Journal of Experimental Psychology:
Learning, Memory, and Cognition
2011, Vol. 37, No. 4, 813–826

0278-7393/11/$12.00 DOI: 10.1037/a0023260

Long-Term Repetition Priming in Spoken and Written Word Production: Evidence for a Contribution of Phonology to Handwriting

Markus F. Damian
University of Bristol

Dusana Dorjee and Hans Stadthagen-Gonzalez
Bangor University

Although it is relatively well established that access to orthographic codes in production tasks is possible via an autonomous link between meaning and spelling (e.g., Rapp, Benzing, & Caramazza, 1997), the relative contribution of phonology to orthographic access remains unclear. Two experiments demonstrated persistent repetition priming in spoken and written single-word responses, respectively. Two further experiments showed priming from spoken to written responses and vice versa, which is interpreted as reflecting a role of phonology in constraining orthographic access. A final experiment showed priming from spoken onto written responses even when participants engaged in articulatory suppression during writing. Overall, the results support the view that access to orthography codes is accomplished via both the autonomous link between meaning and spelling and an indirect route via phonology.

Keywords: word production, handwriting, phonology, orthography, orthographic access

Over the past few decades, a considerable amount of work has been carried out to elucidate the processes and mechanisms underlying spoken word production. As a result, detailed computational accounts of speaking have been brought forward (e.g., Dell, Schwartz, Martin, Saffran, & Gagnon, 1997; Levelt, Roelofs, & Meyer, 1999). Relatively less work has been devoted to an understanding of nonoral forms of production, such as handwriting, typing, or spelling. What is known about written production has mostly come from two streams of research. First, writing (and typing) has been considered a special type of skilled motor behavior, and from such a perspective, the way in which graphemes are converted into overt written output (e.g., allographic selection, size control, muscular adjustments, etc.) has been explored in considerable detail (see, e.g., the framework proposed by van Galen, 1991). Models of this type are typically less concerned with psycholinguistic structures and variables that potentially constrain written production. Second, a good number of studies, mainly from a neuropsychological perspective, have investigated orthographic output tasks such as spelling, that is, the conversion of spoken input into orthographic codes, and written picture naming (e.g., Badecker, 1996; Caramazza & Miceli, 1990; see Houghton & Zorzi, 2003, for a computational model of spelling). Recently, researchers have also begun to investigate orthographic production tasks with chronometric methods (e.g., Bonin, Peereman, & Fayol, 2001; Kandel, Hérault, Grosjacques, Lambert, & Fayol, 2009).

A central theoretical issue in the field concerns the extent to which written production is autonomous from, or dependent on, spoken production. This question relates to the larger issue of how the lexical system is structured. Early theoretical accounts (e.g., Geschwind, 1969; Hecaen & Angelergues, 1965; Lichtheim, 1885; Luria, 1970) characterized handwriting as being entirely dependent on the prior retrieval of phonological codes. According to such obligatory phonological mediation theories, to write a word, one would first have to retrieve its phonological format (i.e., covertly name it), and these sound-based codes would subsequently be converted into graphemic codes. This view is prima facie plausible as spoken language precedes written language, in both ontogenetic and phylogenetic terms (e.g., Scinto, 1986). It is also compatible with most individuals' introspection about how spelling is retrieved, as well as the common occurrence of homophone substitutions (*their* → *there*) and phonologically plausible nonword errors (*error* → *errer*) in writing and typing. However, the assumption that orthographic access is phonologically mediated has fallen out of favor because a number of neuropsychological studies have suggested a dissociation between spoken and written production. For example, in some patients, written picture-naming performance is relatively spared when compared to spoken performance, even though the difficulties in spoken production are not caused by articulatory processes (e.g., Assal, Buttet, & Jolivet, 1981; Bub & Kertesz, 1982; Rapp & Caramazza, 1997; Shelton & Weinrich, 1997). On a phonological mediation account, preserved writing in the context of an inability to name should not be possible.

More specifically, patients have been reported who exhibit inconsistent lexical responses in written and spoken production in response to the same picture. For instance, patient WMA (Miceli,

This article was published Online First April 11, 2011.

Markus F. Damian, School of Experimental Psychology, University of Bristol, Bristol, United Kingdom; Dusana Dorjee, School of Psychology, Bangor University, Bangor, United Kingdom; Hans Stadthagen-Gonzalez, ESRC Centre for Research on Bilingualism in Theory & Practice, Bangor University, Bangor, United Kingdom.

This research was supported by Economic and Social Research Council Grant RES-000-22-2449. We would like to thank Linda Wheeldon for assistance in the design of the materials and Jeff Bowers for helpful comments on earlier versions.

Correspondence concerning this article should be addressed to Markus F. Damian, School of Experimental Psychology, University of Bristol, 12a Priory Road, Bristol BS8 1TU, United Kingdom. E-mail: m.damian@bristol.ac.uk

Benvegnu, Capasso, & Caramazza, 1997) produced inconsistent errors of this type, such that generation of an incorrect phonological word form was followed by a correct orthographic word form or such that generation of a semantic error in one modality was followed by the generation of a different semantic error in the other modality. Such findings (see also Miceli & Capasso, 1997; Miceli, Capasso, & Caramazza, 1999) suggest that access to an orthographic entry does not necessitate prior access to a phonological word form and support the orthographic autonomy hypothesis according to which orthographic representations can be directly accessed from semantic representations, without phonological mediation (e.g., Rapp, Benzing, & Caramazza, 1997).

For these reasons, it is by now relatively uncontroversial that writing does not necessarily depend on prior successful phonological retrieval. However, this does not exclude the possibility of cross-talk between the two representational formats, such as direct links between entries in the phonological and orthographic lexicons, and/or sublexical transcoding routes. Figure 1 presents a rough sketch of the lexical output system, involving both phonological and orthographic processing streams. The orthographic autonomy position stipulates that via Link A, semantic activation can directly propagate to entries in the orthographic lexicon. Despite this link, phonology could still influence and constrain orthographic selection. Miceli et al. (1997) distinguished between a weak and a strong version of orthographic autonomy. The weak autonomy view stipulates that entries in both the orthographic and the phonological lexicons are directly activated from the semantic system (via Links A and B in Figure 1, respectively) and map directly onto each other (via Link C; e.g., Allport & Funnell, 1981; Patterson & Shewell, 1987). By contrast, the strong version of orthographic autonomy denies that there are direct links between entries in the two lexicons and stipulates that phonology may influence orthographic access only via sublexical transcoding routes (Link D in Figure 1). On the basis of the inconsistency of errors across response modalities in their reported patient, Miceli et al. (1997) tentatively argued for the strong version of orthographic autonomy (see also Alario, Schiller, Domoto-Reilly, & Caramazza, 2003).

Only a very few empirical studies have addressed the relationship between phonological and orthographic codes in experimental settings and with chronometric tasks, and the results have not been consistent. In such experiments, the dependent variable is typically the time of first contact of a stylus with a digital graphic tablet, mirroring the oral naming times. For instance, Bonin, Fayol, and Peereman (1998) asked French participants to write down the names of pictures that were preceded by masked nonword primes. A facilitatory effect of orthographic overlap was obtained, but crucially, it was not modulated by whether prime and picture name were homophonic (such as in, e.g., *tygre–tigre* [*tiger*]" vs. *togre–tigre*). This finding was taken to argue against a role of phonology in writing. Contrary evidence comes from a study by Bonin et al. (2001) in which the authors manipulated the consistency of phonology–orthography mappings in picture names to identify the contribution and locus of phonological variables in written picture naming. Assuming direct links between the phonological and the orthographic lexicons, picture names consisting of heterographic homophones (*cygne–sign*) should lead to the activation of a single entry in the phonological lexicon, and this should in turn activate multiple orthographic forms in the orthographic lexicon, inducing a processing cost relative to nonhomophonic control words. However, the results showed no difference in written naming latencies, suggesting that inconsistency defined at the lexical level was irrelevant and, hence, that the two lexicons do not map directly onto each other. By contrast, in a further experiment, word-initial inconsistencies defined at the sublexical level affected writing latencies: Inconsistent picture names were written slower than consistent names. These results were taken to suggest that phonology affects orthographic production mainly via sublexical transcoding (Link D in Figure 1). In a picture-word interference task (Zhang & Damian, 2010), participants wrote down names of pictures while attempting to ignore visual distractor words presented at various time intervals (stimulus onset asynchronies [SOAs]). Distractors were orthographically and phonologically related (*hand,* /hænd/–*sand,* /sænd/), orthographically related but phonologically less related (*hand,* /hænd/–*wand,* /wɒnd/), or unrelated. Both types of related distractors produced priming; however, at an SOA of 0 ms, phonologically related distractors yielded more priming than less related ones. At a later SOA of 100 ms, both types of distractors gave similar priming. This pattern suggests a possibly temporary role of phonology in the generation of written production, such that phonological influences on handwriting arise only in the early stages of orthographic preparation.

