Published in final edited form as:

Read Writ. 2019 January ; 32(1): 65–94. doi:10.1007/s11145-017-9742-4.

Investigating the mechanisms of written word production: Insights from the written blocked cyclic naming paradigm

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Abstract

In three experiments, we examined whether similar principles apply to written and spoken production. Using a blocked cyclic written picture naming paradigm, we replicated the semantic interference effects previously reported in spoken production (Experiment 1). Using a written spelling-to-dictation blocked cyclic naming task, we also demonstrated that these interference effects disappear when the task does not require semantically-mediated lexical selection (Experiment 2). Results are parallel to those reported for the analogous spoken production task of reading aloud. Similar results were observed in written spelling to dictation regardless of whether stimuli consisted of words with high or low probability phoneme-to-grapheme correspondences (Experiment 3) revealing the important role of non-semantically-mediated spelling routes in written word production. Overall, our results support the view that similar mechanisms underlie written and spoken production. This includes an incremental learning mechanism underlying semantically-mediated lexical selection that produces long-lived interference effects when multiple semantically similar items are repeatedly named.

Keywords

blocked cyclic naming; spelling to dictation; semantic interference; lexical selection; written production

In the retrieval and selection of a word for production, other words that share meaning features with the target word also become active. The activation of these semantic neighbors of the target word may influence lexical selection, the process by which a specific word is selected to convey an intended meaning. Understanding the resulting patterns of interference and facilitation caused by the similarity between the multiple words that are simultaneously active during selection has been important for understanding the underlying dynamics of spoken production. In this study, we consider whether the mechanisms proposed to account for the effects of semantic similarity on lexical selection in spoken production also apply to written production.

A Cognitive Architecture of Spoken Production

Before discussing the specific predictions of the current study, we briefly review a general theoretical framework of spoken word production (for review, see Coltheart et al., 2001; Ellis & Young, 1988; Goldrick, Folk, & Rapp, 2010; Nickels, 2001). Figure 1 presents a model of spoken word production that applies not only to conceptually-driven naming but also to reading aloud. It includes three routes that can be used to produce a spoken word: two lexical routes (semantically mediated (SM) and non-semantically mediated (N-SM) as well as the sublexical route. In order to name a picture, the SM lexical route is used. After visual object recognition processing, the meaning features of the item are activated in the semantic system. The semantic features in turn send activation to stored phonological word forms in phonological long-term memory, also called the phonological output lexicon. The activated phonological word forms are words that share semantic features with the target word. At a minimum, the lexical phonological representations contain information about the identity and position of the selected item's phonemes. Selected phonemes are processed by phonological working memory, including the phonological buffer, throughout production of the word, which requires articulatory planning and execution of motor program.

In order to read a written word aloud, any of the three routes may be engaged: the SM or N-SM lexical route or the sublexical route. All routes begin with visual processing to recognize the letters that make up the written word form. When the sublexical route is used, these letters (or graphemes) are converted directly to phonemes based on learned knowledge of the ways in which typically letters map onto sounds in a given language. These phonemes are then held in phonological working memory through oral production. This sublexical route is necessary for oral reading of unfamiliar letter strings (e.g., FLIPE) and may also be useful for reading of regular words. The sublexical system is more likely to generate common, predictable pronunciations for written forms and, in the case of regular words, these are likely to be correct. Irregular words are those which include low probability letter-sound mappings and thus are unlikely to be pronounced correctly via this route, but must instead be looked up in long-term memory. When the SM lexical route is used to read aloud, graphemes activate the stored orthographic word form in orthographic long-term memory, which is also known as the orthographic input lexicon. This representation sends activation to the meaning features in the semantic system. As in picture naming, activation is next sent to stored word forms in phonological long-term memory, and then to phonological working memory and, finally, to articulatory processes. Alternatively, a direct link between orthographic and phonological long-term memory has been posited, which we refer to as the N-SM lexical route (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). There has been some debate regarding whether the existing data require positing the N-SM reading process or instead may be explained based on the interaction of the SM lexical and sublexical processes (e.g., Fischer-Baum & Rapp, 2012; Folk, Rapp, & Goldrick, 2002; Hillis & Caramazza, 1991). We will discuss this issue in more detail below in the context of spelling. Nonetheless, it is important to underscore that if only this direct, N-SM lexical process is used, conceptual semantic information is not necessarily activated. In that case, semantic neighbors would be expected to have a reduced impact in the lexical selection of target word forms.

Semantic Similarity Effects in Spoken Production

Past research investigating the dynamics of spoken production has taken advantage of the different processing possibilities for spoken picture naming and reading aloud. Because spoken picture naming relies on semantically-mediated lexical selection but reading aloud may not require semantic activation, the contrast between the tasks can be used to examine the source and locus of semantic similarity effects.

The literature on spoken picture naming primarily reports long-lasting interference (i.e., reduced speed and/or accuracy) when items are named in the context of multiple semantically similar items. This contrasts with the facilitation (i.e., increased speed and/or accuracy) found when a single semantically related written word is presented immediately before a target picture. Such facilitation is short-lived: the effect disappears when intervening items are inserted (e.g. Wheeldon & Monsell, 1994). Semantic interference effects, on the other hand, are robust and persist over multiple trials. In continuous naming studies, pictures from a variety of semantic categories are interleaved. Participants name each consecutive item from the same category more slowly, even when exemplars of the category are separated by many intervening trials (e.g., Brown, 1981; Damian & Als, 2005; Howard, Nickels, Coltheart, & Cole-Virtue, 2006; see Schnur, 2014 for data on the limitations of the effect). In blocked cyclic naming studies, participants repeatedly name small sets of pictures. They are slower to name the same picture when it is presented in a set of items from the same semantic category than when it is presented in a set of unrelated items (e.g., Belke, Meyer, & Damian, 2005; Crowther & Martin, 2014; Damian, Vigliocco, & Levelt, 2001; Kroll & Stewart, 1994; Schnur, Schwartz, Brecher, & Hodgson, 2006). This task is used in the present study.

Two main accounts have been proposed to account for long-lasting semantic interference effects (Howard et al., 2006; Oppenheim, Dell, & Schwartz, 2010). Under both accounts, long-lasting changes within the production system are due to incremental learning, and interference effects are due to competitive mechanisms. According to Howard and colleagues (2006), interference arises when three properties are present: shared activation, priming, and competition. These properties are also central to the Oppenheim et al (2010) account, and have been applied to explain interference effects due to other types of similarity as well (Breining, Nozari, & Rapp, 2016; Mulatti, Peressotti, Job, Saunders, & Coltheart, 2012). *Shared activation* refers to the mechanism by which activation of a target word results in the activation of related items as well. In semantically-mediated lexical selection, semantic features send activation not only to the target word, but also to other words that share those semantic features. Other types of shared features may also lead to shared activation. For example, Breining, Nozari, and Rapp (2016) reported interference for production of words containing overlapping segments, suggesting that there is shared activation for words that share phonemes and graphemes. *Priming* refers to the property by which selection of a target word makes it more available as a target or competitor on future trials. For example, in semantically-mediated lexical selection, after selection of a correct target, connections between that lexical item and the semantic features that activated it are strengthened. *Competition* refers to the notion that a target word is selected in the context of multiple active words that are also available for selection.

