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Verbal, visual, and spatial working memory in written language production

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Abstract

College students wrote definitions of either abstract or concrete nouns in longhand while performing a concurrent working memory (WM) task. They detected either a verbal (syllable), visual (shape), or spatial (location) stimulus and decided whether it matched the last one presented 15–45 s earlier. Writing definitions of both noun types elevated the response time to verbal targets above baseline. Such interference was observed for visual targets only when defining concrete nouns and was eliminated entirely with spatial targets. The interference effect for verbal targets was the same whether they were read or heard, implicating phonological storage. The findings suggest that language production requires phonological or verbal WM. Visual WM is selectively engaged when imaging the referents of concrete nouns.

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1. Introduction

Language production requires the planning of semantic content and the grammatical encoding of this content (Bock & Levelt, 1994). Imaginal and propositional representations are translated into the ordered words of a phrase, clause, or sentence through grammatical encoding. Spoken output requires phonological encoding, whereas writing requires orthographic encoding either directly from an orthographic lexicon or via phonological mediation (Caramazza, 1991).[1] Phonological encoding in writing may do more than provide an optional means of gaining access to orthography. Lexical entries that are encoded phonologically and heard as an inner voice allow the writer to review and edit a pre-text representation, prior to committing to handwritten or typed output (Chenoweth & Hayes, 2003; Witte, 1987).

Our interest was in examining the degree to which specific components of working memory (WM) support written language production. Because written production is slow compared with speech, it is feasible to measure performance on a concurrent task that uses executive attention plus either verbal, visual, or spatial storage (Jonides & Smith, 1997). Interference with the concurrent task would suggest that one or more processes involved in language production compete for the same WM component. For example, following Baddeley's (1986) seminal model, a phonological loop allows the storage and maintenance of verbal representations. Interference with maintaining a syllable (ba or da) in phonological storage while concurrently writing (i.e., compared with baseline, single task performance) would suggest that writing involves storing phonological representations of the words of a sentence under construction. Understanding the WM requirements of writing is of interest in its own right and may shed light on language production in general to the extent that speaking and writing share processes and requirements.

If a writer encodes lexical entries phonologically during production, then the phonological loop may store these verbal representations either for review or for conversion to the orthographic codes needed in written motor output (Kellogg, 1996). Shelton and Caramazza (1999) noted that writing has traditionally been viewed as dependent on phonological encoding. Consistent with this view, concurrent tasks that make heavy demands on phonological or verbal WM shorten sentence length (Chenoweth & Hayes, 2003; Kellogg, 2004; Levy & Marek, 1998; Power, 1985; Ransdell, Levy, & Kellogg, 2002) and can cause subject–verb agreement errors (Fayol, Largy, & Lemaire, 1994; Largy & Fayol, 2001). For example, Chenoweth and Hayes (2003) found that repeatedly vocalizing the word "tap" suppresses the inner voice that often seems to accompany writing. They tracked pause durations in production and discovered that suppressing covert vocalization reduced the number of words that are produced in rapid succession prior to a long pause (2 s or longer).

Even so, two sources of neuropsychological evidence challenge the view that verbal working is necessary for holding lexical representations during language production. First, Vallar and Baddeley (1984) studied a patient with an impaired phonological loop whose

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[1] Some models of speech production contrast an abstract (lemma) representation of lexical entries that code grammatical categories such as word class and gender with a phonological (lexeme) representation (Bock & Levelt, 1994). Other models assume modality-specific lexical representations where grammatical information is embedded within both phonological and orthographic lexicons (Shelton & Caramazza, 1999). We address here the WM mechanisms that support phonological and orthographic lexical representation, but not the number of levels of lexical representation needed.

memory span was limited to two items following auditory list presentation. This individual showed both normal spoken and written language. In reviewing cases of this type, Gathercole and Baddeley (1993) concluded that the language production process does not appear to require the verbal WM system. Second, writing does not necessarily require phonological processing based on clinical case studies (Shelton & Caramazza, 1999). For example, Shelton and Weinrich (1997) described a patient who could write real words successfully in 85% of the time but could not write a single non-word in which one must use phonological mediation to convert phonemes to graphemes. The patient's ability to retrieve an orthographic lexical representation was intact, despite an impairment in the conversion mechanism.