Overall, some tentative evidence exists suggesting that phonological codes constrain orthographic outputs tasks such as handwriting; however, more evidence is needed to resolve this issue. The experiments reported in this article contribute to this debate by investigating the role of phonology in handwritten word production via the use of persistent repetition priming. The following section outlines the general approach, as well as previous work on persistent effects in spoken production.

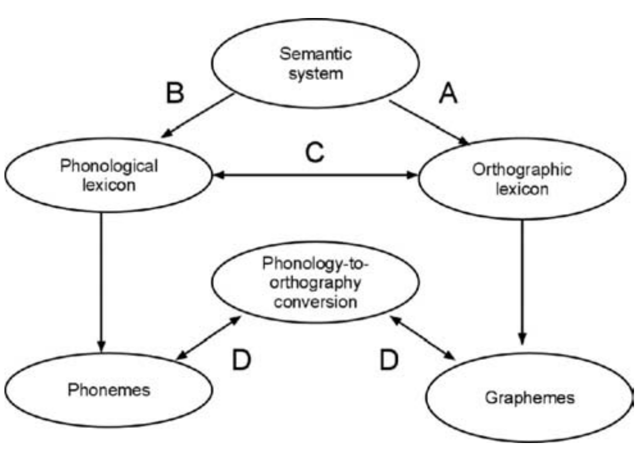

Figure 1. Structure of the production system.

Short-Term Versus Persistent Priming Effects in Lexical Access

A large number of psycholinguistic studies have been devoted to the investigation of priming effects, such as semantic, orthographic, or phonological priming. A common observation is that the priming effects are relatively short lasting (typically in the range of mere seconds). The most commonly used processing metaphor to account for such effects is spreading of activation within a lexical network (e.g., Neely, 1991). However, a different and equally fundamental observation is that priming under certain circumstances can be considerably more persistent. Long-lasting priming effects have been previously studied predominantly from an implicit memory perspective (e.g., Schacter, 1990). According to this approach, such phenomena reflect the operation of memory systems that are functionally separate from those involved in explicit recall and recognition tasks. However, more recently, it has been advocated that persistent priming arises as a side effect of learning within a particular perceptual (and perhaps conceptual) processing system. According to this view, it is unnecessary to postulate a separate memory system (or function) to account for persistent priming; rather, learning processes that take place within perceptual systems manifest themselves as priming in various tasks (see Bowers & Kouider, 2003, for an overview). Hence, effects of this type offer a valuable tool to investigate a particular language domain.

One form of priming that has been shown to persist across considerable time intervals is repetition priming, that is, a processing benefit (faster response times and/or increased accuracy) when a particular stimulus has been processed before. For instance, in spoken word production tasks such as object naming, a picture is named faster and/or more accurately when it is presented again, compared to the initial presentation. This repetition priming has been shown to survive delays of several weeks (e.g., Cave, 1997; Mitchell & Brown, 1988) and possibly as long as one year or longer (e.g., Bock & Griffin, 1998). The priming effect dissociates from participants' ability to recognize an item as having been presented earlier: After substantial delays, episodic memory of the original presentation is much reduced or eliminated, but repetition priming is still observable at full strength (Mitchell & Brown, 1988).

When a picture is repeatedly named, all the cognitive processes involved in the process (object recognition, semantic access, phonological retrieval, articulation) are repeated, and persistent priming could reside at any (or all) of these processing stages (see Barry, Hirsh, Johnston, & Williams, 2001, for discussion). Indeed, both visual and nonvisual contributions to repetition priming in object naming have been documented (see, e.g., van Turennout, Ellmore, & Martin, 2000, for a neuroimaging study identifying the neural correlates of both types of processes). To evaluate whether visual repetition constitutes a necessary condition for repetition priming to arise, Wheeldon and Monsell (1992) asked participants to name pictures on critical target trials but to generate corresponding response words based on short definitions on preceding prime trials (e.g., "What is the largest animal swimming in the sea?"; orally generated answer "whale"). Robust and persistent priming was found, which implies that there are components to repetition priming that are specific to word production and are not attributable to the repetition of a particular image.

One possibility is that access to a particular word form, that is, its phonological representation, is facilitated by repetition. To test this possibility, Wheeldon and Monsell (1992) investigated in a further experiment whether persistent priming is observed when prime and target responses are heterographic homophones, that is, they share their word form but refer to conceptually different entities (*sun–son*; Wheeldon & Monsell, 1992). No priming was found under these circumstances, which suggests that repeated phonological encoding of a response in itself does not support priming.

A further possibility is that persistent repetition priming in picture naming depends on repeated access to conceptual representations. This account was investigated by Monsell, Matthews, and Miller (1992) in an experiment in which fluent bilinguals generated repeated responses to the same conceptual representation in two different languages across prime and target trials (i.e., they responded to a particular definition with an English word and subsequently named a picture corresponding to the same concept, but now with its Welsh name). No priming was found, implying that repetition priming is not mediated by conceptual access.

To account for the overall pattern of findings, Wheeldon and Monsell (1992) and Monsell et al. (1992) suggested that repetition priming in spoken production results from a strengthening of the links between conceptual and phonological codes. Hence, neither conceptual nor phonological access by itself is sufficient to yield repetition priming, but the link between the two representational levels must be engaged for the effect to arise. Such an account of persistent priming fits well with connectionist frameworks of language processing in which learning involves small incremental changes in connection weights (e.g., Harm & Seidenberg, 1999).

Persistent Priming in Orthographic Output Tasks

Given that repetition priming is a well-established phenomenon in domains such as visual word recognition (e.g., Bowers, 1996) and spoken production (e.g., Wheeldon & Monsell, 1992), it is plausible to predict similar effects in orthographic output tasks. If so, such effects may offer insights into lexical access in written word production. However, we are not aware of previous studies that have documented persistent priming in tasks of this type (but see Lambert, Kandel, Fayol, & Esperet, 2007, for a study in which written words were produced multiple times in close succession). Monsell (1987) reported results from an experiment assessing various differences in format (spoken vs. visual) and task requirements (see/hear a word, say word aloud, etc.) and their consequences on repetition priming. In this experiment, writing a missing word within a sentence in a study phase yielded very little (5 ms) repetition priming on a subsequent visual lexical decision probe task. Other than this finding, repetition priming has to our knowledge not been used in the investigation of written production.

In the experiments below, our first aim was to replicate the persistent repetition effect reported by Wheeldon and Monsell (1992) with spoken responses, with a new set of stimuli. Next, we assessed whether a comparable effect could be demonstrated when response words were written, instead of spoken; as will be seen, this was indeed the case.

Subsequently, we addressed the potential role of phonology in the generation of handwritten responses by investigating the possibility of cross-modal repetition effects, such as when a word is initially produced in spoken format and subsequently in written format, or vice versa. Consider a case in which a word is initially produced in spoken format, a process that involves access to the semantic system, retrieval of a word form from the phonological lexicon, and encoding of corresponding phonemes. According to Wheeldon and Monsell (1992), this results in a strengthened link between semantic and phonological codes (Link B in the production system outlined in Figure 1). Subsequently, the same word is produced in written format. According to the orthographic autonomy hypothesis (Rapp et al., 1997), the orthographic lexicon can be directly accessed from conceptual knowledge (Link A in Figure 1).

The relative contribution of phonology can be assessed as follows: If phonology does not contribute to the access of orthographic codes in handwriting, Links C and/or D are functionally irrelevant for the writing of a single word. Hence, Link B, primed via the previous spoken production of the target word, does not affect access to orthographic codes. On the other hand, if phonology contributes to the retrieval of orthographic codes via Links C and/or D, then it is easy to see how cross-modal repetition priming could arise. Link B, primed through the previous spoken production of the target word, allows more efficient access to phonological codes. Subsequent transmission of phonological activation to orthography, via direct mapping between phonological and orthographic lexical entries (Link C) or via sublexical transcoding mechanisms (Link D), will result in speedier and/or more efficient retrieval of orthographic codes. Hence, demonstration of cross-modal repetition priming would constitute strong evidence for the involvement of phonological codes in written word production.

Studies that investigate persistent priming effects can be designed in various ways. They sometimes consist of a single experimental session, possibly itself consisting of several blocks, with prime and target trials interleaved in each block (e.g., Wheeldon and Monsell, 1992; Experiment 1). This design allows the manipulation of the lag between prime and target responses and, hence, a measurement of the time course of priming effects. If the time course of the effect is of less concern, repetition priming could be assessed in a design in which an experiment is subdivided into two phases (study and probe phases), all prime stimuli are administered in the first phase, and all target stimuli are administered in the second phase (e.g., Monsell et al., 1992). In this version, participants are typically instructed that they will take part in two separate experiments, one after the other, with no obvious relation between the two. This design is common in research on visual word recognition (e.g., Bowers, 1996; Bowers & Michita, 1998). In the studies reported below, we chose this latter design and added additional filler trials to both study and probe phases to obscure the fact that a subset of prime trials reappeared in the probe phase.

