210*
Length (*L*)	3	39*	3	344*
Frequency (*F*)	21*	8*	–	–
L × *F*	2	1	–	–
Modality (Mod)	25*	77*	5*	973*
L × Mod	5*	33*	<1	180*
F × Mod	<1	4*	–	–
L × *F* × Mod	<1	<1	–	–
Reading ability (RA)	43*	153*	5*	107*
L × RA	<1	103*	3	<1
F × RA	<1	<1	–	–
L × *F* × RA	2	<1	–	–
Mod × RA	36*	2,256*	1	2,898*
L × Mod × RA	3	50*	2	<1
F × Mod × RA	<1	2	–	–
L × *F* × Mod × RA	2	<1	–	–
Phonological uniqueness point	3	1	–	–
Random effects				
Participants	257*	1,876*	591*	2,913*
Items	1,202*	765*	414*	358*

RTs: response times; *df*: degrees of freedom.
Tests are based on Type III sum of squares and χ^2 values with Kenward–Roger *df*.
*$p < .05$.

overall effects tests using contrast coding and Type III model comparisons are summarised in Table 3. Prior to RT analyses, data from the visual and the auditory task were cleaned separately, first removing inaccurate answers (words: visual 11.44%, auditory 21.85%; pseudowords: visual 11.09%, auditory 12.66%), then RTs above or below a specific cutoff (words: visual 200-7,000 ms: 1.08%, auditory 200-5,000 ms: 0.86%; pseudowords: visual 3.28%, auditory 0.85%). The remaining RTs were logarithmically transformed and model criticism based on a simple model was used for outlier trimming (Baayen & Milin, 2010) by excluding all data points with residuals exceeding 2.5 *SD* (words: visual 1.08%, auditory 0.86%; pseudowords: visual 1.98%, auditory 2.80%). Post hoc comparisons were carried out using cell means coding and single degrees of freedom (*df*) contrasts.

Words

The accuracy analysis revealed main effects of frequency, modality, and reading ability indicating that more errors were made to LF than HF words, more errors were made in the auditory than in the visual task, and more errors were made by poorer readers (–1 *SD*) as compared with better readers (+1 *SD*). There was also an interaction of length and modality: Post hoc comparisons showed that participants made more errors to eight-letter words as compared with four-letter words in the auditory task, $\Delta=6\%$, $b=0.482$, $t=2.00$, $p=.05$, whereas error rates did not differ between eight-letter and four-letter words in the visual task, $\Delta=3\%$, $b=-0.293$, $t=-1.17$, $p=.24$. In addition, modality interacted with reading ability: There were fewer errors in the visual than in the auditory task for better readers, $\Delta=9\%$ $b=-1.190$, $t=-6.41$, $p<.001$, but this difference was less pronounced for poorer readers, $\Delta=8\%$, $b=-0.582$, $t=-3.29$, $p<.001$.

The RT analysis revealed main effects of length, frequency, modality, and reading ability. Frequency additionally interacted with modality: HF words were responded to faster than LF words in the visual task, $\Delta=121$ ms, $b=-0.089$, $t=-3.41$, $p<.001$, but there was no such difference in the auditory modality, $\Delta=1$ ms, $b=-0.012$, $t=0.45$, $p=.65$.