The role of visual WM might be limited to planning the content of the message when the referents of concepts are imaged (Sadoski, Kealy, Goetz, & Paivio, 1997) as opposed to the mandatory stage of linguistic encoding. A concurrent visual–spatial task disrupts written production less than a verbal task (Kellogg, 2004), as one would expect if visual WM plays less of a role. On the other hand, perhaps visual WM at times stores the orthographic representations as an aid to catching spelling, punctuation, and other errors. Further, Hayes (1996) argued that spatial WM allows writers to represent the physical layout of an extended text. The empirical literature on how visual and spatial WM support writing is too limited to evaluate these hypotheses adequately.

The present research, therefore, examined again the assumption that verbal WM is required in written language production and expanded work on the roles played by the visual and spatial components of WM. We replicated the experiment of Sadoski et al. (1997) by making participants write definitions of either concrete or abstract nouns in longhand. They found that writers initiate production faster and compose more detailed, higher quality definitions for concrete compared with abstract nouns. Further, they reported using imagery more often in defining concrete relative to abstract words. We extended their work by having participants perform a concurrent task that required verbal, visual or spatial WM. We expected to replicate their definition findings and to find that only concrete nouns slow responses to a concurrent visual WM task. In contrast, both kinds of nouns were expected to interfere with a verbal WM task. Finally, we expected that the definition task would fail to prompt any demands on spatial WM, neither for concrete nor for abstract nouns, because the layout of an extended text was not developed.

The concurrent WM task was designed to require either the verbal, visual, or spatial component, plus the executive functions demanded in juggling the secondary task with writing (D'Esposito et al., 1995). The verbal WM task required detecting visually presented syllables (ba or da) on a 30 s variable interval schedule and deciding rapidly if it matched the last one presented. In reading the syllables, both phonological and orthographic representations are activated (Massaro & Cohen, 1994). It was desirable to equate the verbal and visual tasks with respect to presentation modality, varying only the kind of materials used. Our aim was to ensure that the two tasks were equally difficult to perform under baseline conditions. Thus, the visual WM task was identical except that visual objects instead of syllables were presented. In both the verbal and visual tasks, the syllables and objects were presented either on the left or right side of the computer screen and the participants ignored the location in making their responses. In the spatial task, the same objects were presented as in the visual task, but the participants ignored their shapes and instead responded when the location was novel compared to the last stimulus presentation.

In Experiment 1, we tested the prediction that both concrete and abstract nouns would reduce the speed of responding to targets in the verbal task, whereas only concrete nouns should interfere with the visual task. In Experiment 2, we examined again the selective interference effect for the visual task and tested our prediction of no interference for a spatial task. Whether the interference observed in the verbal task was phonological in nature was assessed in Experiment 3 by comparing aural with visual presentation of the syllables.

2. Experiment 1

2.1. Methods

College students ($N = 60$) were assigned in equal numbers to one of four groups defined by the factorial combination of materials (concrete versus abstract nouns) and task (verbal versus visual). In each condition, participants wrote definitions of 10 nouns while concurrently performing a WM task that required the detection of a visually presented target and a speeded decision regarding whether to respond. They were instructed to respond by clicking a mouse button whenever the target was different from the last one presented. Thus, the task required maintaining the most recent target in WM, detecting a new target, matching the new target to the one in memory, deciding to respond or to inhibit responding, and updating the most recent target. The time taken to respond was measured in ms along with the percentage of correctly detected targets. The instructions and stimuli were presented with a modified version of SCRIPTKELL (Piolat, Olive, Roussey, Thunin, & Ziegler, 1999).

For the verbal WM task, the targets were two syllables (ba and da). On a 30 s variable interval schedule, one of the two syllables appeared in large letters on a computer screen. At least 15 s separated each stimulus presentation and the maximum inter-stimulus interval was 45 s. Instructions for the verbal task required a response to a syllable that was different from the immediately preceding stimulus. Thus, in the sequence ba ba da ba, the participant was instructed to respond to da and the final ba. For the visual WM task, the same procedure was followed, but the materials were visual shapes (triangle or circle). A large font was used for the syllables, filling approximately 20% of the screen, and the shapes were about equal in size to ensure easy visual detection. Instructions for the visual task required a response to a shape that was different from the immediately preceding stimulus regardless of its location. The computer screen was positioned below a transparent desktop on which the participants wrote the definitions on paper in longhand using their dominant hand. The mouse was positioned near their non-dominant hand for responding to each non-repetition target.