Experiment 1

Method

Participants. Eighteen students at the University of Bristol (Bristol, United Kingdom) participated in the experiment. They were paid a small fee (£7 [approximately $11 U.S.]) or given course credit for their participation. Participants were native English speakers and had normal or corrected-to-normal vision.

Materials and design. Seventy-four target objects were chosen from the Snodgrass and Vanderwart (1980) set, based on the following criteria: (a) name agreement (from the Barry, Morrison, & Ellis, 1997, norms of the Snodgrass & Vanderwart, 1980, set with British participants) $\geq$ 90% (M = 97.5), (b) object names with fewer than eight letters and phonemes (M = 5.6 and 4.6, respectively), (c) spoken and written CELEX (Baayen, Piepenbrook, & Gulikers, 1995) frequencies of $\leq$20 per million (M = 3.1 and 8.2, respectively), as long-term priming effects are likely to be attenuated for higher frequency stimuli (see Wheeldon & Monsell, 1992, Experiment 1).

Subsequently, we generated 74 corresponding definitions, either as dictionary-type ("A long pointed symbol used to display a direction?"–"arrow") or as a fixed expression in which one word was missing ("He is a ____ of laughs"–"barrel"). As in Wheeldon and Monsell (1992), definitions were chosen so as not to involve the description of visual features, to minimize the chance that responding to the definitions would prime subsequent processing of pictorial features of the corresponding target object instead of its name retrieval. We verified on a separate group of six participants that all definitions elicited the desired responses in at least five out of six cases (M = 95%). All target pictures and corresponding definitions are shown in the Appendix.

The experiment consisted of a study phase, in which participants generated responses based on definitions, and a probe phase, in which pictures were named. In the probe phase, all 74 target objects were presented to all participants, but only half of them, rotated across participants, occurred as definitions in the study phase. To reduce potential variability due to stimulus rotation, the resulting two lists were chosen to be statistically matched on familiarity, name agreement, picture-naming times (all from Barry et al., 1997), word length, and spoken and written frequency, using the utility Match (van Casteren & Davis, 2006).

To obscure the priming relationship for the critical subset of items, 80 filler definitions were included in the study phase and 100 filler pictures in the probe phase. Hence, 31.6% (37 out of 117 trials) of the definition responses in the study phase reappeared in the probe phase, and 21.3% (37 out of 174 trials) of pictures in the probe phase had been previously named in response to definitions.

Apparatus. Stimuli were presented from an Intel-based computer on a 19-in. monitor using DMDX 3.0 (Forster & Forster, 2003). Definitions were presented in black Times New Roman 14-point type on white background. Pictures were standardized to a size of approximately 7 $\times$ 7 cm and presented as black-and-white line drawings on white background. Both definitions and pictures were presented in the center of the screen. Spoken responses were recorded with a headset (Sennheiser mb40) with attached microphone, which was connected to the computer. On each trial, DMDX wrote a digital file to the hard disk and, in the probe phase, determined the onset of each vocal response to the nearest millisecond.

Procedure. Participants were tested individually in a quiet room. They were instructed that they would participate in two independent experiments, each one requiring spoken responses. At the start of the study phase, they were instructed that their task was to generate single-word responses to visually presented definition statements and that they should say the response word as quickly and accurately as possible. A practice block of 10 trials was administered in which definitions other than those in the study phase were presented, followed by the 117 study-phase trials. Completion of the study phase took approximately 20 min. After a short break, participants were instructed that in the second (probe) phase, they would see line drawings of everyday objects on the screen and that their task was to name them as quickly and accurately as possible. A practice block of 20 trials was administered in which pictures other than those used in the main experiment were named, followed by the 174 experimental trials. Completion of the probe phase took approximately 20 min. Hence, the entire experimental session consisted of 291 trials and took approximately 45 min to complete.

In the study phase, a stimulus sequence began with a fixation cross (500 ms), followed by a blank-screen interval (500 ms) and then the presentation of a definition for 3,500 ms. Following the definition, there was a 1,000-ms blank-screen pause before a new trial sequence began. The experimenter monitored responses for accuracy online and noted those trials on which responses other than the expected ones were given.

In the probe phase, the stimulus sequence also began with a fixation cross (500 ms) and a blank-screen interval (500 ms). Pictures were presented for 2,500 ms, and responses were measured relative to the onset of the picture. As in the study phase, the experimenter monitored responses for accuracy and additionally for the presence of hesitations, stutters, mouth clicks, and technical malfunctioning. A blank interval of 1,000 ms separated each stimulus sequence from the next.

Results and Discussion

Latencies on probe-phase trials on which the experimenter had identified an error (3.2%) and response times longer than 1,800 ms or shorter than 250 ms (1.3%) were eliminated from the latency analysis. Additionally, latencies on target trials in the repeated condition on which participants had made an error on a corresponding prime trial were excluded (8.3%). Average latencies and error rates of the repeated and control conditions are shown in Table 1, and cumulative response distributions are displayed in Figure 2. Mean response latencies were faster (59 ms) in the repeated than in the control condition, and Figure 2 shows that this effect extended across the entire response time distribution range. Errors were somewhat lower (0.6%) in the repeated than in the control condition.

Table 1
Response Latencies and Errors for Experiments 1–5

Experiment	Condition		
	Control	Repeated	Difference
1: Spoken–spoken			
Response latency (ms)	872 (241)	813 (193)	59**
Errors (%)	3.5 (18)	2.9 (17)	0.6
2: Written–written			
Response latency (ms)	995 (232)	956 (232)	39**
Errors (%)	4.1 (20)	2.6 (16)	1.5
3: Spoken–written			
Response latency (ms)	1,040 (269)	1,008 (268)	32*
Errors (%)	3.3 (18)	4.2 (20)	−0.9
4: Written–spoken			
Response latency (ms)	819 (231)	783 (203)	36**
Errors (%)	3.8 (19)	3.8 (19)	0.0
5: Spoken–written with articulatory suppression			
Response latency (ms)	1,009 (227)	974 (211)	35**
Errors (%)	4.7 (21)	3.5 (18)	1.2

Note. Standard deviations are in parentheses.
* $p < .01$. ** $p < .001$.

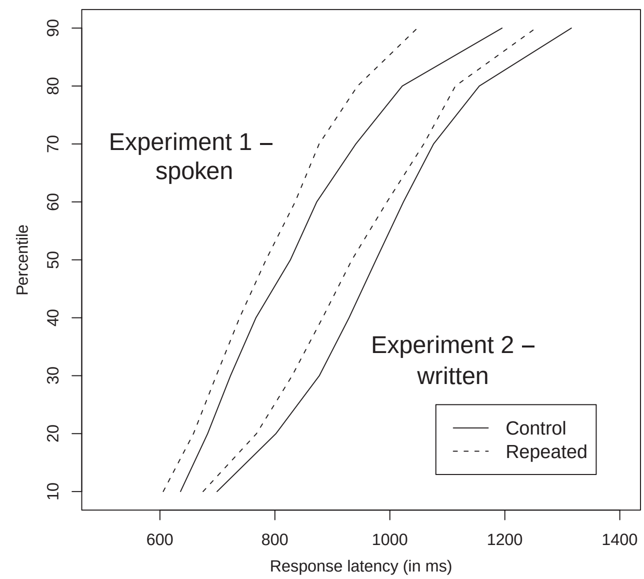

Figure 2. Mean cumulative response distributions for Experiments 1 and 2.

The results of all experiments reported in this article were analyzed using a linear mixed effects methodology (Baayen, 2008; Baayen, Davidson, & Bates, 2008), which simultaneously takes participants and items variability into account, using the software R (R Development Core Team, 2009) with the package lme4 (Bates & Maechler, 2009). An analysis of variance (ANOVA) conducted on the latencies of Experiment 1 with the factor repetition (repeated vs. control) was highly significant, $F(1, 1159) = 20.07$, $MSE = 599{,}313$, $p < .001$. An analysis of the error percentages using logit mixed modeling (Jaeger, 2008) showed that the difference was not significant ($SE = 0.349$, Wald $Z = 0.84$, $p = .400$).

These results replicate, with a new set of stimuli, the previously documented persistent repetition priming effect in spoken word production. The size of the repetition priming effect is generally compatible with previously reported results; for example, Wheeldon and Monsell (1992) reported effects of 77 ms, 46 ms, and 67 ms for their experiments. Having established that a substantial and reliable repetition priming effect can be obtained with our set of target definitions and pictures, we now turn to the question whether a parallel effect can also be found with written responses. The following experiment was identical in design to the first one, except that responses in both study and probe phases were not spoken, but written on a digital tablet, and that response times were measured as the initial time of contact of a stylus with the writing surface.