Under the Howard and colleagues (2006) model, lexical selection is competitive, meaning that selection of a target is directly influenced by the activation of non-target competitors. When there are many strongly active competitors, it takes longer to select the target. This is implemented in their model as lateral inhibition at the lexical level: each lexical item sends inhibition to all other lexical items in proportion to its own activation. Thus highly active competitors inhibit the target word more strongly. In the blocked cyclic naming paradigm, words in related blocks are produced more slowly than words in unrelated blocks because the other words in related blocks are particularly potent competitors: not only does shared activation mean that the target's features activate the lexical representations of the related items, but the connections between those features and the competitor lexical items were strengthened due to priming when they previously served as targets in that block. This strengthening of connections results in incremental learning. As a result, these highly active competitors strongly inhibit the target, making its selection slower and/or less accurate.

Under the Oppenheim and colleagues (2010) model, it is the learning mechanism itself that is competitive, not lexical selection (see Navarrete, Del Prato, Peressotti, & Mahon, 2014 for arguments against competitive selection). The specific incremental learning mechanism they propose not only strengthens connections between selected lexical items and the features that contributed to their activation (as in the Howard et al. approach), but also weakens connections between those same features and the non-target lexical representations that they activated. In the blocked cyclic naming paradigm, words in related blocks are produced more slowly than words in unrelated blocks because the connections between shared features and the target lexical item were weakened on previous trials in which the other related items were targets.

In contrast to the semantic effects found for spoken picture naming, interference is not typically reported in reading semantically blocked items aloud (though see Janssen, Carreiras, & Barber, 2011 for one report of a small interference effect). In fact, Damian et al. (2001) reported facilitation in this task, while others have reported no significant effect of semantic blocking (e.g. Belke, Brysbaert, Meyer, & Ghyselinck, 2005; Belke, 2008, 2013; for review, see Navarrete, Mahon, Lorenzoni, & Peressotti, 2016). The contrast between blocking effects in spoken picture naming and reading aloud has been used to localize the interference effect observed in spoken picture naming to semantically mediated lexical selection, since this is the key process that is necessary for picture naming but not for reading aloud. Furthermore, this locus is consistent with the Howard et al. and Oppenheim et al accounts of the semantic blocking effect that involve strengthening (and/or weakening) of semantic-to-lexical connections.¹

Note that a third task, spoken production of a noun phrase consisting of the correct determiner and a given noun, is sometimes compared to spoken picture naming and reading

¹Some authors have also drawn a parallel to the memory literature concerning retrieval-induced forgetting, whereby participants show reduced recall of previously studied items if they are forced to "actively" retrieve other semantically related items in response to cues between the study and test phases but not if they simply read related words (e.g., Anderson, 2003). According to such an account, it is "active" retrieval that leads to interference. Extending this explanation to the language domain, semantic interference may be seen in picture naming but not in reading aloud because picture naming requires "active" lexical retrieval but reading aloud does not (e.g., Navarrete et al., 2014, 2010, 2016; Oppenheim et al., 2010). Under this explanation, one could consider "active" retrieval to mean semantically-mediated lexical selection.

aloud. In languages with grammatical gender, producing the appropriate determiner requires retrieval of lexical-syntactic information. However, since the noun is given, it is not necessary to retrieve lexical-semantic information. Therefore this task can be used to investigate the role of semantic similarity when lexical-syntactic information but not lexical-semantic information is necessary to complete the task. It contrasts with spoken picture naming, which requires lexical-semantic retrieval, and with reading aloud of bare nouns, which does not require either lexical-semantic or lexical-syntactic retrieval (e.g., Belke, 2013; Damian, Vigliocco, & Levelt, 2001; Navarrete, Mahon, & Caramazza, 2010; Navarrete et al., 2016). Results generally support the proposal that interference arises when lexical-syntactic information is necessary, although inconsistencies have been observed (for review, see Navarrete et al., 2016).

Extensions to Written Production

In the current study, we investigate whether similar mechanisms underlie lexical selection in written and spoken production. We first examine whether the semantic interference effect found in spoken picture naming is replicated in written picture naming. We then ask whether semantic interference effects differ when the task is instead written spelling to dictation, the written production task that is most directly analogous to reading aloud. As in spoken production, finding a contrast between these tasks could allow localization of interference effects to specific components of the production system.

In order to clarify these questions, it is helpful to consider the architecture of written production (Figure 2) and to compare it to the architecture of spoken production (Figure 1) (for review, see Bonin, Méot, Lagarrigue, & Roux, 2015; Bonin, Roux, Barry, & Canell, 2012; Buchwald & Rapp, 2009; Rapp, Epstein, & Tainturier, 2002; Tainturier & Rapp, 2001). Written production is in many ways analogous to spoken production (e.g., Bonin & Fayol, 2000). Again, SM and N-SM lexical routes and a sublexical route have been proposed. In order to write the name of a picture, the SM lexical route is used. The same object recognition processes and activation of the recognized picture's meaning in the semantic system must occur as in saying the name of a picture. From here, spoken and written production diverge because they rely on different output modalities. Producing written output requires accessing the stored word form in orthographic long-term memory (sometimes referred to as the orthographic lexicon) instead of phonological long-term memory. Stored representations here contain information about the identity and position of the graphemes in the word instead of phonemes. These, in turn, are processed by orthographic working memory (including the graphemic buffer) throughout production of the word. When the word spelling is written, production requires letter shape selection, followed by activation of motor programs to carry out the writing. Spelling in other formats or modalities (oral spelling, typing, etc.) requires the selection/assembly of other motor plans and their motor execution.

Written spelling to dictation (i.e. producing the spelling of a word when given its spoken name) is analogous to reading aloud. As indicated in Figure, 2, all routes begin with auditory processing to recognize the phonemes that make up the auditory word form. When the sublexical route is used, these phonemes are converted directly to graphemes and processed

by orthographic working memory through production. This route results in the correct written form for regular words for which the correct spelling is the most likely one given the phonemes involved². To spell irregular words correctly, their representations must be looked up in orthographic long-term memory. When the SM lexical route is used instead of the sublexical route, phonemes activate stored word forms in phonological long-term memory. From this point forward, the same processing is used as in written picture naming, with activation of the semantic representation followed by activation of the long-term orthographic memory representation. The graphemes of this representation are then processed by orthographic working memory through production of the word.

As in reading, a N-SM lexical route has been proposed that directly associates phonological and orthographic word representations. Again, conceptual semantic information is not necessarily activated when this process is engaged and thus semantic neighbors may have a reduced impact on selection of the orthographic word form. Evidence for a N-SM lexical route has been based on studies of individuals with aphasia who correctly spell irregular words despite limited comprehension of those words (Goodman-Schulman, 1988; Goodman & Caramazza, 1986; Hillis & Caramazza, 1991; Patterson, 1986; Roeltgen, Rothi, & Heilman, 1986). For example, as reported by Patterson (1986), GE could correctly write irregular words to dictation though he could not produce the same words in written naming, spoken naming, or reading tasks. Roeltgen, Rothi, and Heilman (1986) reported several cases who substituted semantically incorrect, irregular homophones for target words. This performance pattern has provided the empirical motivation for positing a direct N-SM lexical spelling process. However, an alternative explanation of these cases (that has also been applied in reading, see Caramazza & Hillis, 1991) suggests that success in spelling irregular words despite extremely limited comprehension may occur based on the interaction between the lexical and sublexical routes –what Caramazza & Hillis (1991) referred to as the “summation hypothesis.” The information about the likely graphemes in the word provided by the sublexical route, combined with partial information from the damaged SM lexical route, may provide enough activation for selection of the appropriate orthographic word form, even when it has an irregular spelling. For example, if the dictated word is “knee”, the sublexical route might activate the graphemes involved in plausible spellings like NEE, NEA, and NIE. There might also be partial information from a damaged semantic representation, such as “body part”, that would send activation to the orthographic lexical representation of KNEE as well as to the lexical representations of other body parts such as ELBOW, LEG, EAR, THUMB, etc. These would in turn send activation to their constituent graphemes. Together, the information about graphemes activated by the sublexical route and the information from the damaged SM lexical route may be adequate for selection of the