Baseline measurements were collected for the WM task in isolation, so that the degree of interference in RT could be determined. Also, the definition task was performed as a control condition without the concurrent task for 10 min. The data were collected in three blocks. The procedure began with the WM control block for 12 min followed by the definition control block for 10 min. Extra time was given for the WM task to ensure that it was adequately practiced. Finally, the dual task condition was tested for 10 min. The instructions for each condition were read on the computer screen before beginning each block.

A total of 40 nouns were selected from the Colorado word norms for inclusion in the study (Toglia et al., 1978). Half were concrete nouns (e.g., house, wheat, pencil) that had been rated as easy to image visually. The other half were abstract nouns and were difficult to image (e.g., freedom, moment, duty). Other properties of the nouns, such as familiarity, pleasantness, and length, were approximately equal in the two kinds of materials. The concrete nouns were randomly divided into two sets of 10 and one was assigned to the baseline block and the other to the dual task block. The same procedure was followed for the abstract nouns. The 10 nouns were listed on a page with space provided for each definition.

The instructions for the definition task followed those given by Sadoski et al. (1997). The participants were asked to write a dictionary-style definition for one usage of each word. They were encouraged to a write a clear definition of each word and to not worry if they failed to define all ten words. Finally, they were told to write clearly at a normal rate and not to be excessively concerned with the vocabulary, grammatical correctness, spelling, or editing of the definitions. The latter instruction was designed to place emphasis on language production itself as opposed to the monitoring of production. The definitions were scored on a three-point scale. A score of 0 was assigned if no definition was given for a term in the 10 min allowed. A score of 1 was given if a minimal, poorly detailed definition was provided. This rating was used when only a single assertion was made in defining the noun. A score of 2 was given for an extensive, well-detailed definition that included two or more assertions. A total score was calculated across all 10 nouns with a maximum score of 20. Two judges rated each definition.

2.2. Results

2.2.1. Definitions

The inter-judge reliabilities were $r = .89$ for baseline definitions and $r = .90$ for dual task definitions. Typical examples of definitions which were assigned a rating of "2" and "1" are given in Table 1 for a concrete noun (flower) and an abstract noun (crime). Note that the task instructions to write a dictionary-style definition typically prompted an elliptical construction with the head noun phrase and connecting verb implied rather than stated explicitly (e.g., *A flower is*…). The ratings averaged across the two judges were used in the analyses described next. Replicating Sadoski et al. (1997), an analysis of variance (ANOVA) conducted on the definition scores produced a reliable main effect of materials, $F(1,56) = 41.25$, MSE = 5.64, $p < .001$. The concrete nouns ($M = 18.9$) received higher scores overall than the abstract nouns ($M = 16.1$). No other effects were reliable. The kind of WM task performed did not affect performance on the primary composition task. This indicates that the participants gave priority to the composition task.

In fact, the scores were just as high in the dual task condition ($M = 17.4$) as in the baseline or control condition ($M = 17.6$). The secondary task of detecting either a new syllable or a new shape did not disrupt language production processes. This result further strengthens

Table 1
Examples of dictionary-style definitions assigned ratings of detailed (2) versus minimal (1) definitions

Noun defined	Dictionary-style definition written
Detailed (2) rating assigned	
Flower	"the part of the plant that blooms a certain time of year which can be colorful and have a nice scent"
Crime	"an unlawful act committed against an individual or society as a whole, something prohibited or taboo"
Minimal (1) rating assigned	
Flower	"a type of vegetation that blossoms"
Crime	"a violation of the law"

the case that language production proceeded normally, as would be expected if writing took priority.

2.2.2. Secondary task

Adding the secondary task to writing reliably interfered with the accuracy of responding to the secondary task. Overall, the proportion of correct responses dropped from .88 during baseline to .83 during dual task conditions. The reduction in accuracy was about the same for either the verbal or visual task and for both types of nouns, suggesting that the executive functions required to carry out two tasks at once were overloaded. The effect was not limited to verbal or visual WM. The main effect of measurement condition was the only reliable effect in the analysis of the proportion of correct responses, $F(1,56) = 15.23$, $MSE = 48.4$, $p < .001$, in the ANOVA. Thus, performance suffered to some extent when the WM tasks were combined with writing definitions, but accuracy was still high with fewer than 20% missed targets.