Experiment 2

Method

Participants. Eighteen students at the University of Bristol, none of whom had taken part in the first experiment, participated and received course credit. All were native English speakers and had normal or corrected-to-normal vision.

Materials and design. These were the same as in Experiment 1.

Apparatus. As in the earlier experiment, stimuli were presented on a 19-in. monitor using DMDX. Written responses were collected with a pressure-sensitive WACOM Intuos A4 graphic tablet and a WACOM inking digitizer pen. Definitions and pictures were displayed toward the bottom of the screen, rather than in the more customary central position, to minimize eye movements between the displays and the writing surface. A sheet of paper was placed on the tablet, and participants wrote down the response word on each trial. Using an inking pen as the stylus yielded a record of the responses, which allowed us to identify errors and to eliminate latencies on corresponding trials. Within the response period of each trial, DMDX registered successive contact on- and offsets of the digital pen with the tablet. From these, the initial time of contact was extracted as the dependent variable.

Procedure. Participants were tested individually. They were instructed that they would participate in two experiments, each requiring a written word as a response on each trial. Participants were instructed to hold the stylus just above the corresponding line on the response sheet in anticipation of the response, such that the response would not require an arm movement. Additionally, during the practice block, participants who dropped the stylus onto the sheet at the beginning of the trial, paused until they had identified the response, and then started moving the pen were explicitly instructed not to do so. It was ensured that all participants complied with the instructions before testing began.

The sequence of study and probe phases, as well as the number of practice and critical trials within each phase, was identical to Experiment 1. The timing of the events within each trial was slightly adjusted to take into account the slower execution speed of written responses. In the study phase, a stimulus sequence began with a fixation cross (500 ms), followed by a blank-screen interval (500 ms) and presentation of a definition for 4,500 ms. There was a 1,000-ms blank-screen pause after the sentence was displayed and before a new trial sequence began. In the probe phase, the stimulus sequence also began with a fixation cross (500 ms) and a blank-screen interval (500 ms). Pictures were presented for 3,500 ms, and responses were measured relative to picture onset.

Results and Discussion

Latencies on target-phase trials on which participants had made an error (3.3%), response times longer than 1,800 ms or shorter than 250 ms (3.4%), and latencies on repeated targets on which participants had made an error on the corresponding prime trial (5.2%) were eliminated. Table 1 shows latencies and errors, and Figure 2 shows the response time distributions. An ANOVA showed that response latencies were significantly faster (39 ms) in the repeated than in the control condition, $F(1, 1171) = 12.03$, $MSE = 353{,}105$, $p < .001$. A logit mixed modeling analysis on the error percentages showed no significant difference ($SE = 0.370$, Wald $Z = 1.52$, $p = .128$).

Compared to the first experiment, the results of Experiment 2 exhibited overall slower latencies (difference: 132 ms); the finding of slower responses in written than in spoken responses is generally compatible with previous reports (e.g., Bonin, Chalard, Méot, & Fayol, 2002). More importantly, the results clearly demonstrate that persistent repetition priming was present in a written word production task. The size of the repetition priming effect (39 ms) is somewhat smaller than the one obtained in the first experiment (59 ms). A joint analysis conducted on the combined latency data of the first two experiments showed a main effect of response mode, $F(1, 2330) = 12.00$, $MSE = 357{,}787$, $p < .001$; a main effect of repetition, $F(1, 2330) = 29.62$, $MSE = 882{,}900$, $p < .001$; but no interaction between response mode and repetition ($F < 1$, $p = .403$).

Hence, with a methodology parallel to the one used in spoken production (Experiment 1 and earlier studies such as Wheeldon & Monsell, 1992), written word production is subject to similar repetition priming. The source could be in the process of accessing the orthographic lexicon or in graphemic retrieval, or it could be due to motoric processes (i.e., preparation and execution of the motoric aspects of the response could be rendered faster and more efficient through repeated production). Of course, a further—and, from our point of view, most interesting—possibility is that it could be due to the involvement of phonological variables: If phonological representations contribute to and support handwritten word production, then it is plausible that this is where the priming effect arises. It is also possible that repetition priming arises from multiple sources.

One way of distinguishing effects of response planning from those of execution is to analyze word durations. It is conceivable that repetition priming could affect not only response preparation but also the speed with which a response is executed. Wheeldon and Monsell (1992) computed durations of spoken responses in their study of repetition priming and found, in their first two experiments, no differences between repeated and control items and, in their third experiment, a small but significant facilitation effect. They concluded that the latter effect was probably attributable to priming of speech articulation and was independent of the much larger repetition priming effect arising in word preparation.

We applied this logic to written word production and analyzed word duration. In our experiment, all successive stylus on- and offsets of contact with the digital tablet within each trial were recorded; hence, we were able to extract response durations on each trial. Durations on trials on which response latencies were considered invalid (according to the criteria outlined in the section on the latency analysis) were excluded (8.6%). Additionally, durations on a proportion of trials (6.0%) on which the final recorded event on a trial was not a stylus offset but rather an onset (most likely because participants had not completed response execution by the time the response window of 3.5 s had elapsed) were also excluded. Average durations for the control and the repeated conditions were very similar (1,811 vs. 1,828 ms, respectively). The difference of 17 ms did not differ significantly from zero, $F(1, 1156) = 0.53$, $p = .466$. Hence, repetition priming in handwritten word generation exerts a clear effect on response preparation, but evidently not on execution, providing some evidence against a motoric locus of the effect.

In the next two experiments, we focused on the potential contribution of phonology to writing, and we investigated whether priming is observed when words are produced in spoken format in the study phase but are written in the probe phase (Experiment 3), or vice versa (Experiment 4). In this cross-modal version of the repetition priming paradigm, graphemic production only takes place in either the study or the probe phase, but not in both. Hence, obtaining priming would further rule out motoric priming as the sole source of the results of Experiment 2. Furthermore and more interestingly, finding priming in the cross-modal version would suggest a phonological contribution. Hence, the cross-modal repetition priming task presents a test for the more general claim that orthographic word production is at least partially supported by phonological codes.

Experiment 3

Method

Participants. Twenty students at the University of Bristol, none of whom had taken part in the first two experiments, participated and received course credit. All were native English speakers and had normal or corrected-to-normal vision.

Materials, design, apparatus, and procedure. These were identical to those used in Experiments 1 and 2. However, in the study phase, participants produced their responses to the definitions in spoken form (as in Experiment 1), and in the probe phase, they wrote down their responses on the graphic tablet (as in Experiment 2). All other characteristics of the experiment were identical to the earlier experiments.

Results and Discussion

Latencies on target-phase trials on which participants had made an error (3.8%), response times longer than 1,800 ms or shorter than 250 ms (5.9%), and latencies on repeated targets on which participants had made an error on the corresponding prime trial (6.5%) were eliminated. Table 1 shows latencies and errors, and Figure 3 shows response time distributions. An ANOVA showed that response latencies were significantly faster (32 ms) in the repeated than in the control condition, $F(1, 1300) = 7.47$, $MSE = 277{,}013$, $p = .006$. A logit mixed modeling analysis on the error percentages showed no significant difference ($SE = 0.296$, Wald $Z = 0.99$, $p = .325$).

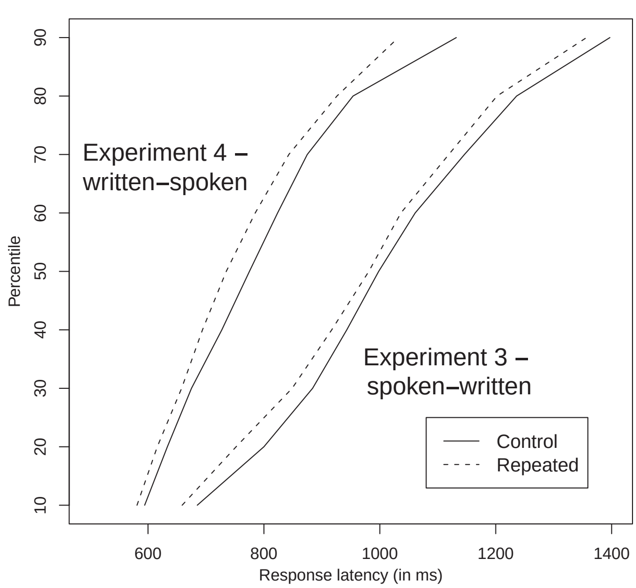

Figure 3. Mean cumulative response distributions for Experiments 3 and 4.