²Note that the concepts of regularity and consistency are not exactly the same (e.g., Bonin et al., 2001; Jared, 2002; Lee, Tsai, Su, Tzeng, & Hung, 2005). Regularity is defined in terms of grapheme-to-phoneme correspondences (e.g., Coltheart et al., 2001). Words that have highly probable correspondences are considered regular (e.g. CAT), while those that do not are considered irregular/exception words whose spellings must be retrieved from long-term memory (e.g. YACHT). Regularity is sometimes treated as a categorical concept: if even one of the correspondences in a word is low probability, the word is irregular. On the other hand, consistency refers to broader orthography-phonology mappings (e.g., Peereman & Content, 1999; Seidenberg & McClelland, 1989). The patterns of letters in consistent words are always pronounced the same way (e.g., -UST in DUST), whereas the patterns of letters in inconsistent words have multiple possible pronunciations (e.g. -INT in MINT and PINT). Consistency is sometimes treated as a more graded measure. Overall, it is difficult to disentangle regularity and consistency in alphabetic languages. In the current work, we will manipulate phoneme-to-grapheme correspondences and refer to this as a manipulation of regularity.

appropriate form KNEE even though its spelling is irregular/unpredictable and, therefore, not reliably produced by the sublexical route. Such selection likely involves feedback from orthographic working memory (McCloskey, Macaruso, and Rapp, 2006), where graphemes are activated by both types of information, that may constrain lexical selection in orthographic long-term memory by increasing the activation of lexical representations that contain likely graphemes (e.g. KNEE will be more active than THUMB since THUMB does not contain any of the plausible graphemes from the sublexical route). The summation account of the pattern of good spelling of irregular words in the face of poor comprehension is very difficult to distinguish from the possibility of the direct link between phonological and orthographic word forms. However, it is important to underscore that both alternatives propose that non-semantically mediated processing can make important contributions to correct word spelling. Given that, to date, this evidence has come entirely from individuals with acquired deficits, it is important to understand if these processes play a similar role when neurotypical adults produce written word spellings.

Within the framework provided by the functional architecture of spelling described just above and depicted in Figure 2, we hypothesize that analogous effects of semantic similarity will be found for written naming and written spelling to dictation as have been reported for spoken picture naming and reading aloud. That is, we expect to find semantic interference effects for written picture naming, but not for written spelling to dictation. Such a finding that would allow us to localize the observed interference effects in written picture naming to semantically-mediated lexical selection in line with the models proposed to explain the mechanisms underlying lexical selection in spoken production³. The existing limited research directly investigating the nature of lexical selection in written word production supports this possibility: Nozari and colleagues (2016) reported semantic interference for written and spoken naming of pictures presented for repeated naming in semantically-related two-item blocks.

However, it is not necessarily the case that written and spoken production rely on the same types of mechanisms. There are important differences between the two modalities. In the adult system, written words are produced over a much longer time course and in a more serial fashion than are spoken words. These substantive differences in response execution may influence the temporal dynamics of these systems. Furthermore, while written language certainly depends on spoken language during development, many findings support the autonomy of written word production in the adult expert system. Evidence for the dissociability of the two systems come from studies of individuals who are impaired in lexical selection in spoken production but relatively intact in lexical selection in the written modality or vice versa (e.g., Miceli & Capasso, 1997; Rapp, Benzing, & Caramazza, 1997; Tainturier, Moreaud, David, Leek, & Pellat, 2001). For example, case R.G.B. (Caramazza & Hillis, 1990) made semantic errors in spoken picture naming (e.g., picture of mittens → "sock") but not in written picture naming. Such findings would not be predicted if

³As in reading aloud, one could consider semantically-mediated lexical selection to be "active" retrieval. In accordance with the parallels between the memory and language literatures drawn previously, one would again expect to see semantic interference for written picture naming but not written spelling to dictation since written picture naming requires "active" retrieval but written spelling to dictation does not.

written lexical access was necessarily mediated by spoken lexical access in adulthood. In neurotypical adults too, although phonological information may be automatically activated during written production (e.g., Alario, De Cara, & Ziegler, 2007; Humphreys, Evett, & Taylor, 1982; Rastle & Brysbaert, 2006; Zhang & Damian, 2010), phonological mediation between semantic processing and orthographic lexical retrieval is not obligatory (Bonin, Fayol, & Peereman, 1998; Shen, Damian, & Stadthagen-Gonzalez, 2013; but see Afonso & Álvarez, 2011). Therefore, different mechanisms could conceivably underlie lexical selection of phonological vs. orthographic word forms.

Despite the functional independence between spoken and written word production processes, similar organizational principles have been observed in previous research (Bonin & Fayol, 2000). For instance, grammatical category plays a similar role in the organization of lexical entries for both spoken and written production (Rapp & Caramazza, 1997). Moreover, activation of non-target “neighborhood” words during both lexical phonological and lexical orthographic processing is driven by similar factors, including position-specific form overlap, lexical frequency, grammatical category, target length, and initial segment identity (Goldrick et al., 2010). Similarly, spoken and written picture naming latencies are driven by the same factors, which include image variability, image agreement and age of acquisition (Bonin, Chalard, Méot, & Fayol, 2002). Other evidence suggests that segmental encoding, the process following lexical selection that identifies the segments that make up a word, relies on an incremental learning mechanism like that proposed for spoken lexical selection in both the spoken and written modalities (Breining et al., 2016). Given these similarities, one might expect similar activation principles for lexical selection in written and spoken production.

In summary, while there is evidence that spoken and written production follow a set of general cognitive principles, this is not because written production relies on spoken production. This distinction has two consequences: (1) One cannot assume that principles observed in spoken production necessarily generalize to written production; (2) Observing comparable effects in both modalities points to the domain-generality of core cognitive principles, regardless of the domain-specific representations on which those principles operate.

The Current Study

In the present study, we investigate the extent to which activation and selection principles are shared across modalities, addressing two issues. First, we examine the dynamics of semantically-mediated lexical selection. In written production, do semantic interference effects arise due to use of the SM lexical route? In Experiment 1, we use a written version of the blocked cyclic naming paradigm, in which participants write the names of the same pictures in semantically similar homogeneous blocks and in unrelated heterogeneous blocks, to determine if semantic interference effects are observed in written word production as they are in spoken word production. In Experiment 2, we use a written spelling to dictation task with the same materials in order to test whether the effects of semantic similarity are changed when semantically-mediated lexical selection is not necessary. A reduction or reversal of the effect would be in line with results from reading aloud reported in the spoken

literature, indicating that similar principles underlie semantically-mediated lexical selection in both modalities.

