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Tracking the transition from sublexical to lexical processing: On the creation of orthographic and phonological lexical representations

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Short article

Tracking the transition from sublexical to lexical processing: On the creation of orthographic and phonological lexical representations

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Participants read aloud nonword letter strings, one at a time, which varied in the number of letters. The standard result is observed in two experiments; the time to begin reading aloud increases as letter length increases. This result is standardly understood as reflecting the operation of a serial, left-to-right translation of graphemes into phonemes. The novel result is that the effect of letter length is statistically eliminated by a small number of repetitions. This elimination suggests that these nonwords are no longer always being read aloud via a serial left-to-right sublexical process. Instead, the data are taken as evidence that new orthographic and phonological lexical entries have been created for these nonwords and are now read at least sometimes by recourse to the lexical route. Experiment 2 replicates the interaction between nonword letter length and repetition observed in Experiment 1 and also demonstrates that this interaction is not seen when participants merely classify the string as appearing in upper or lower case. Implications for existing dual-route models of reading aloud and Share's self-teaching hypothesis are discussed.

Keywords: Nonword letter length; Reading aloud; Lexical entries.

Treisman (1961) introduced the concept of a mental "dictionary" (the lexicon) with individual "dictionary units" (lexical entries) representing words. This lexicon was thought of as a mental store of all words known to the individual and has become a central component of various computational (and noncomputational) models of visual word recognition and reading aloud (e.g., Coltheart, Rastle, Perry, Langdon, & Zeigler, 2001; McClelland & Rumelhart, 1981; Morton, 1969; Perry, Ziegler, & Zorzi, 2007). Despite the presence of multiple lexicons (orthographic and phonological) in such models, relatively little attention has been paid to the issue of how a

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letter string becomes part of a lexicon, in contrast to the amount of research devoted to other issues in the context of these models (but see Bowers & Michita, 1998; Share, 1995). The present experiments report a novel approach to determining how a letter string comes to be represented in both the orthographic input and phonological output lexicons.

Dual-route accounts of reading aloud

Coltheart and colleagues' (2001) dual-route cascaded (DRC) model of visual word recognition and reading accounts for a wide variety of reading related behaviours. The DRC model is dual route in that it generates a phonological code from print by recourse to *lexical* and *nonlexical* routines.

The lexical route consists of an orthographic lexicon and a phonological lexicon. The orthographic lexicon contains a single node for each uniquely spelled word that the model knows. Similarly, the phonological lexicon contains a single node for each uniquely sounded word that the model knows. Letter units activate words in the orthographic lexicon. Activation in the orthographic lexicon feeds back to the letter level and forward to the phonological lexicon. Activation from the phonological lexicon feeds back to the orthographic lexicon and forward to the phoneme system. The lexical route can read aloud all the words it knows and is required to correctly read aloud words that do not follow the typical spelling-to-sound rules (exception words such as *pint*).

The nonlexical route translates print into sound sublexically via a set of grapheme–phoneme correspondence rules applied left to right, one letter at a time. This route produces a correct pronunciation for words that follow typical spelling-to-sound rules (regular words such as *mint*) and is required to read nonwords (e.g., *frane*) aloud. Coltheart and colleagues (2001) explicitly note that, in DRC, letter strings that must be read via the serial, nonlexical routine (i.e., nonwords) yield a letter length effect in which longer strings take more time to read aloud. Coltheart and colleagues also note that, in DRC, the time to start reading monosyllabic words aloud is unaffected as letter length increases when the lexical route generates a pronunciation, given that letter identification occurs in parallel.[1]

A second model is the connectionist dual-process model (CDP+; Perry et al., 2007), which also has a serial-processing nonlexical route. Perry et al. also explicitly note that CDP+ produces an effect of letter length in the context of reading nonwords aloud, but not monosyllabic words (see also Perry & Ziegler, 2002).[2]

There is both broad and deep evidence for a serial nonlexical process (see Rastle & Coltheart's, 2006, review). For example, Weekes (1997), using a set of monosyllabic items ranging from 3 to 6 letters, reported that the time it takes to begin pronouncing a monosyllabic nonword increases as letter length increases (see also Perry & Ziegler, 2002). Other well-established phenomena consistent with this account include the position of irregularity effect, the position of bivalence effect, the position-sensitive Stroop effect, the exaggerated letter length effect in surface dyslexia, the whammy effect, and the onset effect observed in masked form priming (see Rastle & Coltheart's, 2006, review).