The fact that significant repetition priming persists even across response modalities (from spoken to written responses) suggests that access to phonological codes supports at least a portion of the effect obtained in the written–written case (Experiment 2). Before we discuss the implications of this finding, we report the next experiment, which tested the reverse case, namely, potential priming from written onto spoken responses.

Experiment 4

Method

Participants. Twenty students at the University of Bristol, none of whom had taken part in the earlier experiments, participated and received course credit. All were native English speakers and had normal or corrected-to-normal vision.

Materials, design, apparatus, and procedure. These were identical to those used in Experiment 3, except that the response modes in study and test phases were reversed: In the study phase, participants wrote down their responses on the graphic tablet, and in the test phase, they produced their responses to pictures in spoken form.

Results and Discussion

Latencies on target-phase trials on which participants had made an error (3.8%), response times longer than 1,800 ms or shorter than 250 ms (1.4%), and latencies on repeated targets on which participants had made an error on the corresponding prime trial (3.6%) were eliminated. An ANOVA showed that response latencies were significantly faster (36 ms) in the repeated than in the control condition, $F(1, 1348) = 10.45$, $MSE = 338{,}181$, $p < .001$. A logit mixed modeling analysis on the error percentages showed no significant difference ($SE = 0.304$, Wald $Z = 0.01$, $p = .99$).

The results hence parallel those from Experiment 3 in that clear evidence for cross-response mode repetition priming was obtained. We interpret this finding as evidence for the role of phonology in written word generation. However, there is an alternative account of the results of Experiment 4: While participants wrote down a word, they simultaneously read the generated output. As visual word recognition is generally believed to involve automatic phonological encoding, this would lead to the activation of sound-based representations. If so and written responses are generated in the study phase, then priming onto a subsequent probe phase requiring spoken responses is perhaps not very surprising, and simply reflects the sounding out of the generated written output in the study phase. By contrast, in Experiment 3, written responses were produced in the probe phase, and hence, response latencies reflected processes preceding the execution of the response. Under these circumstances, obtaining priming from a prior spoken production of a target word is evidently a relatively pure measure of the degree of phonological involvement. For this reason, in our view, the results of Experiment 3 are stronger than those of Experiment 4 in providing evidence concerning the role of phonology in handwriting.

If it is indeed the case that handwritten words are phonologically encoded after they have been produced (see above), then it is perhaps surprising that the size of the priming effect in Experiments 3 and 4 is virtually identical (a joint analysis showed no interaction between experiment and repetition priming, $F < 1$). In Experiment 3, in which written words were produced in the probe phase, the results reflect exclusively phonological contributions before a response was initiated, whereas the results of Experiment 4 presumably exhibit these preresponse conditions, plus, additionally, the priming from phonological recoding of a response after it has been produced. Evidently, it is the case that once the phonological lexical entry has been primed, additional priming does not accrue a further benefit on subsequent target retrieval.

In the final experiment, we tested whether the involvement of phonological codes in the generation of written words is to some extent optional. Given that the evidence for an autonomous link between conceptual and orthographic codes is strong (see the introduction), it is possible that the simultaneous activation of phonological codes, although empirically demonstrable (see Experiment 3), is not necessary and that the contribution of this route may be turned off with an appropriate experimental manipulation. Zhang and Damian (2010) reported a picture-word interference experiment involving written responses in which a contribution of phonological overlap between distractors and picture names emerged (i.e., the distractor *sand* primed written picture naming of *hand* more than *wand* did). However, in a second experiment, this effect disappeared when participants engaged in articulatory suppression while writing down the response words. This technique, commonly used in short-term memory research, involves asking participants to perform a secondary task consisting of the reciting of nonsense syllables or words or counting aloud. In short-term memory tasks, this diminishes the classic indicators of phonological rehearsal (word length and phonological similarity effects; e.g., Baddeley, Thomson, & Buchanan, 1975), and it is typically assumed that articulatory suppression prevents refreshing of memory traces via subvocal naming and entering of items into the phonological loop. Given that, in Zhang and Damian's work, this technique evidently reduced the contribution of phonology to written word generation, in our final experiment, we repeated the design of Experiment 3 (spoken responses in the study phase, written responses in the probe phase), but in the probe phase, participants were asked to count aloud on each trial while they wrote down their responses.

Experiment 5

Method

Participants. Eighteen students at the University of Bristol, none of whom had taken part in the earlier experiments, participated and received course credit. All were native English speakers and had normal or corrected-to-normal vision.

Materials, design, apparatus, and procedure. These were identical to those used in Experiment 3, except that in the probe phase, participants were instructed that their main task was to write down the names of presented pictures as fast and accurately as possible. Additionally, they were asked to count aloud from one to 10, starting on each trial as soon as the fixation dot appeared on the screen. Informal tests conducted prior to the setting up of the experiment had shown that the time involved in counting to 10 roughly covered the time it took participants to prepare and write down the picture name.

Results and Discussion

Latencies on target-phase trials on which participants had made an error (4.1%), response times longer than 1,800 ms or shorter than 250 ms (3.8%), and latencies on repeated targets on which participants had made an error on the corresponding prime trial (6.0%) were eliminated. Table 1 shows latencies and errors, and Figure 3 shows response time distributions. An ANOVA showed that response latencies were significantly faster (35 ms) in the repeated than in the control condition, $F(1, 1145) = 12.40$, $MSE = 376{,}803$, $p < .001$. A logit mixed modeling analysis on the error percentages showed no significant difference ($SE = 0.318$, Wald $Z = 1.07$, $p = .296$).

Given that Experiment 5 was identical to Experiment 3 in all aspects other than the presence of articulatory suppression, a joint analysis was conducted on the combined latency data. These showed no effect of experiment ($F < 1$, $p = .370$); an overall effect of repetition, $F = 17.68$, $MSE = 598{,}167$, $p < .001$; but no interaction between experiment and repetition ($F < 1$, $p = 1.00$).

Hence, engaging in articulatory suppression while writing down response words had only minor effects on writing speed and accuracy compared to the condition without articulatory suppression. Importantly, the repetition priming effect was still present at full strength. Evidently, phonology is involved in written word production despite the articulatory suppression manipulation; hence, it is not the case that the involvement of phonological codes in written word generation is to some extent optional. An interesting issue remains why the articulatory suppression manipulation evidently reduced the role of phonology in the picture-word task reported by Zhang and Damian (2010) but not in the repetition priming effect reported here. One possibility is that in the picture-word task, articulatory suppression primarily affects distractor, rather than target, processing. Given that priming in this task arises from participants involuntarily processing a printed distractor word, perhaps articulatory suppression prevents or reduces phonological recoding of the visually presented word. Some evidence exists that this might be the case (Kleiman, 1975; but see Besner, 1987). If so, we would argue that the repetition priming results reported in the current article constitute clearer evidence than the picture-word findings concerning the role of phonology in written word generation.

General Discussion

In five experiments, we utilized persistent repetition priming to identify the contribution of phonological codes to written word generation. Experiment 1 replicated, with a new set of stimuli, the previously reported finding (e.g., Wheeldon & Monsell, 1992) that generating a spoken word in a study phase in response to definitions substantially primes picture naming of the same word in a probe phase. Experiment 2 demonstrated a parallel effect when responses were handwritten, rather than spoken. Experiments 3 and 4 showed that repetition priming was obtained even when responses were spoken in the study phase and written in the probe phase or written first and then spoken. Finally, Experiment 5 demonstrated that, when responses were spoken in the study phase and produced in written form in the test phase with concurrent articulatory suppression, repetition priming still persisted.

The results of Experiment 2 constitute, to our knowledge, the first instance of documented persistent repetition priming in written word generation. As outlined in the introduction, given the preponderance of long-lasting priming in various input modalities and specifically orthographically based priming (e.g., Bowers & Michita, 1998), this finding is perhaps expected. However, it remains of high interest that the extent of priming in Experiment 2 relatively closely resembles the findings of Experiment 1 with spoken responses.

We interpret the results of Experiment 3 and 4, showing priming from spoken to written production and vice versa, as suggesting that the activation of phonological codes contributes to the generation of handwritten responses. According to the position advocated by Wheeldon and Monsell (1992), repetition priming in spoken responses arises from the increased availability of a word form due to an incremental strengthening of the link between conceptual and form-related representations (Link B in Figure 1). In Experiment 3, if this is what took place in the study phase with spoken responses, then finding priming on subsequent writing of the same word (as we did) necessarily implies involvement of phonological codes in access to orthographic representations. The results of this experiment and, to a lesser extent (see above), the data of Experiment 4 in which study and probe modality were reversed hence constitute evidence that phonology supports and constrains orthographic access in written word production.

How Do Phonological Codes Contribute to Written Word Generation?