There were no reliable differences in the accuracy of detecting targets between the verbal ($M = 86.0$) and visual ($M = 89.8$) tasks when they were performed in isolation in the control condition. Similarly, the baseline response time (RT) was comparable for the verbal ($M = 866$ ms) and visual ($M = 850$ ms) tasks. The two tasks were of roughly equal difficulty when performed in isolation. It is possible, then, to attribute differences in response times under dual task conditions to the differential impact of writing on the verbal versus the visual concurrent task.

The means and their standard errors for RT to hits in the target detection task are presented in Fig. 1. The mean RT increased reliably when tested in the dual task situation in all cases except the abstract-visual condition. The largest increase observed was in the concrete-visual condition. This pattern was supported by a reliable measurement × materials × task interaction, $F(1,56) = 9.48$, $p < .01$. A main effect of measurement condition, $F(1,56) = 53.51$,

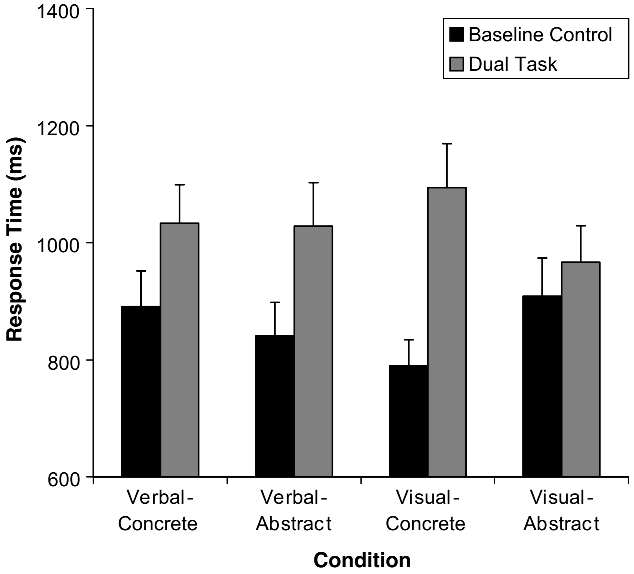

Fig. 1. Mean response times (ms) and standard errors for baseline control and dual task conditions in Experiment 1.

$p < .001$, and materials × measurement interaction, $F(1,56) = 4.57$, $p < .05$, MSE = 17.0, for all effects were the only other reliable sources of variance.

Thus, writing definitions slowed the time needed to respond to the targets in the verbal task by 165 ms, averaged across the concrete and abstract noun conditions. The visual task was slowed even more, by 304 ms, with concrete nouns that presumably evoked images in planning the content of the definition. In contrast, there was minimal interference (58 ms) in responding to visual targets when writing definitions about abstract nouns. An ANOVA on the difference scores (dual task – baseline) revealed a main effect of materials, $F(1,56) = 4.56$, $p < .05$, and an interaction of materials × task, $F(1,56) = 9.48$, $p < .01$, MSE = .03, for both effects. A planned contrast revealed that the mean for the visual-concrete condition was reliably greater than the mean for the visual-abstract condition, $t(28) = 3.85$, $p < .001$. The small difference in interference obtained in the verbal-concrete versus the verbal-abstract conditions was unreliable, $t < 1.0$.

2.3. Discussion

As hypothesized, writing definitions of both concrete and abstract words interfered with a concurrent verbal WM task. This outcome suggests that during sentence construction, phonological representations of the words to be output are temporarily maintained in verbal WM. By contrast, the visual WM task revealed interference only when writing definitions of concrete nouns. This selective interference effect likely arises during the planning stage of language production, when one might form a mental image of the referent of a concrete noun. Abstract nouns do not cause such interference because they do not necessarily elicit a high degree of imagery.

Of importance, the visual and verbal tasks used in the present study were comparable in difficulty under baseline, control conditions. The different levels of RT observed under dual task conditions can thus be confidently assigned to problems in combining writing with the concurrent task rather than the task per se. Moreover, the selective interference found for the visual task also makes it unlikely that only executive attention or any other domain-general resource was called upon by language production in this task. If that were the case, then the same level of interference should have been obtained regardless of the type of task and noun. The relative lack of interference with the visual task for abstract nouns is problematic for an account based solely on sharing attention or other central executive resources to cope with the dual task demands. The small 58 ms interference effect found in the visual-abstract condition probably reflects the competition for the central executive component of WM. The much larger interference effects observed in the other conditions appear to arise at least partly from the demands on the verbal and visual WM components. It is of interest to note that the planning demands that concrete words make on visual WM were particularly heavy, judging from the 318 ms interference effect.