The letter length effect

Although neither DRC nor CDP + consider how lexical entries are acquired, in both cases it is not

[1] We are aware of the reports by New, Ferrand, Pallier, and Brysbaert (2006) and Balota et al. (2007) that response time (RT) increases as letter length increases. However, in the former case, the task is lexical decision, and the increase in RT as letter length increases does not appear before the word is 7 letters long. Our experiment concentrates on letter strings that vary between 3 to 6 letters. Balota et al. report a letter length effect when reading words aloud, but many of their stimuli are multisyllabic (known to affect reading aloud times) and longer than 6 letters.

[2] We do not discuss PDP models here given that no currently implemented one produces a letter length effect during reading aloud.

difficult to see how the formation of such entries can be indexed. Specifically, according to both of these accounts, if a letter string does not have entries in both the orthographic and phonological lexicons it must be read aloud via the sublexical route, which will result in a letter length effect because this process is serial and left to right and must be completed before an articulation starts. If a letter string does have lexical entries in the orthographic and phonological lexicons it can be read aloud via the lexical route and hence need not yield a letter length effect. It is important to note that if a word does have lexical representations it can still be read sublexically and thus can still show a letter length effect. However, for a word to be read lexically it must have representations in the orthographic input lexicon and phonological output lexicon. Thus, the absence of a letter length effect when reading aloud provides a plausible index of the existence and use of lexical entries (at least in the case of short, 3-to-6-letter monosyllabic strings).

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The self-teaching hypothesis

Share (1995) proposed that the application of sublexical spelling-to-sound correspondences when reading functions as a self-teaching mechanism that enables the reader to learn word-specific print-to-sound associations. Repeated reading of a nonword should thus quickly lead to the formation of item-specific print-to-sound associations that bypass serial sublexical processing. Here we consider the joint effects of letter length and nonword repetition. A reduction in the effect of letter length as a function of nonword repetition would be consistent with Share's hypothesis.

EXPERIMENT 1

Participants read aloud a set of monosyllabic nonwords that were repeated four times. A set of nonwords were used that are known to produce a letter length effect on their first presentation in skilled readers (the item set from Weekes, 1997) and to also produce a letter length effect in both DRC and CDP+ (see Coltheart et al., 2001; Perry et al., 2007).

If repetition leads to the formation of lexical entries in both the orthographic and the phonological lexicons then the effect of letter length should get smaller as the number of blocks (repetitions) increases because reading via the lexical route is independent of letter length (at least for monosyllabic items 3 to 6 letters long). If repetition does not lead to the formation of lexical entries then the effect of letter length should remain constant as the number of blocks (repetitions) increases because reading aloud such items will always be dependent on the serially based nonlexical route.

Method

Participants

A total of 18 undergraduate students from the University of Waterloo were each granted experimental credit towards a psychology course.

Stimuli

The stimulus set consisted of the 100 monosyllabic nonwords taken from Weekes (1997; except for the items "frosh" and "blog", which are words; these were replaced with "fitch" and "beld"). This set of items, among others (see Perry & Ziegler, 2002), is known to show a letter length effect. There were an equal number of 3-, 4-, 5-, and 6-letter strings.

Apparatus

Stimuli were displayed on a 17″ monitor and were displayed in 16-point Times New Roman font on a black background. Vocal responses were collected using a Plantronics LS1 microphone headset. Responses were recorded using DMDX software (Forster & Forster, 2003). Using this software in conjunction with CheckVocal (Protopapas, 2007) allows one to determine RTs using the waveform and hence serves to reduce measurement error associated with voice key timing (Rastle & Davis, 2002).

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Procedure

Participants were tested individually and were seated approximately 50 cm from the screen. At this distance, 3-letter nonwords were approximately 1.5 cm in length, and 6-letter nonwords were approximately 3 cm in length. All items were centred on the screen. Participants were instructed that when a letter string appeared, their task was to pronounce it as quickly and as accurately as possible. Responses were coded offline as correct, incorrect, or mistrial (e.g., no response) by the experimenter.

Each trial started with a fixation point. A letter string was then presented at fixation until a vocal response was detected. A set of eight practice trials served to familiarize the participant with the task and allowed the experimenter to adjust the microphone sensitivity to minimize spoiled trials. There were four blocks, each block containing the same 100 nonwords. Each participant received a different random order of items within each block. Participants were given a self-timed break after each block.