Our findings imply the contribution of an indirect transmission route from concepts to orthography via phonology. As outlined in the introduction, obligatory phonological mediation in access to orthographic output codes is no longer considered a tenable theoretical position. Hence, the question concerns the exact cross-talk between the two representational formats. Miceli et al. (1997) distinguished between a weak and a strong autonomy view. According to the weak position, entries in both the phonological and orthographic lexicons are activated from the semantic system and map directly onto each other (Link C in Figure 1; e.g., Allport & Funnell, 1981; Patterson & Shewell, 1987). In this way, orthographic access, although not phonologically mediated, is heavily constrained by simultaneous activation of corresponding phonological word forms. By contrast, a strong version of orthographic autonomy stipulates that phonology may influence orthographic access exclusively via sublexical transcoding routes (Link D in Figure 1) and denies that there are direct links between entries in the two lexicons (e.g., Alario et al., 2003).

Whether or not direct links between the two lexicons exist in the context of orthographic output tasks such as writing raises larger issues of how orthographic and phonological subsystems of language relate to each other. A vast amount of research has been devoted to the reading aloud of single words, and a central issue is how to account for the transformation of a written word (or nonword) into spoken output. The dual route model of reading aloud postulates a sublexical, a lexical, and a semantic route mediating between orthography and phonology, much like in Figure 1 when read from right to left (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Alternatively, connectionist approaches (e.g., Plaut, McClelland, Seidenberg, & Patterson, 1996) combine the sublexical and the lexical routes into a single nonspecific transformation process, with an optional semantic route. Finally, the summation hypothesis (Hillis & Caramazza, 1991) denies a direct link between the orthographic and phonological lexicons and argues that reading aloud can be accomplished based on the simultaneous availability of semantic and sublexical routes. Neuropsychological case studies may speak to the existence of the various postulated mechanisms. Traditionally, the existence of phonological and surface dyslexias has been interpreted as resulting from the selective impairment of lexical and sublexical routes (e.g., Coltheart, Curtis, Atkins, & Haller, 1993). However, this view and the associated need to postulate separate conversion routes are controversial (e.g., Plaut et al., 1996), and the issue remains unresolved.

With regard to spoken and written output tasks, such as object naming, which are driven by semantic input, a limited number of neuropsychological case studies exist. In multiple picture-naming tasks, participants are presented with a picture and are asked to produce multiple naming responses in both oral and written formats in close succession. Patients who produce large numbers of semantic errors are assumed to suffer from a lexical-semantic deficit. A certain subgroup of patients will, under such circumstances, produce inconsistent responses, that is, name the picture differently orally and in writing, and crucially, for those patients producing inconsistent responses, the orthography-to-phonology and phonology-to-orthography conversion routes are evidently unavailable (i.e., they are unable to read or write nonwords; e.g., Alario et al., 2003; Beaton, Guest, & Ved, 1997; Miceli et al., 1997; Rapp et al., 1997). This pattern has been used to argue against a close mapping between the orthographic and phonological lexicons: If the sublexical transcoding routes are not available, then lexical selection is carried out relatively independently in oral and written formats, resulting in inconsistent responses when a large number of errors are being produced due to semantic impairment. As summarized in the introduction, the only evidence from healthy individuals with regard to whether handwriting is constrained by sublexical and/or lexical phonological codes was reported in Bonin et al. (2001). They showed that word-initial sound-to-spelling inconsistencies had a detrimental effect on writing, suggesting the operation of a sublexical phonological route contributing to orthographic retrieval. By contrast, written naming of pictures with heterographic homophone names was equally as fast as that of control pictures, which was taken as evidence against a direct link between orthographic and phonological lexicons.

The findings reported in this article allow only limited insight into the exact nature of the phonology-to-orthography conversion that evidently takes place during handwritten word production. Our results merely support the general notion that sound-based codes influence orthographic output tasks. In the context of persistent repetition priming, the possibility that no direct links exist between the phonological and the orthographic lexicons allows an interesting prediction: Less cross-modal repetition priming should be found for targets with inconsistently than consistently spelled words. This is because, for inconsistent items, the postulated sublexical transcoding between sounds and graphemes (Link D in Figure 1) should contribute very little to graphemic retrieval. Whether this is the case is of course an empirical question. Unfortunately, an experiment to test this prediction may be difficult, if not impossible, to design due to the constraints on stimulus selection in the current experimental task.

The Locus of Repetition Priming in Written Tasks

It is important to note that our demonstration of repetition priming with written responses (Experiment 2) by itself is not informative with regard to the source of priming and, more generally, the possibility of persistent effects in the orthographic system. Repetition priming in written tasks could arise from accessing the orthographic lexicon, from processes within the lexicon such as temporarily lowered firing thresholds as a consequence of recent retrieval, or from motorically based processes (i.e., the preparation and execution of a motoric pattern may be primed by prior retrieval of the same exact code). Of course, written repetition priming could arise—partially or exclusively—from phonological involvement, given that the cross-modal Experiments 3 and 4 suggest that phonological codes support and constrain orthographic retrieval. It would hence be interesting to identify explicitly orthographic components that exhibit repetition priming.

Unfortunately, this is rather difficult due to the intricate interrelatedness of orthographic and phonological codes in alphabetic languages. One could dissociate motoric from more abstract sources of written repetition priming by testing for priming between heterophonic homographs (e.g., study phase: "I want to [tear, /tɛər/] my hair out!"; probe phase: picture of a tear, /tɪər/; see Orliaguet & Boë, 1993, for a related approach of using homographic and homophonic stimuli). If motoric variables contribute to written repetition priming, one would still expect priming because the motoric pattern is shared between study and probe phases. By contrast, a null finding would locate the effect at a more abstract level. Unfortunately, it is very difficult (if not impossible) to identify the appropriate stimuli due to the scarcity of homographic heterophones in English. Furthermore, a null finding would exclude motoric sources of priming but would still not allow distinguishing between phonological and orthographic contributions: Repetition priming would no longer be expected if it is phonologically based as the two phonological word forms differ. Neither would priming be expected if it involves incrementing a link between concepts and orthographic form (Link A in Figure 1) because two different conceptual entries link to the same graphemic form. Hence, it is at present unclear how an explicitly orthographic locus of repetition priming in written tasks could be demonstrated. This, however, does not take away from our ultimate goal, which was to use repetition priming to gauge the relative contribution of phonology to orthographic output tasks.

A Lemma Account of Repetition Priming?

The logic underlying the work reported in this article may be challenged by an alternative account of repetition priming effects in production tasks. According to prominent theories of spoken word production (e.g., Levelt et al., 1999), lexical access is a two-step process consisting of selection of a lemma, that is, an abstract representation of syntactic–semantic properties of a word, followed by access to the word's form (phonological encoding). According to Wheeldon and Monsell (1992), repetition priming effects in spoken word production result from the modification of the link between a word's conceptual and phonological representations. If lexical access indeed occurs in two steps, then repetition priming could in principle result from the link between concepts and lemmas, from the link between lemmas and word forms, or from both.

Lemmas are conceived as modality-unspecific abstract codes, that is, one and the same lemma is assumed to support word processing and production in various modalities (e.g., visual word recognition, speech perception, spoken and written picture naming). Hence, if repetition priming results in a strengthened link between conceptual and lemma codes, then it would not be very surprising that the observed effect was essentially identical with spoken and written responses (Experiments 1 and 2) and was preserved in our cross-modal experiments (Experiments 3 and 4). In all cases, the same lemma representation is assumed to mediate lexical access, and hence, comparable degrees of priming should be found. This possibility would undermine our claim that the results of our cross-modal experiments demonstrate the role of phonology in written production.

It is not straightforward to counter this argument, not the least because the necessity of postulating lemma representations in the first place remains highly controversial (e.g., Caramazza, 1997). In the literature on visual word recognition, the finding that cross-modal long-term priming (e.g., from repeating a spoken word to visual lexical decision) is substantially reduced or even eliminated, compared to a unimodal case (e.g., Bowers & Michita, 1998), is incompatible with the idea that processes operating at the abstract lemma level underlie long-term priming. A direct test of the lemma account with our current methodology would consist of identifying an experimental task that requires lemma access but no retrieval of word forms and then assessing whether repetition priming persists even under such circumstances. However, whether such a task exists is questionable, given recent evidence for cascadedness in spoken production (e.g., Morsella & Miozzo, 2002).