The second issue addressed by this study concerns the contribution of non-semantically mediated spelling routes. What role do they play in neurotypical written word production? To address this question, in Experiment 3, we investigated the possible role of N-SM lexical and/or sublexical processes in spelling words with low probability phoneme-to-grapheme correspondences (irregular words). If the results of Experiments 1 and 2 reveal that the blocked cyclic naming task in picture naming vs. written spelling to dictation can be used to manipulate SM lexical processing, then we can create an experimental situation for neurotypical individuals in which the use of the SM lexical route is reduced due to the use of the written spelling to dictation task. This is somewhat analogous to the situation in which individuals with acquired deficits are limited in their use of the SM lexical route due to semantic deficits. We can then examine if semantic interference effects are observed in spelling to dictation of irregular words, which require lexical but not semantic processing. If semantic interference effects are not observed for irregular words in written spelling to dictation, this would indicate that non-semantically-mediated spelling processes do contribute to lexical spelling in neurotypical production and that their use is part of healthy written word production, not merely a compensatory strategy that becomes necessary after damage.

Experiment 1: The Effect of Semantic Similarity on Written Picture Naming

In Experiment 1, we investigated the effects of semantic overlap in a written blocked cyclic picture naming paradigm to see if the interference that has been widely reported in spoken production occurs when the modality is instead writing. Finding such interference would suggest that similar mechanisms underlie lexical selection in both modalities.

Method

Participants—Twenty adults (mean age 19.7 years, 11 males, 19 right handed) participated. For all the experiments reported in this paper, participants were native English-speaking undergraduate students at Johns Hopkins University who gave informed consent and received course credit in exchange for participation. No individual participated in more than one experiment reported here.

Stimuli—Thirty-six items, consisting of six exemplars of each of six categories (animals, body parts, clothes, furniture, toys, eating utensils), were selected from those used by Schnur and colleagues (2006) in a spoken blocked cyclic picture naming task. Homogeneous blocks consisted of all six items from the same category. Heterogeneous blocks consisted of one item from each of the six categories (Table 1). Items shared few segments: within each list the mean position-independent orthographic overlap, defined as the total number of letters shared by two strings regardless of position, was equally low for homogeneous (0.21) and heterogeneous (0.20) lists (Goldrick et al., 2010). Stimuli were black and white line-drawings of objects taken from Snodgrass and Vanderwart (1980) or that were freely available online.

Procedure—The experiment was run using E-Prime 2 Professional (Psychology Software Tools, Pittsburgh, PA). Picture stimuli (7 inches by 5 inches) were displayed at the center of a monitor (19 inches by 12 inches) placed approximately 20 inches in front of the participants. In the familiarization phase, participants saw each line drawing along with its label, which they read silently.

Participants were trained to use a graphics tablet (Wacom Bamboo) to write their responses. Responses were constrained to a 2.5-inch $\times$ 1-inch rectangle centered at the bottom of the responsive surface. Participants began each trial with the pen placed on a starting point marked on a non-responsive edge of the tablet one inch below the writing surface. They were instructed to begin writing as soon as they knew the name of the picture. When the writing surface was touched, response time (RT) was recorded and the picture was replaced by the participant's pen strokes. After writing a response, participants returned the pen to the marked starting point and advanced to the next trial by pressing a button with their non-dominant hand. Screen shots of completed responses were used to score accuracy.

Participants completed 36 practice trials in which they wrote the name of each item once, receiving corrective feedback for non-target responses. On each trial, a fixation cross appeared on the screen for 1000 milliseconds. Then a stimulus picture was presented on the screen until participants initiated a written response or for 3000 milliseconds if no response was made.

Participants next completed six homogenous and six heterogeneous blocks, presented in pseudorandom order and separated by breaks. Each block consisted of four cycles through the six pictures from one list presented in random order. Individual trial structure was identical to the practice session.

Analysis

Error responses in which participants did not write the intended label or spelled it incorrectly were removed from further analysis, as were outlier responses with response times greater than 2.5 standard deviations from each participant's overall mean. In order to more closely approximate a normal distribution and reduce skewness, response times were log-transformed⁴.

Log-transformed response times were analyzed using linear mixed effects models with random effects using lme4 package version 1.1–12 (Bates, Mächler, Bolker, & Walker, 2015) in R version 3.2.4 (R Core Team, 2016). Two models were constructed. The first model included data from all four cycles for completeness in reporting; the second excluded data from the first cycle since past results indicate that block type interference effects do not typically emerge until after the first cycle which is dominated by initial facilitation due to short-lived semantic priming (Damian & Als, 2005; Navarrete et al., 2014). It was important to evaluate this second model as any null effects of block type in the first model could be due to opposing effects in the first vs. later cycles. The two models had the same structure. Each included block type (heterogeneous vs. homogeneous), cycle (1–4 in the first model;

⁴Across the studies reported here, similar results were obtained for models including raw and log-transformed response times.

2–4 in the second), and the two-way interaction between them as fixed effects. Block type was contrast coded as heterogeneous=1, homogeneous=-1. Cycle was centered and scaled. A full random structure was implemented, with random intercepts for subjects and items as well as random slopes of block type, cycle, and their interaction over subjects and items. For all mixed effects models presented in this paper, we report p -values derived from the t -values using the normal approximation (Mirman, 2014).

Results

Of the total 5760 trials, 4.17% were excluded from further analysis due to incorrect responses, or outlier status. As depicted in Figure 3 and Table 2, participants were faster to initiate production of items in heterogeneous blocks than in homogeneous blocks ($t=-3.80$, $p<.001$ in the model including data from all four cycles, $t=-3.80$, $p<.001$ in the model excluding data from the first cycle.) When data from the first cycle was included, there was a significant effect of cycle ($t=-7.45$, $p<.001$) such that responses in later cycles were significantly faster than responses in earlier cycles, as well as a significant interaction of block type and cycle ($t=-2.17$, $p=.030$) such that speed advantage for heterogeneous blocks increased as more cycles were completed. However, when the first cycle was excluded from the model, neither the main effect of cycle ($t=-1.37$ $p=.171$) nor the interaction of block type and cycle ($t=-1.05$ $p=.295$) was significant.

Discussion

This experiment replicated -in the domain of writing- the semantic interference effect previously reported in spoken production (e.g., Belke, Meyer, & Damian, 2005; Crowther & Martin, 2014; Damian, Vigliocco, & Levelt, 2001; Kroll & Stewart, 1994; Schnur, Schwartz, Brecher, & Hodgson, 2006). This finding is consistent with the idea that similar dynamics underlie lexical selection across the written and spoken modalities, and more specifically with the notion that lexical selection in writing relies on an incremental learning process that generates long-lived interference effects. The finding of a significant cycle effect only when the first cycle is included in the analysis is consistent with past reports of a benefit of repetition between the first and second cycles (e.g. Belke, Meyer, et al., 2005; Schnur et al., 2006).

Experiment 2: The Effect of Semantic Similarity on Written Spelling to Dictation

In Experiment 2, we changed the task from written picture naming to written spelling to dictation. According to the cognitive architecture presented in Figure 2, this task does not require semantically mediated lexical selection. As discussed in the introduction, the interference due to semantic similarity that is seen in picture naming has not been observed in the analogous spoken production task of reading aloud. This experiment allowed us to determine if similar effects are observed in written spelling to dictation.

Method

Participants—Twenty native English-speaking undergraduate students (mean age 19.8 years, 6 male, 18 right handed) participated in the experiment in exchange for course credit.