It is recognized that a domain-general, executive component is correlated with general intelligence (Hambrick, Kane, & Engle, 2005) and undoubtedly plays an important role in language production, especially in extended text production. Written composition is a complex cognitive task involving long-term memory, reasoning, decision making, and problem solving in addition to language production. Although the domain-general WM component is necessary for written composition (Kellogg, 1996), the evidence of the present experiments indicates that it is not sufficient. The verbal and visual WM components also have a role in certain aspects of language production.

Accuracy in detecting targets dropped when performing the task in conjunction with writing than when performed in isolation. Because executive functions are overloaded when two tasks are combined, this drop in performance is understandable. Accuracy performance dropped about the same degree for verbal and visual tasks with either concrete or abstract nouns, indicating a sharing of common executive resource of WM. By contrast, the RT results appear to show sensitivity to the specific type of information storage required. Defining abstract nouns did not reliably slow responses to the visual task, but they did to the verbal task.

In replication of the results obtained by Sadoski et al. (1997), the definitions of concrete nouns were judged to be richer in detail compared with abstract nouns. This result is consistent with the view that concrete nouns evoked imaginal and verbal codes during language production, whereas abstract nouns involved only verbal codes. Note that it cannot be effectively argued that the abstract words are simply more difficult to define, and, hence, cause more interference in general. If this were the case, then RT interference ought to be greater for abstract words than for concrete words regardless of whether the WM task required verbal or visual resources.

3. Experiment 2

The primary purpose of Experiment 2 was to replicate the selective interference found for visual targets using a larger sample size than that used in Experiment 1. One might also argue that the triangles and circles were perhaps coded verbally as well as visually in Experiment 1, implying that part of the RT interference observed could have reflected the dependence of writing on verbal WM. This interpretation cannot account for the selective interference in writing definitions of concrete but not abstract nouns. Still, it would be useful to replicate the effect using unfamiliar shapes that are not readily named.

Finally, it was also of interest to determine whether spatial as well as visual interference would be obtained for concrete nouns. Conceivably, the visual detection task made demands on both visual and spatial WM despite the fact that changes in the location of the object were irrelevant to the decision task. We assessed this possibility by instructing the participants to respond when the object appears in a new location, regardless of its shape. If this location detection task also reveals interference for concrete but not abstract nouns, then it can be concluded that imaging the referent of concrete nouns involves spatial as well as visual WM.

One might anticipate spatial interference for both concrete and abstract nouns for two reasons. It can be argued that writers develop a spatial representation of the layout of an extended text (Hayes, 1996). It can also be argued that spatial information is required in handwriting (Van Galen, 1991) and if it is stored in spatial WM, then both abstract and concrete nouns should interfere with spatial target detection. Alternatively, interference may be negligible for spatial targets for both types of nouns. Although spatial parameters must be set in handwriting, the task is heavily practiced in college students and most likely automatic. At the same time, it seemed unlikely that the participants would develop a spatial representation of the layout in our definition task. This is unlikely because the sentences generated across items did not cohere as a text. Thus, we anticipated that shifting from verbal and visual targets to spatial targets would totally eliminate the interference effect.

Fig. 2. Stimuli used in the visual WM task of Experiment 2.

3.1. Method

The materials and procedures of Experiment 1 were used again. The visual task was replicated with the exception that two shapes were used that could not be as readily named and verbalized compared with a triangle and circle. The two shapes were selected from the Microsoft Word alternative symbol set for Arial type fonts with the objective of being simple and easily discriminated. These stimuli are shown in Fig. 2. Each shape was presented on either the left or the right side of the screen, as in Experiment 1.

College students ($N = 80$) were assigned in equal numbers to one of four groups defined by the factorial combination of materials (concrete versus abstract nouns) and task (visual versus spatial). Instructions for the visual task again required a response to a shape that was different from the immediately preceding stimulus regardless of its location. The spatial task used exactly the same materials but called for a response when the location was different from the immediately preceding stimulus regardless of the shape.