Perhaps the strongest evidence against a lemma-based locus of repetition priming comes from related findings reported by Wheeldon and Monsell (1994). They investigated, in an experimental paradigm similar to the one used in Wheeldon and Monsell (1992), the effects of semantic competitors. They tested for the effects of priming from a study-phase response to a definition ("the largest creature that swims in the sea?"; answer: "whale") to a probe-phase response consisting of a semantic competitor ("shark"). Semantic inhibition was found, which is most easily accounted for by postulating a strengthened link between concepts and lemma representations: Such an increment would subsequently render a semantically related lemma more difficult to access because the originally accessed lemma now constitutes a more potent competitor. By interleaving prime and probe trials, they were able to obtain a time-course estimate of this effect, and the results showed that although the effect persisted over at least three intervening trials, it disappeared when assessed between experimental blocks (see also Tree & Hirsh, 2003, for a similar time-course analysis). This observation is in stark contrast to the repetition priming effect reported in Wheeldon and Monsell (1992) and others, which persists over much larger time intervals. Given the diverging time-course characteristics of semantic competitor versus repetition priming, Wheeldon and Monsell postulated two different underlying mechanisms: priming between concepts and lemmas for semantic competitor priming and priming between lemmas and word forms for repetition priming. This account to date is the only one that could explain both semantic inhibition and repetition priming, as well as their respective time courses. If correct, it would invalidate the possibility that repetition priming residing at the lemma level, or between conceptual and lemma representations, could account for the findings reported in the current article.

In summary, our results demonstrate long-lasting repetition priming in the production not only of spoken but also of written words. Furthermore, the finding that priming was also found when words were spoken in the study phase and written in the probe phase, and vice versa, strongly argues for a phonological contribution to the generation of orthographic output codes.

References

Alario, F., Schiller, N., Domoto-Reilly, K., & Caramazza, A. (2003). The role of phonological and orthographic information in lexical selection. *Brain and Language, 84,* 372–398. doi:10.1016/S0093-934X(02)00556-4

Allport, D. A., & Funnell, E. (1981). Components of the mental lexicon. *Philosophical Transactions of the Royal Society of London, 295,* 397–410. doi:10.1098/rstb.1981.0148

Assal, G., Buttet, J., & Jolivet, R. (1981). Dissociations in aphasia: A case report. *Brain and Language, 13,* 223–240. doi:10.1016/0093-934X(81)90092-4

Baayen, R. H. (2008). *Analyzing linguistic data: A practical introduction to statistics using R.* Cambridge, England: Cambridge University Press.

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language, 59,* 390–412.

Baayen, R. H., Piepenbrock, R., & Gulikers, L. (1995). *The CELEX Lexical Database (Release 2)* [CD-ROM]. Philadelphia: Linguistic Data Consortium, University of Pennsylvania.

Baddeley, A., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior, 14,* 575–589. doi:10.1016/S0022-5371(75)80045-4

Badecker, W. (1996). Representational properties common to phonological and orthographic output systems. *Lingua, 99,* 55–83. doi:10.1016/0024-3841(96)00005-8

Barry, C., Hirsh, K. W., Johnston, R. A., & Williams, C. L. (2001). Age of acquisition, word frequency, and the locus of repetition priming of picture naming. *Journal of Memory and Language, 44,* 350–375. doi:10.1006/jmla.2000.2743

Barry, C., Morrison, C. M., & Ellis, A. W. (1997). Naming the Snodgrass and Vanderwart pictures: Effects of age of acquisition, frequency, and name agreement. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 50*(A), 560–585.

Bates, D. M., & Maechler, M. (2009). lme4: Linear mixed-effects models using S4 classes—R Package Version 0.999375–31 [Computer software]. Retrieved from http://CRAN.R-project.org/package=lme4

Beaton, A., Guest, J., & Ved, R. (1997). Semantic errors of naming, reading, writing, and drawing following left-hemisphere infarction. *Cognitive Neuropsychology, 14,* 459–478. doi:10.1080/026432997381547

Besner, D. (1987). Phonology, lexical access in reading, and articulatory suppression: A critical review. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 39*(A), 467–478.

Bock, J. K., & Griffin, Z. M. (1998, November). *Components of long-lasting repetition priming in picture naming.* Poster session presented at the 39th Annual Meeting of the Psychonomic Society, Dallas, TX.

Bonin, P., Chalard, M., Méot, A., & Fayol, M. (2002). The determinants of spoken and written picture naming latencies. *British Journal of Psychology, 93,* 89–114.

Bonin, P., Fayol, M., & Peereman, R. (1998). Masked form priming in writing words from pictures: Evidence for direct retrieval of orthographic codes. *Acta Psychologica, 99,* 311–328. doi:10.1016/S0001-6918(98)00017-1

Bonin, P., Peereman, R., & Fayol, M. (2001). Do phonological codes constrain the selection of orthographic codes in written picture naming? *Journal of Memory and Language, 45,* 688–720. doi:10.1006/jmla.2000.2786

Bowers, J. S. (1996). Different perceptual codes support word and pseudoword priming: Was Morton right all along? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22,* 1336–1353. doi:10.1037/0278-7393.22.6.1336

Bowers, J. S., & Kouider, S. (2003). Developing theories of priming with an eye on function. In J. S. Bowers & C. S. Marsolek (Eds.), *Rethinking implicit memory* (pp. 19–40). Oxford, England; Oxford University Press.

Bowers, J. S., & Michita, Y. (1998). An investigation into the structure and acquisition of orthographic knowledge: Evidence from cross-script Kanji-Hiragana priming. *Psychonomic Bulletin & Review, 5,* 259–264. doi:10.3758/BF03212948

Bub, D., & Kertesz, A. (1982). Evidence for lexicographic processing in a patient with preserved written over oral single word naming. *Brain, 105,* 697–717. doi:10.1093/brain/105.4.697

Caramazza, A. (1997). How many levels of processing are there in lexical access? *Cognitive Neuropsychology, 14,* 177–208. doi:10.1080/026432997381664

Caramazza, A., & Miceli, G. (1990). The structure of graphemic representations. *Cognition, 37,* 243–297. doi:10.1016/0010-0277(90)90047-N

Cave, C. B. (1997). Very long-lasting priming in picture naming. *Psychological Science, 8,* 322–325. doi:10.1111/j.1467-9280.1997.tb00446.x

Coltheart, M., Curtis, B., Atkins, P., & Haller, M. (1993). Models of reading aloud: Dual-route and parallel-distributed-processing approaches. *Psychological Review, 100,* 589–608. doi:10.1037/0033-295X.100.4.589

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review, 108,* 204–256. doi:10.1037/0033-295X.108.1.204

Dell, G. S., Schwartz, M. F., Martin, N., Saffran, E. M., & Gagnon, D. A. (1997). Lexical access in aphasic and nonaphasic speakers. *Psychological Review, 104,* 801–838. doi:10.1037/0033-295X.104.4.801

Forster, K. I., & Forster, J. C. (2003). DMDX: A Windows display program with millisecond accuracy. *Behavior Research Methods, Instruments, & Computers, 35,* 116–124. doi:10.3758/BF03195503

Geschwind, N. (1969). Problems in the anatomical understanding of the aphasias. In A. L. Benton (Ed.), *Contributions to clinical neuropsychology* (pp. 107–128). Chicago, IL: Aldine.

Harm, M. W., & Seidenberg, M. S. (1999). Phonology, reading acquisition, and dyslexia: Insights from connectionist models. *Psychological Review, 106,* 491–528. doi:10.1037/0033-295X.106.3.491

Hecaen, H., & Angelergues, R. (1965). *Pathologie du language* [Pathology of language] (Vol. 1). Paris, France: Larousse.

Hillis, A., & Caramazza, A. (1991). Mechanisms for accessing lexical representations for output: Evidence from a category specific semantic deficit. *Brain and Language, 40,* 106–144.

Houghton, G., & Zorzi, M. (2003). Normal and impaired spelling in a connectionist dual-route architecture. *Cognitive Neuropsychology, 20,* 115–162. doi:10.1080/02643290242000871

Jaeger, T. F. (2008). Categorical data analysis: Away from ANOVAs (transformation or not) and towards logit mixed models. *Journal of Memory and Language, 59,* 434–446. doi:10.1016/j.jml.2007.11.007

Kandel, S., Hérault, L., Grosjacques, G., Lambert, E., & Fayol, M. (2009). Orthographic vs. phonologic syllables in handwriting production. *Cognition, 110,* 440–444. doi:10.1016/j.cognition.2008.12.001

Kleiman, G. M. (1975). Speech recoding in reading. *Journal of Verbal Learning and Verbal Behavior, 14,* 323–339. doi:10.1016/S0022-5371(75)80013-2

Lambert, E., Kandel, S., Fayol, M., & Esperet, E. (2007). The effect of the number of syllables on handwriting production. *Reading & Writing, 21,* 859–883. doi:10.1007/s11145-007-9095-5

Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences, 22,* 1–75. doi:10.1017/S0140525X99001776

Lichtheim, L. (1885). Über Aphasie [On aphasia]. *Deutsches Archiv für Klinische Medizin, 36,* 204–268.

Luria, A. R. (1970). *Traumatic aphasia.* The Hague, the Netherlands: Mouton.