Stimuli—The same thirty-six items used in Experiment 1 were also used in this experiment. However, instead of black and white line drawings, stimuli were recordings of each word taken from the LDC American English Spoken Lexicon (University of Pennsylvania). Silence was added to the beginning of each file to normalize the length: all files had a total duration of 1100 milliseconds and ended with the spoken word. Response time for written responses was measured relative to the beginning of each spoken stimulus.⁵

Procedure—The procedure was identical to Experiment 1, except that participants heard auditory stimuli presented over headphones instead of viewing pictures. They were instructed to begin writing the word that they heard as soon as possible.

Analysis—Data were analyzed as in Experiment 1, with the exception that an additional covariate, acoustic duration, was included in the fixed effects structure to control for different lengths of the spoken word stimuli. This covariate was centered and scaled. The random effects structure was also expanded to include the random slope of acoustic duration over subjects.

Results

Of the total 5760 trials, 5.19% were excluded from further analysis due to incorrect responses or outlier status. In the text below, only the results of the model excluding the first cycle are reported as this model and the model including the first cycle yielded consistent results. As depicted in Figure 4 and Table 3, participants were not significantly faster to initiate production in heterogeneous blocks or in homogeneous blocks ($t=0.95$, $p=.344$). There was a significant effect of cycle such that responses were faster as the experiment progressed ($t=-2.18$, $p=.029$). There was not a significant interaction of block type and cycle ($t=0.82$, $p=.413$). Participants were slower to begin writing words with longer acoustic durations ($t=5.96$, $p<.001$).

Discussion

In contrast to the results of Experiment 1, no semantic interference effect was observed in Experiment 2. This is congruent with the null effects or facilitation observed in spoken production when participants read aloud blocked words (Belke, 2008, 2013; Belke & Stielow, 2013; Damian et al., 2001), further bolstering the claim that written and spoken production are carried out via similar mechanisms. This finding also allows localization of the semantic interference effect to semantically-mediated lexical selection, a process that is necessary for the written picture naming task (in which interference was found) but which is not obligatory for the written spelling to dictation task (in which interference was not observed).

⁵Note that similar results were obtained in Experiments 2 and 3 when response time was measured from the beginning of each recording (including the added silence) regardless of whether the real acoustic duration of the word was taken into account.

We should note that the words used in Experiments 1 and 2 had fairly regular phoneme-to-grapheme correspondences. Using the published probabilities that a certain phoneme would be written with a certain corresponding grapheme given its syllable position (Fry, 2004; Hanna, Hanna, Hodges, & Rudorf, 1966), we calculated the mean probability across all segments in each word to get a measure of average probability and the probability of the least probable segment in each word. The latter could be the key factor if we assume that a word can only be as regular as its most irregular segment. We found that, on a scale of 1–100, the mean of mean probabilities was 66.84 (standard deviation=17.4) and the mean of minimum probabilities was 29.9 (standard deviation=32.5). These high values indicate that many/most of these words could be spelled using sublexical information alone. Given this, these stimuli do not allow us to evaluate if semantically mediated lexical processing is required for less predictable, irregular words that cannot be reliably spelled correctly via the sublexical process.

Experiment 3: The Effect of Semantic Similarity on Written Spelling to Dictation for Items with High and Low Phoneme-to-Grapheme Correspondence Probabilities

Experiment 2 demonstrated that neurotypical individuals do use at least one of the non-semantically-mediated spelling routes to perform written spelling to dictation. Experiment 3 follows up on this finding. Do these routes contribute only when lexical selection is unnecessary, as when sublexical information suffices to produce correct spellings for words with highly predictable spellings, or do they also play a role when lexical information must be retrieved but semantic information is not needed, as when irregular words are spelled?

In Experiment 3, we compare written spelling to dictation of words with high and low probability phoneme-to-grapheme correspondences. Words with high probability correspondences are spelled regularly and can be correctly assembled via the sublexical route. As in Experiment 2, we hypothesized that there would not be a significant semantic interference effect in this condition. Words with low probability correspondences are irregular, and the correct spelling must be retrieved from long-term memory via the lexical route. If non-semantically-mediated spelling routes are responsible for spelling these words in neurotypical individuals, as has been found in individuals with acquired semantic deficits, semantic interference should not be observed in this condition. On the other hand, if the non-semantically mediated spelling routes are insufficient for spelling these words, then semantic interference should be observed in this condition.

Method

Participants—Twenty-one adults (mean age 19.3 years, 5 males, 19 right handed) participated in the condition involving words with high probability phoneme-to-grapheme correspondences. A separate group of twenty-one adults (mean age 19.4 years, 9 male, 18 right handed) participated in the low probability condition. Participants were native speakers of English who received course credit for participating. A cross-subjects design was used to avoid the possibility that spelling both types of words, might bias against sublexical (non-semantically mediated) processing and favor lexical processing (e.g., Bonin, Collay, Fayol,

& Méot, 2005). In other words, using a cross-subjects design maximizes the possibility of differential use of semantically mediated and unmediated processes for the two word types.

Stimuli—For each condition, thirty-six items (Tables 4 and 5) consisting of six exemplars from six categories were selected. As in the previous experiments, all items appeared in both homogeneous and heterogeneous blocks. Within each condition, items within each homogeneous blocks were more similar to each other than items in heterogeneous blocks according to measures of semantic similarity consisting of WordNet path distance between the words in a hierarchical lexical database (Princeton University), $t(10)=2.74$, $p<0.02$, mean difference=0.076, SE=0.028, 95% CI=0.01–0.14 for the high probability condition; $t(6.57)=5.63$, $p=0.001$, mean difference=0.083, SE=0.015, 95% CI=0.05–0.12 for the low probability condition; and Latent Semantic Analysis (Landauer et al., 1998), $t(10)=2.50$, $p=0.03$, mean difference=0.135, SE=0.054, 95% CI=0.01–0.25 for the high probability condition; $t(5.53)=2.74$, $p=0.04$, mean difference=0.140, SE=0.051, 95% CI=0.01–0.27 for the low probability condition. Homogeneous and heterogeneous groups within each condition did not differ in position-independent orthographic overlap, $t(10)=0.42$, $p=0.68$, mean difference=0.012, SE=0.029, 95% CI=–0.08–0.05 for the high probability condition; $t(10)=0.39$, $p=0.71$, mean difference=0.008, SE=0.020, 95% CI=–0.04–0.05 for the low probability condition.

Using the phoneme-to-grapheme correspondence frequencies by position in syllables that was reported by Hanna, Hanna, Hodges, and Rudolf (1966) and updated by Fry (2004), we calculated the mean phoneme-to-grapheme correspondence probability for each word, as well as the minimum phoneme-to-grapheme probability. Across the two conditions, words in the high probability condition had higher mean phoneme-to-grapheme correspondence probabilities (mean=89.88), than those in the low probability condition (mean=44.42), $t(41.60)=16.58$, $p<0.001$, mean difference=45.46, SE=2.74, 95% CI=39.9–51.0 as well as higher minimum phoneme-to-grapheme correspondence probabilities (mean=75.36), than those in the low probability condition (mean=2.17), $t(39.60)=26.81$, $p<0.001$, mean difference=73.19, SE=2.73, 95% CI=67.7–78.7. Stimuli across the two conditions were matched on frequency as well as length in letters, phonemes, and syllables using values from the MRC Psycholinguistic Database (Coltheart, 1981).

As in Experiment 2, auditory stimuli consisted of recordings of each word taken from the LDC American English Spoken Lexicon (University of Pennsylvania). Silence was added to the beginning of each file to normalize the length to a total duration of 1100 milliseconds ending with the spoken stimulus.

Procedure—The procedure was identical to Experiment 2.