Results

Trials on which there was a mistrial (the microphone did not trigger properly or the participant coughed or stuttered; 0.8%) or an incorrect response (3.3%) were removed prior to RT analysis. The remaining RTs were submitted to a recursive data-trimming procedure using a cut-off of 2.5 standard deviations in each cell resulting in an additional 2.1% of the RT data being removed. A 4 (block: 1, 2, 3, 4) × 4 (letter length: 3, 4, 5, 6) analysis of variance (ANOVA) was conducted on both mean RT and percentage errors data. In the subject analysis (F_1), block and letter length were treated as within-subject factors, whereas in the item analysis (F_2) block was treated as a within-items factor, and letter length was treated as a between-items factor. The RT and error data for participants can be seen Table 1. One participant's data were discarded due to a large number of errors (21%).

RTs. There was a significant main effect of block, $F_1(3, 51) = 4.1$, $MSE = 2{,}739$, $p = .01$; $F_2(3, 288) = 48.5$, $MSE = 292$, $p < .01$, such that participants responded more quickly as blocks increased. There was also a main effect of letter length in the subject analysis, $F_1(3, 51) = 6.4$, $MSE = 999$, $p < .01$, such that participants took longer to respond as the number of letters in the nonword increased, but this effect was not significant in the item analysis, $F_2(3, 96) = 1.5$, $MSE = 5{,}790$, $p > .05$. Most critically, there was a significant Block × Letter Length interaction, $F_1(9, 285) = 2.3$, $MSE = 584$, $p < .05$; $F_2(9, 285) = 3.5$, $MSE = 292$, $p < .05$, in which the magnitude of the letter length effect gets smaller across blocks.

Errors. In the subject analysis, there was no main effect of block ($F < 1$) and no main effect of letter length ($F = 1$). There was also no

Table 1. *Mean response times and mean percentage error in reading aloud as a function of number of letters and block in Experiment 1*

	Letter length							
	1		*2*		*3*		*4*	
Block	*RT*	*%E*	*RT*	*%E*	*RT*	*%E*	*RT*	*%E*
1	501	3.3	509	3.3	515	1.6	538	2.4
2	471	3.1	490	2.4	498	1.3	507	3.6
3	485	2.9	487	2.4	493	1.3	501	2.0
4	486	2.4	497	1.6	492	1.1	486	2.9

Note: RT = mean response time in ms. %E = mean percentage error.

Block × Letter Length interaction ($F < 1$). In the item analysis, there was a main effect of block, $F_2(3, 288) = 2.7$, $MSE = 0.001$, $p > .05$, and a main effect of letter length, $F_2(3, 96) = 4.3$, $MSE = 0.001$, $p < .01$, but no Block × Letter Length interaction ($F_2 = 1$).

Discussion

The results of Experiment 1 are clear. Overall, longer letter strings took more time to read aloud than shorter ones. This replicates previous work by Weekes (1997) as well as others. The novel result is that the effect of letter length decreased as the number of repetitions increased. This reduction in the letter length effect across blocks suggests that these letter strings come to be read, at least sometimes, via the lexical route and thus must be represented in participants' orthographic and phonological lexicons.

EXPERIMENT 2

According to Share's (1995) self-teaching hypothesis, the formation of lexical representations requires the generation of a phonological code. Thus, repetition of a letter string in a context where a phonological code need not be generated (e.g., when participants make a case decision, rather than read aloud) should not lead to the formation of a lexical entry. This prediction is tested in Experiment 2.

Two groups of participants underwent two different training phases. Participants were presented with the same set of 50 nonwords four times (i.e., 50 nonwords appeared four times across four blocks—once per block). In the *case decision group* participants decided whether nonwords were presented in upper case or lower case. In the *reading aloud group* participants read the nonwords aloud. Following the training phase, both groups read aloud the 50 nonwords (Block 5; see Figure 1 for a schematic of the experimental design).

A critical test of Share's (1995) hypothesis comes in the comparison between the effects of repetition in the reading aloud and case decision groups. If phonological recoding is a necessary condition for the formation of lexical entries in both orthographic and phonological lexicons then the letter length effect in Block 5 following four blocks of reading aloud should be smaller than the letter length effect in Block 5 following four blocks of case decision. In contrast, if mere exposure to the letter string is sufficient to form both orthographic and phonological lexical entries then the letter length effects in Block 5 should be equivalent across the case decision and reading aloud groups.