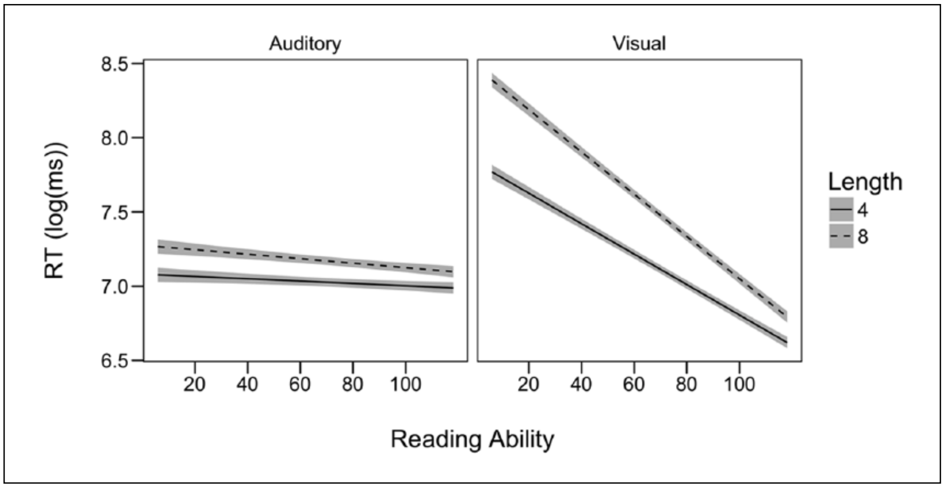

Figure 2. Three-way interaction of length, modality, and reading ability for the RTs to words.

Furthermore, length interacted with modality, as well as with reading ability, and they entered into a three-way interaction of Length × Modality × Reading Ability (see Figure 2). Reading ability modulated the length effect in the visual modality much stronger than in the auditory modality: In the auditory modality, four-letter words were responded to faster than eight-letter words by both better, $\Delta = 122$ ms, $b = -0.104$, $t = -2.54$, $p = .011$, and by poorer, $\Delta = 172$ ms, $b = -0.138$, $t = -3.36$, $p < .001$, readers. In the visual modality, length effects were much stronger for poorer, $\Delta = 818$ ms, $b = -0.427$, $t = -10.19$, $p < .001$, than for better, $\Delta = 245$ ms, $b = -0.233$, $t = -5.61$, $p < .001$, readers.

Pseudowords

The error rates analysis revealed main effects of modality and reading ability, indicating that more errors were made in the auditory task and more errors were made by poorer readers. No other effects reached significance.

The RT analysis revealed main effects of length, modality, and reading ability. Length interacted with modality: Four-letter words were responded to faster than eight-letter words in the auditory task, $\Delta = 102$ ms, $b = -0.038$, $t = -4.08$, $p < .001$, and this difference was greater in the visual modality, $\Delta = 862$ ms, $b = -0.214$, $t = -22.66$, $p < .001$. In addition, modality and reading ability interacted: Answers in the auditory modality were faster than in the visual modality for better readers, $\Delta = 177$ ms, $b = -0.052$, $t = -7.42$, $p < .001$, and this cross-modal difference was more pronounced for poorer readers, $\Delta = 1{,}465$ ms, $b = -0.356$, $t = -49.43$, $p < .001$.

Speed–accuracy trade-off

Error rates to words were remarkably high, especially in the auditory modality (21.85%). Closer inspection revealed that the long low-frequency words in the auditory modality were most error-prone due to a subset of words in this condition with an average performance at chance. To rule out that effects were distorted by problems with these particular items, we reran all analyses excluding these items. The pattern of effects, both in the error rate and the RT analysis, remained stable.

Because RT analyses are based on correct answers only, RTs to low-frequency words in the auditory modality might have been underrepresented, thus concealing auditory frequency effects in the RTs. To address the issue of a potential speed–accuracy trade-off, we additionally ran an analysis using an integrated measure of RT and error rate. Following the recommendations by Vandierendonck (2017, 2018), we calculated the linear integrated speed–accuracy score (LISAS) per subject per condition. LISAS is a balanced combination of speed and accuracy, because it weights the contribution of both performance measures by taking into account their *SD*s. It can be interpreted as RTs adapted for incorrect responses. We fitted a linear-mixed effects model for LISAS with length, frequency, modality, and reading ability as fixed effects and participant as a random effect. The results of this analysis (reported in Table 4) mirror the pattern observed for the RTs as reported above with the only difference that the interaction of length and frequency reached significance for LISAS, indicating stronger frequency effects for short words as compared with long words. Importantly, however, all interactions involving modality remained unchanged, ruling out the possibility that frequency effects in the auditory modality were concealed by the high amount of errors in the auditory domain.

Discussion

Models of reading development assume that beginning readers decode a word by translating each letter into its corresponding sound and then check for a match in

Table 4. Results from mixed effects models for LISAS with length, frequency, modality, and reading fluency, as fixed effects, and participant as random intercepts.