3.2. Results

3.2.1. Definitions

The inter-judge reliabilities were .88 for baseline definitions and .93 for dual task definitions and again the ratings were averaged for further analyses. The judges used in Experiment 2 tended to give lower scores overall than was observed in Experiment 1. The main effect of materials, $F(1,76) = 16.52$, MSE = 8.63, $p < .001$, was reliable, with concrete nouns ($M = 14.8$) yielding higher scores than abstract nouns ($M = 12.9$). This outcome replicated Experiment 1 and Sadoski et al. (1997). The only other reliable source of variance was the interaction of measurement × materials, $F(1,76) = 4.37$, MSE = 1.96, $p < .05$; this arose because the advantage in ratings for concrete over abstract terms was slightly larger in the baseline than in the dual task conditions.

3.2.2. Secondary task

The accuracy data revealed no significant sources of variance, with participants performing nearly as well in the dual task condition ($M = .93$) as in the baseline condition ($M = .92$). The participants tended to perform better on the spatial task ($M = .94$) relative to the visual task ($M = .91$), $p < .07$. The RT data are presented in Fig. 3. Under both baseline and dual task conditions of measurement, the visual task took reliably longer to perform correctly

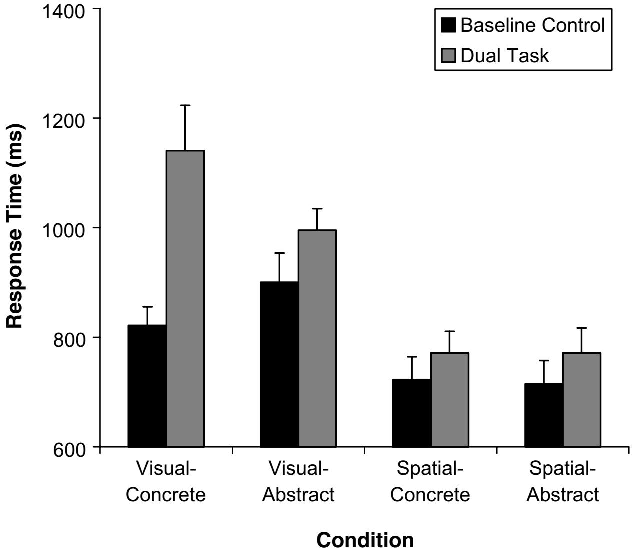

Fig. 3. Mean response times (ms) and standard errors for baseline control and dual task conditions in Experiment 2.

than the spatial task, $F(1,76) = 27.16$, $\mathrm{MSE} = 70{,}743$, $p < .001$. The ANOVA revealed a main effect of measurement condition, $F(1,76) = 24.05$, $p < .001$, an interaction of measurement × task, $F(1,76) = 8.72$, $p < .01$, an interaction of measurement × materials, $F(1,76) = 4.23$, $p < .05$, and an interaction of measurement × task × materials, $F(1,76) = 4.87$, $p < .05$, $\mathrm{MSE} = 27{,}412$, for all effects.

An ANOVA performed on the difference scores (dual task – baseline control) highlights the predicted interaction of task × materials, $F(1,76) = 4.87$, $p < .05$, $\mathrm{MSE} = 54{,}824$, with respect to how writing interfered with the secondary task. The spatial-concrete ($M = 48$ ms) and spatial-abstract ($M = 56$ ms) conditions did not differ, $t < 1.0$. However, the contrast between the visual-concrete ($M = 318$ ms) and the visual-abstract ($M = 95$ ms) conditions was reliable, $t(38) = 2.32$, $p < .05$. The RT increase of 318 ms between baseline and dual task conditions for visual targets when concrete nouns were used replicated closely the 304 ms increase observed in Experiment 1. The 95 ms interference effect for abstract nouns was statistically not different from the 58 ms effect observed in Experiment 1 ($t < 1.0$ in a cross-experiment comparison).

3.3. Discussion

The findings of Experiment 2 indicate that the writing task selectively interferes with the concurrent visual WM task. Interference is observed in defining concrete nouns presumably because the writer forms a mental image of the referent in planning sentence content (Sadoski et al., 1997). The referents of abstract nouns, in contrast, do not consistently make demands on visual WM.