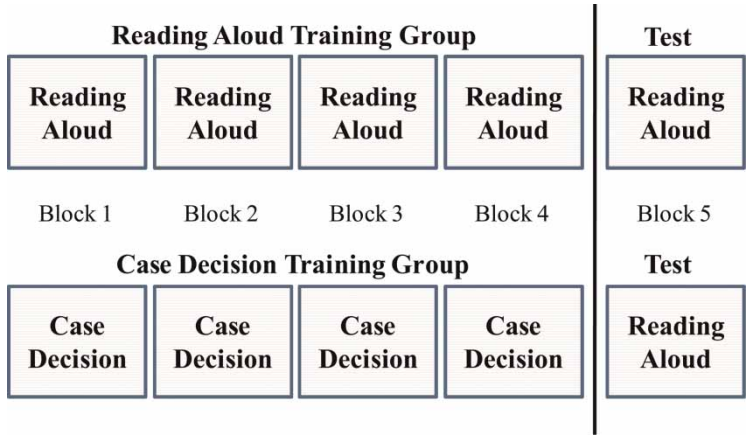

Figure 1. *Sequence of events for the reading aloud training group and the case decision training group .*

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Method

Participants

A total of 40 undergraduate students from the University of Waterloo were each granted experimental credit towards a psychology course.

Stimuli

The stimulus set consisted of the 50 monosyllabic 3- and 6-letter nonwords from Weekes (1997). Each participant received a different random order of items within each block. Half the nonwords appeared in upper case (i.e., BEZ), and half appeared in lower case (bez). Whether a nonword appeared in upper or lower case changed randomly across blocks. For the sake of simplicity, we removed the 4- and 5-letter nonwords from the previous experiment.

Apparatus

The apparatus was identical to that used in Experiment 1.

Procedure

Participants were tested individually. In the four blocks of the case decision task, participants were asked to verbally identify the case in which a letter string was presented by responding "upper" or "lower" aloud. In the four blocks of the reading aloud task, participants were asked to read the letter string aloud. In the fifth block (the test block) all participants were instructed to read aloud the letter string.

Each trial started with a fixation point. A letter string was then presented at fixation until a vocal response was detected. A set of six practice trials served to familiarize the participant with the task. Participants were given a self-timed break after each block. Responses were coded offline as correct, incorrect, or mistrial by the experimenter.

Results

Trials on which there was a mistrial (0.5%) or an incorrect response (1.1 %) were removed prior to RT analysis. The remaining RTs were submitted to the same recursive data-trimming procedure as that used in Experiment 1. In the subject analysis (F_1), block and letter length were treated as within-subject factors, whereas in the item-analysis (F_2) block was treated as a within-items factor, and letter length was treated as a between-items factor. Mean RTs and errors as a function of block, letter length, and group can be seen in Table 2.

RTs and errors. A 5 (block: 1–5) × 2 (letter length: 3 vs. 6) ANOVA was conducted for the reading aloud group. As in Experiment 1, there was a significant Block × Letter Length interaction in which

Table 2. *Mean response times and mean percentage error in reading aloud as a function of number of letters, block, and group in Experiment 2*

	Letter length							
	Reading aloud				*Case decision*			
	3		*6*		*3*		*6*	
Block	*RT*	*%E*	*RT*	*%E*	*RT*	*%E*	*RT*	*%E*
1	595	2.1	641	3.3	586	0.9	602	0.5
2	564	0.6	604	1.7	599	0.5	602	0.2
3	580	0.8	602	2.3	604	1.4	607	0.6
4	576	1.0	611	2.2	613	0.6	625	0.4
5	567	1.3	580	2.7	630	2.9	676	6.6

Note: RT = mean response time in ms. %E = mean percentage error.
Both groups read aloud in Block 5.

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the magnitude of the letter length effect decreased across blocks, $F_1(4, 76) = 3.9$, $MSE = 475$, $p < .01$; $F_2(1, 46) = 42.2$, $MSE = 764$, $p < .01$. A parallel analysis of the errors for the subject data yielded a main effect of letter length, $F_1(1, 19) = 5.0$, $MSE = 20$, $p = .04$, such that more errors were made on 6-letter nonwords than on 3-letter nonwords. However, there was no effect of letter length in the item data ($F < 1$). There was no letter length by block interaction in either the subject data or the item data (Fs < 1).