Analysis—Log-transformed response times from both conditions (high and low probability) were entered into linear mixed effects models. The structures of these models added the fixed effect of condition and its two- and three-way interactions with block type and cycle to the model structures utilized in Experiment 2. Condition was coded as high=1, low=–1. The random effects structures were not changed as the two conditions relied on different items and subjects. Separate models with the same structures used in Experiment 2

were also constructed to evaluate effects within the high and low probability conditions, allowing for evaluation of whether the same effects observed in the combined model are present in for both individual conditions or whether the patterns of effects differ for the two.

Results

Of the total 6048 trials in the high probability condition, 3.09% were excluded from further analysis due to incorrect responses or outlier status, as were 3.70% of the 6048 trials in the low probability condition.

Figure 5 depicts the results. The left panel shows the high probability condition, and the right panel shows the low probability condition. Tables 6–8 show the results of the models. Table 6 includes models of the combined data from the high and low probability conditions; Table 7 includes models of the data from the high probability condition; and Table 8 includes models of the data from the low probability condition. In the text below, we report the results of the models excluding the first cycle, noting the results of the models including the first cycle only where they diverged.

In the combined analysis, there was no overall effect of condition ($t=-1.01$, $p=.313$). Critically, there was no interaction of condition and block type ($t=0.47$, $p=.640$), indicating that the effect of block type was consistent across the high and low probability conditions. Overall, blocking did not lead to semantic interference. The effect of block type was not significant in the combined model excluding data from cycle 1 ($t=1.62$, $p=.105$) although significant facilitation was observed in the combined model including data from cycle 1 ($t=1.98$, $p=.048$) such that participants were faster to respond to items presented in homogeneous as compared to heterogeneous blocks. In the models that separately evaluated the high and low probability conditions, there were no significant effects of block type in either the high probability condition ($t=1.68$, $p=.093$) or the low probability condition ($t=0.74$, $p=.459$).

In the combined analysis, there was a significant effect of cycle ($t=-5.75$, $p<.001$) whereby participants were faster to respond to items presented in later cycles. There was not a significant interaction of condition and cycle ($t=-0.81$, $p=.420$), indicating that the increase in speed across the experiment did not differ for the high and low probability conditions. Furthermore, the separate analyses showed significant effects of cycle in both the high probability condition ($t=-4.51$, $p<.001$) and the low probability condition ($t=-3.51$, $p<.001$).

In the combined analysis, there was a significant interaction between block type and cycle in the model excluding data from the first cycle ($t=2.27$, $p=.023$), reflecting a larger increase in speed over cycles for homogeneous blocks than heterogeneous blocks, although the interaction was not significant in the model including data from the first cycle ($t=0.82$, $p=.410$). The three-way interaction between condition, block type, and cycle was not significant ($t=1.20$, $p=.231$). Looking within each condition separately, there was a significant interaction of block type and cycle in the high probability condition ($t=2.41$, $p=.016$) such that there was a larger increase in speed over cycles for homogeneous blocks than heterogeneous blocks. The interaction of block type and cycle was not significant in the low probability condition ($t=0.75$, $p=.451$).

In terms of acoustic duration, participants were faster to respond to words with shorter durations in the combined analysis ($t=10.55$, $p<.001$). This significant effect also observed in the separate analyses of the high probability condition ($t=6.26$, $p<.001$) and the low probability condition ($t=8.53$, $p<.001$).

Discussion

The results of this experiment did not show semantic interference for written spelling to dictation of words with high probability phoneme-to-grapheme correspondences, in line with the results of Experiment 2 and past results from studies of reading aloud. The block type effect was no different when stimuli were words with low probability phoneme-to-grapheme correspondences: again, there was no semantic interference. These findings suggest that non-semantically-mediated spelling routes play an important role in neurotypical written spelling to dictation, both when the task can be completed sublexically (as with regular words with high probability phoneme-to-grapheme correspondences) and when lexical but not semantic retrieval is required (as with irregular words with low probability phoneme-to-grapheme correspondences). In contrast to the null effects of semantic similarity, there were effects of cycle in both the high and low probability conditions indicating that responses in later cycles were faster than responses in earlier cycles. Finding this effect of cycle as well as an interaction of cycle with block type in some models demonstrated that there was adequate statistical power to detect at least some effects.

General Discussion

In three experiments, we examined the effects of semantic similarity on written word production. The key findings are as follows: (1) Experiment 1 replicated the semantic interference effect found in spoken blocked cyclic picture naming in the written modality. (2) Experiment 2 showed that the semantic interference effect disappeared when the task was changed from written picture naming to written spelling to dictation. This is parallel to the results found in spoken production for the task of reading aloud. The combined results of Experiments 1 and 2 support the proposal that long-lived semantic interference effects in naming are caused by incremental learning in semantically-mediated lexical selection. (3) Experiment 3 demonstrated that there was not significant semantic interference for written spelling to dictation regardless of whether the words to be written had high or low probability phoneme-to-grapheme correspondences, showing that non-semantically-mediated spelling routes contribute to neurotypical written spelling to dictation.

Shared Principles for Speaking and Writing

The results of these experiments have several implications for theories of word production. The work reported here fills an important gap in research by directly investigating the mechanism of lexical selection in written word production. A key implication of our results is that they provide evidence of shared principles across modalities of production. The results we report for written production in Experiments 1 and 2 are consistent with the results that have been reported previously for spoken production. They are important not only for our understanding of the written production system itself but also because they provide evidence of the domain-generalty of core cognitive principles. While our results do

not allow us to adjudicate between the different specific mechanisms proposed by Howard and colleagues (2006) and Oppenheim and colleagues (2010), they are consistent with the view that semantic interference arises during semantically-mediated lexical selection due to the three properties of shared activation, priming, and competition regardless of whether the modality of production is written or spoken.

Non-Semantically Mediated Spelling Processes

The results of this study also provide further understanding of the role of non-semantically-mediated spelling processes. The semantic interference effect observed when words are produced via semantically-mediated lexical selection in written picture naming (Experiment 1) disappeared when semantic access was not required (Experiment 2). In addition to bolstering the interpretation that semantic interference arises during semantically-mediated lexical selection, this result demonstrated that non-semantically-mediated spelling routes contribute to neurotypical written spelling to dictation. Experiment 3 followed up on this finding, investigating whether this contribution was limited to situations in which spellings can be produced using only sublexical information. The fact that semantic interference was not found for written spelling to dictation of words with low probability phoneme-to-grapheme correspondences, which cannot be spelled correctly using sublexical information alone, indicates that non-semantically-mediated spelling routes contribute even when lexical retrieval is required. In fact, the effect of blocking did not differ for words with low probability phoneme-to-grapheme correspondences that require lexical information to be retrieved from long-term memory and words with high probability phoneme-to-grapheme correspondences that can be spelled sublexically.