	χ^2
Fixed effects	
Intercept	2,885.45*
Length (*L*)	245.76*
Frequency (*F*)	41.78*
$L \times F$	6.55*
Modality (Mod)	269.15*
$L \times$ Mod	63.50*
$F \times$ Mod	9.95*
$L \times F \times$ Mod	<1
Reading ability (RA)	177.28*
$L \times$ RA	53.43*
$F \times$ RA	2.33
$L \times F \times$ RA	<1
Mod $\times$ RA	839.78*
$L \times$ Mod $\times$ RA	40.46*
$F \times$ Mod $\times$ RA	<1
$L \times F \times$ Mod $\times$ RA	<1
Random effects	
Participants	272*

LISAS: linear integrated speed–accuracy score; *df*: degrees of freedom. Tests are based on Type III sum of squares and χ^2 values with Kenward–Roger *df*.
*$p < .05$.

their phonological lexicon (e.g., Grainger et al., 2012; Share, 1995). This strategy is especially successful in languages with transparent grapheme-to-phoneme mapping (Martens & de Jong, 2006; Schmalz et al., 2013). The BIAM (Diependaele et al., 2010; Grainger & Ferrand, 1994) illustrates this view of phonological reading by featuring a route from visual input to the phonological lexicon that is also used by the auditory modality (see Figure 1). Using this route in visual word recognition should lead to increased length effects compared with auditory word recognition, while frequency effects should be comparable across modalities if the same phonological lexicon is used. With increasing reading ability, children might rely more on direct orthographic access (e.g., Grainger & Ziegler, 2011). Thus, for better readers, who do not use effortful grapheme–phoneme translations, length effects should be of comparable size across modalities, while (written) frequency might play a more important role for visual word recognition. In the present study, we compared length and frequency effects in visual and auditory word recognition in third graders learning to read a transparent language and we examined how the effects are modulated differently by reading ability.

We found that word recognition differs across modalities both overall and with respect to certain aspects. First of all, error rates in the auditory modality were strikingly high compared with the visual one. Although Marinelli et al. (2011) found equally high error rates in an auditory lexical decision task, this pattern is astounding as the auditory modality is the predominant form of processing linguistic stimuli and even children already have many years of experience with it. A possible reason is that each auditory stimulus was only hearable once, whereas visual stimuli remained on screen and could be attended to repeatedly until decision-making. In natural spoken language, uncertainties about word identity, especially for low-frequency words, can be counteracted by context, which is lacking in a lexical decision task, leaving more room for failure to correctly recognise a word. This explanation is supported by the presence of a length effect in the error rates to words in the auditory, but not in the visual modality, suggesting that long words, requiring prolonged attention when listening, were particularly error-prone. However, as the post hoc analyses showed, failure to recognise some long low-frequency words in the auditory modality did not drive our observed pattern of results in the RTs.

With regard to the RTs, there were strong length effects for words and pseudowords in both modalities. For the visual modality, this is in line with previous studies on length effects in children reading in a transparent language (e.g., Burani et al., 2002; Spinelli et al., 2005; Van den Boer et al., 2012, 2013; Zoccolotti et al., 2005) and also with findings on auditory word recognition (e.g., Ernestus & Cutler, 2015). Importantly, for words, we found that reading ability strongly modulated length effects in the visual modality, while the impact of reading ability on length effects in the auditory modality was small. This supports the hypothesis that poorer readers rely more on phonological recoding when reading a word (cf. Schmalz et al., 2013; Ziegler et al., 2014), using the same pathway that is involved in auditory word recognition. This mechanism fits with the BIAM (Diependaele et al., 2010; Grainger & Ferrand, 1994) and the suggestion made by Martens and de Jong (2006) that beginning readers translate letters into sounds, which enhances the length effect. With increasing reading ability, children rely less on this procedure. Thus, length effects do not differ much across modalities in good readers (Ferrand et al., 2018). Another explanation for the decreased length effect in better readers is that phonological decoding becomes more efficient. However, the finding of frequency effects in the visual domain suggests that the orthographic pathway is involved even in beginning readers (cf. Burani et al., 2002; Schmalz et al., 2013) and renders a mere speed-up of phonological processing unlikely.