We also conducted a 2 (group: reading aloud vs. case decision) × 2 (length: 3 vs. 6 letters) ANOVA with group as a between-subjects factor on the data from Block 5. Most critically, there was a Group × Letter Length interaction, $F_1(1, 38) = 7.1$, $MSE = 787$, $p < .01$; $F_2(1, 92) = 3.9$, $MSE = 1{,}028$, $p = .05$, such that the size of the letter length effect for the reading aloud group (13 ms) was smaller than the size of the length effect in the case decision group (45 ms). A parallel analysis of the errors yielded a main effect of letter length in the subject data, $F_1(1, 38) = 4.7$, $MSE = 20$, $p < .05$, and a marginal effect in the item data, $F_2(1, 92) = 3.4$, $MSE = 0.001$, $p = .07$, such that more errors were made on the 6-letter stimuli than on the 3-letter stimuli, but no group by letter length interaction (Fs < 1). An ANOVA comparing the letter length effect on RT in Block 1 of the reading aloud group with the letter length effect in Block 5 of the case decision group yielded no difference (Fs > 1).

A 4 (block: 1–4) × 2 (length: 3 vs. 6 letters) ANOVA conducted for the case decision group yielded a main effect of block, $F_1(3, 57) = 2.9$, $MSE = 1{,}534$, $p < .05$; $F_1(3, 138) = 10.9$, $MSE = 485$, $p < .01$, such that case decisions were made more slowly in Block 4 than in Block 1. In the subject data, there was no effect of letter length, $F_1(1, 19) = 3.6$, $MSE = 833$, $p > .05$, but there was an effect in the item analysis, $F_2(1, 46) = 4.4$, $MSE = 716$, $p < .05$, and no Block × Letter Length interaction, $F_1(3, 57) > 1$; $F_2(3, 138) = 1.9$, $MSE = 716$, $p > .05$. A parallel analysis conducted on the errors yielded no main effect of block in either the subject analysis or the items analysis (Fs < 1). Furthermore, there was no effect of letter length, $F_1(1, 57) = 2.3$, $MSE = 0.000$, $p > .05$; $F_2(3, 138) = 0.6$, $MSE = 0.000$, $p > .05$, nor a Block × Letter Length interaction (Fs < 1).

Case decision task

The case decision task in Experiment 2 was chosen because it does not require the generation of a phonological code. According to Share's (1995) self-teaching hypothesis, the generation of a phonological code is a prerequisite for the formation of a lexical entry. Our results are consistent with this prediction. It is interesting to note that many researchers believe that the generation of a phonological code occurs automatically (e.g., Frost, 1998; Van Orden, Pennington, & Stone, 1990). Thus, a phonological code should have been generated in the case decision task. If this is the case (and this is not undisputed; see Reynolds & Besner, 2006), then it suggests that the "automatic" generation of a phonological code is not sufficient to form a lexical representation (at least in the present context). Rather, it may be that the "explicit" generation of a phonological code is required (though not necessarily aloud; silent reading would probably also work; see Bowey & Muller, 2005).

The idea that a phonological code is automatically generated in the case decision task may serve as a tentative explanation of the small letter length effect found in the item, but not subject, analysis of the case decision task. Another curious result in the case decision task is the main effect of block wherein participants got slower as the experiment progressed. This effect may reflect a decrease in arousal given the simple nature of the case decision task (e.g., Mackworth, 1968).

GENERAL DISCUSSION

The results of these two experiments are consistent with the argument that the generation of a phonological code leads to the formation of both orthographic and phonological lexical entries. This transition from reading via a nonlexical route to reading via the lexical route (i.e., via the creation

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of lexical entries) was indexed by a reduction in the magnitude of the letter length effect. When participants repeatedly read aloud nonwords the letter length effect was reduced. This transition from reading via a nonlexical route to reading via the lexical route appears critically dependent on repeated reading aloud as opposed to mere repeated exposure to the letter string given that repeated case decisions in Experiment 2 did not reduce the letter length effect when participants were asked to read these items aloud in Block 5. These results thus provide strong support for Share's (1995) self-teaching hypothesis and, at the same time, provide a novel, conceptually grounded means through which to further assess issues surrounding the formation of lexical representations.