We consider three possible interpretations of this finding. First, our manipulation of high and low probability may not have resulted in sufficiently large differences to be detected given the experimental conditions we adopted. In line with this possibility, we did not find a main effect of high vs. low probability condition in the combined analysis of Experiment 3. This contrasts with past research in which regularity effects have been observed such that written spelling to dictation responses are faster for regular words than for irregular words (e.g., Bonin et al., 2005; Bonin, Peereman, & Fayol, 2001; Delattre, Bonin, & Barry, 2006). However, these previous studies used French stimuli. To our knowledge, regularity effects in written spelling to dictation have not been reported in neurotypical individuals for English stimuli. Note that, in English, regularity effects have not always been found for the analogous spoken production task of reading aloud, with research indicating that there is a frequency by regularity interaction such that regularity effects are observed for low frequency words but not consistently for high frequency words (e.g., Coltheart et al., 2001; Fischer-Baum, Dickson, & Federmeier, 2014; Paap & Noel, 1991). Similar effects may occur in written spelling to dictation, making it more difficult to observe a difference between the high and low probability conditions, unless sufficiently low frequency words are used. In our Experiment 3, mean Kucera and Francis (1967) written frequencies were 27.2 (standard deviation=59.86). Thus, one account of our failure to find a main effect of regularity could be related to the relatively high frequency of the stimuli used. Certainly the issue of a possible interaction of regularity and frequency in written spelling to dictation in

English merits investigation in future work as it is important to know if the semantically mediated spelling route in spelling to dictation is deployed only for lower frequency words.

The other two possibilities are consistent with the idea that non-semantically-mediated spelling routes play a role in written word production. One account of the absence of the semantic blocking effect in the face of correct spelling of irregular words is that written spelling to dictation relies largely on the direct N-SM lexical route that connects phonological and orthographic long-term memory representations without necessarily contacting semantic representations. Given the proposal that it is specifically the semantic-to-lexical connections (involved in “active” retrieval) that lead to interference, long-lasting semantic interference would not be observed since these connections are not used by the direct N-SM route. Alternatively, the failure to find semantic interference in written spelling to dictation could occur in a system that does not include a N-SM lexical process if the results are instead due to the interaction of the SM lexical and the sublexical routes, both of which are active in production including during written spelling to dictation (Bonin, Collay, Fayol, & Méot, 2005; Bonin et al., 2015; Bonin, Méot, Millotte, & Barry, 2013; Rapp et al., 2002; Tainturier & Rapp, 2001). The output of the sublexical route may constrain the selection of lexical representations via feedback from orthographic working memory (see discussion in the introduction for details). Under this view, even if the SM lexical route is active, the sublexical constraints might reduce its impact. By rapidly increasing the activation of a target word (e.g., KNEE) well beyond the activation of non-target competitors (e.g., THUMB and EAR) competition in lexical selection is reduced and any changes due to incremental learning may be very small. One piece of evidence consistent with possible activity of the SM route is the observation of a significant block type effect in the combined analysis of Experiment 3 that included data from the first cycle, suggesting initial semantic facilitation that seems unlikely if the SM route is entirely inactive. However, the data we have collected in the present study do not allow us to distinguish between the two possibilities regarding the role of non-semantically-mediated spelling routes. (See Hillis & Caramazza, 1991 for discussion of similar interpretive difficulties in cognitive neuropsychological cases.) Further investigation with different methods should be undertaken to examine the possible interpretations and their consequences.

Summary

Overall, the results of this study reveal that similar organizational principles and mechanisms are used in both written and spoken word production. Specifically, the findings are consistent with an incremental learning mechanism that underlies semantically-mediated lexical selection. However, this mechanism is not the predominant driver of activation and selection when semantic access is not required, as in written spelling to dictation. In that situation, non-semantically-mediated spelling processes make important contributions to written word production, even in neurotypical individuals.

Acknowledgments

We are grateful for the support provided by NIH grant DC006740 for the investigation of the neural and cognitive bases of post-stroke recovery in dysgraphia.

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Fig. 1.

A cognitive architecture of spoken production. Three routes can be used to produce spoken words: semantically mediated (SM) and non-semantically mediated (N-SM) lexical routes as well as the sublexical route. In reading aloud, any of the three routes can be used. All begin with visual processing to recognize the graphemes in the written word form. When the sublexical route is used, graphemes are directly converted to phonemes. When the SM lexical route is used, graphemes activate the stored word form in orthographic long-term memory, which then activates meaning features in the semantic system and then the stored word form in phonological long-term memory. Alternatively, the N-SM lexical route (depicted with a dashed line) can be used, bypassing the semantic system. All routes result in selected phonemes that are held in phonological working memory throughout production of the spoken word. In spoken picture naming, the SM lexical route is used as visual object recognition processes provide input to the semantic system.

Fig. 2.

A cognitive architecture of written production. As in spoken production, three routes can be used to produce written words: semantically mediated (SM) and non-semantically mediated (N-SM) lexical routes as well as the sublexical route. In written spelling to dictation, any of the three routes can be used. All begin with auditory processing to recognize the phonemes in the spoken word form. When the sublexical route is used, phonemes are directly converted to graphemes. When the SM lexical route is used, phonemes activate the stored word form in phonological long-term memory, which then activates meaning features in the semantic system and the stored word form in orthographic long-term memory. Alternatively, the N-SM lexical route (depicted with a dashed line) can be used, bypassing the semantic system. All routes result in selected graphemes that are held in orthographic working memory throughout production of the written word. In written picture naming, the SM

lexical route is used as visual object recognition processes provide input to the semantic system,.

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Fig. 3.

Results of Experiment 1: The effect of semantic similarity on response times for written picture naming of words in semantically homogeneous versus semantically heterogeneous blocks. Error bars represent the between-subjects standard errors of the means, corrected for repeated measures using the Cousineau (2005) method.

Fig. 4. Results of Experiment 2: The effect of semantic similarity on response times for written spelling to dictation of words in semantically homogeneous versus semantically heterogeneous blocks. Error bars represent the between-subjects standard errors of the means, corrected for repeated measures using the Cousineau (2005) method.

Fig. 5.

Results of Experiment 3: The effect of semantic similarity on response times for written spelling to dictation of words with high and low probability phoneme-to grapheme correspondences presented in semantically homogeneous versus semantically heterogeneous blocks. The left panel shows the results of the high probability condition. The right panel shows the results of the low probability condition. Error bars represent the between-subjects standard errors of the means, corrected for repeated measures using the Cousineau (2005) method.

Items used in Experiments 1 and 2. The six items in each row form a homogeneous block, with all items drawn from the same semantic category. The six items in each column form a heterogeneous block, with items drawn from different semantic categories.

Table 1

heterogeneous blocks					
homogeneous blocks	bear	cat	skunk	goat	horse
	dog	arm	skirt	chair	kite
	fork	pitcher	knife	balls	blocks
	cup	bat	table	dress	ear
	spoon	top	bed	glove	nose
	glass	doll	sofa	hat	chair

Table 2

Results of the analysis of the models of written picture naming in Experiment 1.

Fixed effects	Including All Cycles				Excluding First Cycle			
	Coefficient	SE	<i>t</i>	<i>p</i>	Coefficient	SE	<i>t</i>	<i>p</i>
Intercept	6.65	0.04	187.71	<.001	6.63	0.04	182.82	<.001
Block type (heterogeneous vs. homogeneous)	-0.02	<0.01	-3.80	<.001	-0.02	<0.01	-3.80	<.001
Cycle	-0.03	<0.01	-7.45	<.001	<0.01	<0.01	-1.37	.171
Block type*Cycle	-0.01	<0.01	-2.17	.030	<0.01	<0.01	-1.05	.295
Random effects	Variance				Variance			
Item intercept	0.00055				0.00058			
Block type Item slope	0.00031				0.00040			
Cycle Item slope	0.00005				0.00002			
Block type*Cycle Item slope	0.00005				0.00004			
Subject intercept	0.02469				0.02587			
Block type Subject slope	0.00008				0.00016			
Cycle Subject slope	0.00011				0.00009			
Block type*Cycle Subject slope	0.00001				0.00001			
Residual	0.02588				0.02421			

Table 3

Results of the analysis of the models of written spelling to dictation in Experiment 2.