Interestingly, frequency effects emerged only in the visual but not in the auditory modality, as also reported by Marinelli et al. (2011). The reason for this is not clear. One potential explanation is that our frequency manipulation was based on written but not spoken language, which generally is better to predict frequency effects in the auditory domain (Ernestus & Cutler, 2015). To test this, we compared our written frequencies with spoken language frequencies based on children's television and movie subtitles. Results showed that both types of frequencies were highly correlated, $r \sim 0.6$, $t > 5.6$, $p < .001$. This makes it unlikely that the modality-specific frequency effect resulted from the use of written frequencies.

In contrast to the length effect, reading ability does not modulate the frequency effect differentially in the two modalities. This is in line with Marinelli et al. (2011) who also found an interaction of frequency and modality for both dyslexics and controls. It confirms that some orthographic processing is already involved in all beginning readers (cf. Schmalz et al., 2013; Sulpizio & Colombo, 2013) and frequency effects do not increase with reading ability (cf. Burani et al., 2002). Note that the involvement of the phonological and orthographic route in beginning readers in the present study contradicts the pattern found using pseudohomophone and transposed letter effects that has been taken to support the multiple-route model (Grainger et al., 2012; Ziegler et al., 2014). The latter suggests that phonological processing decreases while orthographic processing increases across development. In contrast, our results suggest that the orthographic pathway is in place by third grade and contributes to word recognition regardless of reading ability, while reliance on the phonological pathway influences poorer readers more than better readers.

Turning to the pseudowords, we find a further indication against a mere speed-up of phonological decoding, and for the idea that increasing reading ability is associated with decreasing reliance on phonology. If better reading ability led to faster letter-to-phoneme translations, this should manifest in the pseudoword data in the form of a stronger impact of reading ability on length effects in the visual as compared with the auditory modality, which we did not observe. While the differences in RTs to pseudowords were greater for poorer than for better readers and the length effect was stronger for visually than auditory presented pseudowords, there was no three-way interaction of length, modality, and reading ability for pseudowords: Reading ability did not modulate the length effect for pseudowords differently in the two modalities. Pseudowords cannot be read orthographically, so letter-to-phoneme translation is indispensable, irrespective of the level of reading ability. This also fits in the framework of the BIAM (Diependaele et al., 2010; Grainger & Ferrand, 1994).

The two most prominent models of auditory word recognition, the cohort model (Marslen-Wilson, 1973, 1987) and the TRACE model (McClelland & Elman, 1986), assume that at any given point during spoken word retrieval, all possible candidates sharing the sound sequence are activated. Therefore, the phonological uniqueness point has been suggested as one of the most important variables for auditory word recognition. We have not found an influence of the uniqueness point in our study. This is not surprising given that the uniqueness point of our stimuli strongly correlated with length (in letters and phonemes), so that it could not influence RTs over and above length. Moreover, it has been shown that participants in a lexical decision task tend to wait until the end of the word to rule out that there might still follow input rendering the stimulus a nonword (Ernestus & Cutler, 2015; Ferrand et al., 2018).

Taken together, our study shows that visual and auditory lexical decision in third graders learning to read a transparent language uses shared as well as modality-specific processes. In the context of the BIAM (Diependaele et al., 2010; Grainger & Ferrand, 1994), this implies that albeit beginning readers still rely heavily on phonological decoding and structures of auditory word processing, some amount of orthographic processing is already involved. With increasing reading ability, children rely less on the phonological route and this can be measured by the relative differences in marker effects between auditory and visual lexical decision. To further investigate the developmental aspects, future studies should use more age groups, ideally in a longitudinal fashion.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

Note

1. Note that, because we approached this question from the perspective of the acquisition of mechanisms of reading, we focused on lexical variables from the written domain, thus using length in letters to measure the length effect in both modalities. However, in a transparent language like German, length in letters and length in phonemes are highly correlated, due to the straightforward mapping of letters onto phonemes.

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