The formation of a lexical entry

The reduction in the letter length effect is taken here to reflect the formation of a lexical entry. Each reading of a nonword allows for the establishment and strengthening of a whole-item print-to-sound association (creation of orthographic and phonological entries along with a connection between them). This allows for reading to occur via the faster lexical route and also allows reading to be less influenced by letter length. This latter fact makes it difficult to account for our results in terms of repetition priming at an "input" or "output" stage. In the context of dual-route models like DRC and CDP+, in order for the length effect to be reduced or eliminated a lexical entry would have to have been formed. That said, the present results do reflect a form of repetition priming in the sense that the repeated presentation of a nonword leads to a change in the orthographic and phonological structure of the word-processing system. This account is consistent with results reported by Zoccolotti et al. (2005) demonstrating that the letter length effect on reading aloud words decreased from 1st to 3rd grade.[3]

Lexical representations in the DRC and CDP+ models are abstract in the sense that a single canonical representation exists for each word in the lexicon. This view can be contrasted with representations that are *episodic* such that each word has a separate representation for each encounter. The present results are of course consistent with such an "episodic lexicon" (e.g., see Goldinger, 1998). Framed in terms of Logan's (1988) instance theory, the present results reflect a gradual transition from *algorithmic* processing to *direct retrieval*. That is, the present results can be understood as reflecting an unique illustration of this transition because they not only demonstrate the characteristic speed-up associated with repetition, but also demonstrate the shift from performance dominated by algorithmic processing (affected by letter length) to direct retrieval (not affected by letter length). In the context of Logan's (1988) instance theory, the formation of a lexical entry arises via the effect of repetition. Specifically, the repeated presentation of a nonword would lead to the formation of instances in memory that would race with the length-sensitive algorithm. As the number of instances (repetitions) increases the likelihood of the algorithm winning would decrease, and as such the length effect would decrease. If an account is to be developed in terms of episodic retrieval a mechanism through which a letter length effect could emerge (for example, the first time a letter string is encountered) needs to be postulated. In Logan's (1988) theory the algorithm would need to produce a letter length effect. The computational models of reading discussed here provide such a mechanism (serial sublexical spelling–sound conversion).

Time-course of the formation of a lexical entry

The account provided here for the letter length by repetition interaction suggests that a lexical entry can be formed very rapidly. Specifically, after

[3] Martens and DeJong (2008) reported that repetition reduced the size of the letter length effect for nonwords in dyslexic children. However, they were unable to find a letter length effect in their control group (i.e., an age-matched group) despite numerous demonstrations to that effect (e.g., Weekes, 1997; and here).

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only a few repetitions (i.e., 3 or 4) and a short amount of time (i.e., less than 30 minutes) we have provided evidence that a lexical entry can be formed. It remains to be seen how resilient these representations would be over time.

The rapid formation of a lexical entry as seen here appears inconsistent with a report by Dumay and Gaskell (2007) suggesting that a night's sleep was required to form a lexical entry. However, there are a number of potentially important differences between the Dumay and Gaskell study and the present investigation. First, Dumay and Gaskell were studying the formation of a lexical entry following spoken word presentation whereas the present work was concerned the formation of a lexical entry following visual word presentation. Second, Dumay and Gaskell used lexical competition in the context of a pause detection task where we used letter length effects in the context of reading aloud. And, Dumay and Gaskell was a study of spoken-word recognition whereas the present investigation was a study of reading.

The different presentation modalities, indices of lexicalization, and/or tasks could be responsible for the differences in results. For example, the presence/absence of letter length effects in reading aloud may be a more sensitive measure of presence in the lexicon than lexical competition in spoken-word recognition. Consistent with this claim (i.e., that the differences across modalities accounts for the differences observed in the time to acquire lexical entries) Bowers, Davis, and Hanley (2005) demonstrated lexicalization on the day of training, though these effects increased after sleep. Future work directly comparing the formation of lexical entries across modalities and the relative sensitivity of different indices is needed before any strong inferences can be drawn.

An alternative account

An alternative account of the nonword letter length by repetition interaction that has been suggested to us by colleagues attributes it to an improvement in the efficiency of sublexical processing. Repetition may simply strengthen the connections between particular graphemes and particular phonemes. This account strikes us as strained to say the least, given the vast experience in translating graphemes to phonemes that university-level readers bring to the present experiments.

CONCLUSION

The present experiments demonstrate that one way a letter string can come to be represented in the orthographic and phonological lexicons is through repeated reading aloud. This demonstration, along with the novel use of the letter length effect as an index of the transition from sublexical to lexical processing, opens up numerous avenues for future research.

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