Fixed effects	Including All Cycles				Excluding First Cycle			
	Coefficient	SE	t	p	Coefficient	SE	t	p
Intercept	6.64	0.05	139.19	<.001	6.63	0.05	136.04	<.001
Block type (heterogeneous vs. homogeneous)	<0.01	<0.01	0.82	.410	<0.01	<0.01	0.95	.344
Cycle	-0.02	0.01	-3.08	.002	-0.01	<0.01	-2.18	.029
Acoustic duration	0.04	0.01	5.91	<.001	0.04	0.01	5.96	<.001
Block type*Cycle	<0.01	<0.01	0.92	.357	<0.01	<0.01	0.82	.413
Random effects	Variance				Variance			
Item intercept	0.00142				0.00139			
Block type Item slope	0.00007				0.00008			
Cycle Item slope	0.00002				0.00002			
Block type*Cycle Item slope	<0.00001				0.00001			
Subject intercept	0.04462				0.04662			
Block type Subject slope	0.00018				0.00018			
Cycle Subject slope	0.00048				0.00029			
Acoustic duration Subject slope	0.00013				0.00014			
Block type*Cycle Subject slope	0.00002				0.00006			
Residual	0.02478				0.02426			

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Table 4

Items used in Experiment 3: High Probability Phoneme-to-Grapheme Correspondences. The six items in each row form a homogeneous block, with all items drawn from the same semantic category. The six items in each column form a heterogeneous block, with items drawn from different semantic categories.

homogeneous blocks						heterogeneous blocks					
pig	crab	rat	panda	wasp	squid	pig	crab	rat	panda	wasp	squid
rib	mouth	hand	tooth	scalp	chin	rib	mouth	hand	tooth	scalp	chin
corn	banana	ham	oil	brownie	taco	corn	banana	ham	oil	brownie	taco
bed	stool	bench	lamp	cot	crib	bed	stool	bench	lamp	cot	crib
blimp	sled	ferry	van	raft	taxi	blimp	sled	ferry	van	raft	taxi
cloud	mist	wind	tornado	storm	frost	cloud	mist	wind	tornado	storm	frost

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Table 5

Items used in Experiment 3: Low Probability Phoneme-to-Grapheme Correspondences. The six items in each row form a homogeneous block, with all items drawn from the same semantic category. The six items in each column form a heterogeneous block, with items drawn from different semantic categories.

homogeneous blocks						heterogeneous blocks					
owl	dove	crow	goose	eagle	robin						
knee	eye	thumb	ear	toe	stomach						
almond	Tea	juice	rye	sugar	berry						
kettle	utensil	knife	bowl	funnel	jar						
wedge	pulley	hoe	axe	wrench	chisel						
trolley	kayak	hearse	rocket	bicycle	yacht						

Table 6

Results of the analysis of the models of combined high and low probability phoneme-to-grapheme correspondence conditions in written spelling to dictation in Experiment 3.

Fixed effects	Including All Cycles				Excluding First Cycle			
	Coefficient	SE	t	p	Coefficient	SE	t	p
Intercept	6.72	0.02	272.38	<.001	6.70	0.03	266.61	<.001
Condition (high vs. low p-to-g probability)	-0.02	0.02	-0.96	.340	-0.03	0.03	-1.01	.313
Block type (heterogeneous vs. homogeneous)	0.01	<0.01	1.98	.048	0.01	<0.01	1.62	.105
Cycle	-0.03	<0.01	-11.04	<.001	-0.01	<0.01	-5.75	<.001
Acoustic duration	0.04	<0.01	10.00	<.001	0.04	<0.01	10.55	<.001
Condition*Block type	<0.01	<0.01	0.04	.970	<0.01	<0.01	0.47	.640
Condition*Cycle	<0.01	<0.01	-1.44	.151	<0.01	<0.01	-0.81	.420
Block type*Cycle	<0.01	<0.01	0.82	.410	<0.01	<0.01	2.27	.023
Condition*Block type*Cycle	<0.01	<0.01	1.65	.099	<0.01	<0.01	1.20	.231
Random effects	Variance		Variance		Variance		Variance	
Item intercept	0.00085				0.00075			
Block type Item slope	0.00017				0.00013			
Cycle Item slope	0.00001				0.00002			
Block type*Cycle Item slope	0.00001				0.00001			
Subject intercept	0.02496				0.02599			
Block type Subject slope	0.00018				0.00022			
Cycle Subject slope	0.00012				<0.00001			
Acoustic duration Subject slope	0.00022				0.00016			
Block type*Cycle Subject slope	0.00006				0.00005			
Residual	0.02768				0.02759			

Table 7

Results of the analysis of the models of the high probability phoneme-to-grapheme correspondence condition in written spelling to dictation in Experiment 3.

Fixed effects	Including All Cycles				Excluding First Cycle			
	Coefficient	SE	t	p	Coefficient	SE	t	p
Intercept	6.70	0.04	152.76	<.001	6.68	0.04	150.10	<.001
Block type (heterogeneous vs. homogeneous)	0.01	<0.01	1.63	.104	0.01	<0.01	1.68	.093
Cycle	−0.03	<0.01	−8.27	<.001	−0.01	<0.01	−4.51	<.001
Acoustic duration	0.04	0.01	5.96	<.001	0.04	0.01	6.26	<.001
Block type*Cycle	<0.01	<0.01	2.03	.042	0.01	<0.01	2.41	.016
Random effects	Variance				Variance			
Item intercept	0.00094				0.00078			
Block type Item slope	0.00010				0.00011			
Cycle Item slope	0.00001				0.00002			
Block type*Cycle Item slope	<0.00001				0.00002			
Subject intercept	0.03970				0.04099			
Block type Subject slope	0.00012				0.00013			
Cycle Subject slope	0.00015				<0.00001			
Acoustic duration Subject slope	0.00031				0.00025			
Block type*Cycle Subject slope	0.00001				0.00004			
Residual	0.02928				0.02919			

Results of the analysis of the models of the low probability phoneme-to-grapheme correspondence condition in written spelling to dictation in Experiment 3.

Table 8

Fixed effects	Including All Cycles				Excluding First Cycle			
	Coefficient	SE	t	p	Coefficient	SE	t	p
Intercept	6.74	0.02	297.18	<.001	6.73	0.02	286.87	<.001
Block type (heterogeneous vs. homogeneous)	0.01	<0.01	1.24	.216	<0.01	0.01	0.74	.459
Cycle	-0.02	<0.01	-6.86	<.001	-0.01	<0.01	-3.51	<.001
Acoustic duration	0.05	0.01	8.28	<.001	0.05	0.01	8.53	<.001
Block type*Cycle	<0.01	<0.01	-0.50	.619	<0.01	<0.01	0.75	.451
Random effects	Variance				Variance			
Item intercept	0.00078				0.00075			
Block type Item slope	0.00024				0.00016			
Cycle Item slope	0.00005				0.00003			
Block type*Cycle Item slope	0.00002				0.00001			
Subject intercept	0.01026				0.01099			
Block type Subject slope	0.00023				0.00032			
Cycle Subject slope	0.00010				<0.00001			
Acoustic duration Subject slope	0.00012				0.00009			
Block type*Cycle Subject slope	0.00012				0.00006			
Residual	0.02599				0.02591			