Miceli, G., Benvegnu, B., Capasso, R., & Caramazza, A. (1997). The independence of phonological and orthographic lexical forms: Evidence from aphasia. *Cognitive Neuropsychology, 14,* 35–69. doi:10.1080/026432997381619

Miceli, G., & Capasso, R. (1997). Semantic errors as neuropsychological evidence for the independence and the interaction of orthographic and phonological word forms. *Language and Cognitive Processes, 12,* 733–764. doi:10.1080/016909697386673

Miceli, G., Capasso, R., & Caramazza, A. (1999). Sublexical conversion procedures and the interaction of phonological and orthographic forms. *Cognitive Neuropsychology, 16,* 557–572. doi:10.1080/026432999380726

Mitchell, D. B., & Brown, A. S. (1988). Persistent repetition priming in picture naming and its dissociation from recognition memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 14,* 213–222. doi:10.1037/0278-7393.14.2.213

Monsell, S. (1987). On the relationship between lexical input and output pathways for speech. In A. Allport, D. MacKay, W. Prinz, & E. Sheerer (Eds.), *Language perception and production* (pp. 273–311). London, England: Academic Press.

Monsell, S., Matthews, G. H., & Miller, D. C. (1992). Repetition of lexicalization across languages: A further test of the locus of priming. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 44*(A), 763–783.

Morsella, E., & Miozzo, M. (2002). Evidence for a cascade model of lexical access in speech production. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28,* 555–563. doi:10.1037/0278-7393.28.3.555

Neely, J. H. (1991). Semantic priming effects in visual word recognition: A selective review of current findings and theories. In D. Besner & G. W. Humphreys (Eds.), *Basic processes in reading: Visual word recognition* (pp. 264–336). Hillsdale, NJ: Erlbaum.

Orliaguet, J.-P., & Boë, L.-J. (1993). The role of linguistics in the speed of handwriting movements: Effects of spelling uncertainty. *Acta Psychologica, 82,* 103–113. doi:10.1016/0001-6918(93)90007-E

Patterson, K., & Shewell, C. (1987). Speak and spell: Dissociations and word-class effects. In M. Coltheart, G. Sartori, & R. Job (Eds.), *The cognitive neuropsychology of language* (pp. 273–294). London, England: Erlbaum.

Plaut, D. C., McClelland, J. L., Seidenberg, M. S., & Patterson, K. (1996). Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Review, 103,* 56–115. doi:10.1037/0033-295X.103.1.56

R Development Core Team. (2009). *R: A language and environment for statistical computing.* Vienna, Austria: R Foundation for Statistical Computing.

Rapp, B., Benzing, L., & Caramazza, A. (1997). The autonomy of lexical orthography. *Cognitive Neuropsychology, 14,* 71–104. doi:10.1080/026432997381628

Rapp, B., & Caramazza, A. (1997). The modality-specific organization of grammatical categories: Evidence from impaired spoken and written sentence production. *Brain and Language, 56,* 248–286. doi:10.1006/brln.1997.1735

Schacter, D. L. (1990). Perceptual representation systems and implicit memory: Toward a resolution of the multiple memory systems debate. In A. Diamond (Ed.), *Development and neural bases of higher cognition* (pp. 543–571). New York, NY: New York Academy of Sciences.

Scinto, L. F. (1986). *Written language and psychological development.* New York, NY: Academic Press.

Shelton, J. R., & Weinrich, M. (1997). Further evidence for a dissociation between output phonological and orthographic lexicons: A case study. *Cognitive Neuropsychology, 14,* 105–129. doi:10.1080/026432997381637

Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology: Human Learning and Memory, 6,* 174–215. doi:10.1037/0278-7393.6.2.174

Tree, J. J., & Hirsh, K. W. (2003). Sometimes faster, sometimes slower: Associative and competitor priming in picture naming with young and elderly participants. *Journal of Neurolinguistics, 16,* 489–514.

van Casteren, M., & Davis, M. H. (2006). Mix: A program for pseudorandomization. *Behavior Research Methods, 38,* 584–589. doi:10.3758/BF03193889

van Galen, G. P. (1991). Handwriting: Issues for a psychomotor theory. *Human Movement Science, 10,* 165–191. doi:10.1016/0167-9457(91)90003-G

van Turennout, M., Ellmore, T., & Martin, A. (2000). Long-lasting cortical plasticity in the object naming system. *Nature Neuroscience, 3,* 1329–1334. doi:10.1038/81873

Wheeldon, L., & Monsell, S. (1992). The locus of repetition priming of spoken word production. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology, 44*(A), 723–761.

Wheeldon, L., & Monsell, S. (1994). Inhibition of spoken word production by priming a semantic competitor. *Journal of Memory and Language, 33,* 332–356. doi:10.1006/jmla.1994.1016

Zhang, Q., & Damian, M. F. (2010). Impact of phonology on the generation of handwritten responses: Evidence from picture-word interference tasks. *Memory & Cognition, 38,* 519–528. doi:10.3758/MC.38.4.519

Appendix

Materials Used in Experiments 1–5

Table A1
Set A

Item	Target	Definition
1	arrow	A long pointed symbol used to display a direction
2	balloon	A ball filled with air and attached to a string, used for celebrations
3	barrel	He is a ____ of laughs
4	camel	Animal with a hump that lives in the desert
5	candle	A tube of wax with a wick which is burnt
6	carrot	Bugs Bunny's favourite vegetable is a ____
7	cigar	He lit a large Cuban ____
8	clown	Comic entertainer in a circus
9	donkey	Can talk the hind legs off a ____
10	drum	Instrument with a skin you beat with sticks
11	elephant	Large grey animal with ivory tusks
12	envelope	A white paper container used for sending letters through the post
13	fox	Sly like a ____
14	frog	If you kiss one it may turn into a prince
15	giraffe	The tallest land animal from Africa
16	harp	Stringed instrument played by angels
17	jug	A large glass container that is used to hold and pour liquids
18	kangaroo	An Australian animal which bounces with its hind legs
19	kettle	Polly put the ____ on
20	ladder	It has rungs you climb up
21	leaf	She was shaking like a ____
22	lemon	Easy peasy, ____ squeezy
23	owl	Nocturnal bird thought to be wise
24	pear	A fruit like an apple that tapers towards the stalk
25	pig	A ____ in a poke
26	rabbit	I am sure he will pull a ____ out of the hat
27	ruler	Object used to measure and draw straight lines
28	scissors	Sharp implement used to cut hair
29	seahorse	Small marine fish with a prehensile tail, swims in an upright position
30	snowman	Figure of a person built in Wintertime outdoors
31	spider	It spins a web to catch its prey
32	stool	You sit on one at the bar in a pub
33	tomato	Vegetable used to make ketchup
34	trousers	Clothing you wear on your legs
35	trumpet	He is blowing his own ____
36	violin	A wooden musical instrument that uses a bow
37	zebra	To talk the stripes off a ____

(*Appendix continues*)

Table A2
Set B

Item	Target	Definition
1	anchor	Object used to secure a ship at the bottom of the sea
2	apple	An ____ a day keeps the doctor away
3	ashtray	An object you put a burning cigarette on
4	axe	Implement with a sharp metal head for chopping up wood
5	banana	Fruit with a yellow skin you can slip on
6	basket	Don't put all your eggs in one ____
7	boot	A Wellington is a kind of ____ worn in wet weather
8	button	A round disk, attached to clothes to fasten them
9	cannon	He's a loose ____
10	comb	Piece of plastic with teeth for tidying the hair
11	fork	A device with three prongs used to eat food
12	glove	A warm covering you put your hand into
13	grapes	The fruit used to make wine
14	hammer	Tool used to knock in a nail
15	kite	Light paper structure flown on a string in the wind
16	lion	Known as king of the beasts
17	nail	You knock it with a hammer
18	onion	Vegetable that makes your eyes water when chopped
19	peacock	Proud as a ____
20	pen	You use one to write with in ink
21	pencil	A writing device with a graphite mine
22	penguin	Flightless bird from Antarctica
23	pepper	We had a stuffed bell ____ for lunch
24	pumpkin	It is used to make lanterns on Halloween
25	sandwich	Two slices of bread with a filling inside
26	screw	He has a ____ loose
27	snail	Slow moving slug that carries its shell on its back
28	snake	A ____ in the grass
29	sock	You put one on before you put on a shoe
30	spoon	Piece of cutlery used to eat liquids, such as soup
31	swan	Water bird with a long graceful white neck
32	thimble	You wear one to protect your finger while sewing
33	toaster	Kitchen appliance used for making bread crisp by heating it
34	umbrella	You carry one in case of rain
35	vase	A decorative container for flowers
36	whistle	The farmer beckoned the sheep dog with a shrill ____
37	windmill	Dutch building with rotating sails

Received October 19, 2010
Revision received January 19, 2011
Accepted January 24, 2011 ■