Because the results of Experiment 1 and 2 were similar for the visual task, it can be safely concluded that the RT interference effect occurred because the objects presented in the secondary task were visually encoded. The shapes used in Experiment 2 could not be as easily verbally encoded compared with the triangle and circle used in Experiment 1.

Finally, the lack of significant interference for the spatial task is consistent with our expectations that the definition task fails to make significant demands on spatial WM. The slight increase in RT under dual task compared with baseline conditions probably reflects the demand made on executive attention when any two tasks are combined. We recognize that spatial codes are activated during handwriting (Van Galen, 1991), but they do not appear to be maintained in spatial WM or their storage is so undemanding as to be undetectable using our methods. In any case, it is of interest that the spatial task failed to reveal interference for either concrete or abstract nouns. This null effect contrasts with the robust verbal interference effects obtained for both types of nouns and the selective visual interference effect found only with concrete nouns.

One might argue that the lack of interference in the spatial conditions arises because of a floor effect. That is to say, the spatial task might be relatively easy compared with the visual task, allowing participants to combine it with writing more readily. It is true that RT to the spatial task was reliably faster than to the visual task in both the dual task and baseline measurement conditions. Even so, a reliable increase in RT above the baseline level would still be expected if the writing task required spatial WM.

In future research, the spatial task demands could be increased by requiring maintenance of three locations instead of two in an effort to equate RT to the two-choice visual task. Unfortunately, this would also confound the response selection requirements of the task with the distinction between visual versus spatial WM components. At this point in time, it is best to conclude that handwritten definitions in college students do not appear to require spatial WM, but further study is warranted. We anticipate that the two-choice spatial task would reveal reliable interference if the spatial planning demands of the writing task were increased (e.g., giving directions) or if the spatial parameters for motor output were not automatically processed (e.g., in young children's handwriting).

4. Experiment 3

The orthographic encoding of graphemes can be accomplished by direct retrieval of word spelling from an orthographic output lexicon without phonological mediation (Caramazza, 1991). Computing orthography does not necessarily require a conversion of syllables to graphemes. Direct orthographic encoding, therefore, could have slowed RT on the verbal task used here because the phonological segments were visually presented. That is to say, the visual presentation of ba and da allowed for the possibility of orthographic as well as phonological interference. We tested this possibility by switching to aural presentation of the verbal task. If aural presentation diminishes or even eliminates the degree of RT interference obtained with visual presentation, then it can be concluded that orthographic representations were stored in verbal WM. On the other hand, if aural and visual presentation yield the same degree of interference, then it is likely that only phonological representations were stored during language production, consistent with the phonological loop model of verbal WM (Baddeley, 1986).

4.1. Method

The method used in the verbal condition of Experiment 1 was replicated. In addition, a phonological condition was tested in which the same syllables were presented aurally instead of visually. Participants listened to the stimuli using stereo headphones with each syllable being heard in either the left or the right channel. The instructions were identical in both conditions and required a response to a syllable that was different from the immediately preceding stimulus, regardless of its left–right location. College students ($N = 64$) were assigned in equal numbers to one of four groups defined by the factorial combination of materials (concrete versus abstract nouns) and task presentation (read versus heard).

4.2. Results and discussion

The inter-judge reliabilities were .90 for baseline definitions and .88 for dual task definitions and again the ratings were averaged for further analyses. Concrete nouns again received a reliably higher definition score than did abstract nouns, $F(1,60) = 44.60$, $MSE = 7.18$, $p < .001$. No other sources of variance were reliable. There was a tendency, however, for the read presentation condition ($M = .94$) to support a higher level of accuracy compared with heard presentation condition ($M = .91$), $p < .07$.

There were no significant sources of variance in the analysis of secondary task accuracy. Overall accuracy was .93, comparable to the findings of Experiment 2 and slightly higher than that observed in Experiment 1. The mean RTs are shown in Fig. 4. The RT ANOVA revealed only a main effect of measurement condition, with baseline RT ($M = 915$ ms) being faster than dual task RT ($M = 1017$ ms), $F(1,60) = 12.71$, $MSE = 25{,}835$, $p < .001$. It made no difference whether the verbal task was presented visually as in the read condition or aurally as in the heard condition. Thus, the findings indicate that writing interferes with the storage of phonological representations in verbal WM, as outlined in the introduction. Orthographic representations do not appear to be involved in the verbal interference effects observed in Experiments 1 and 3.

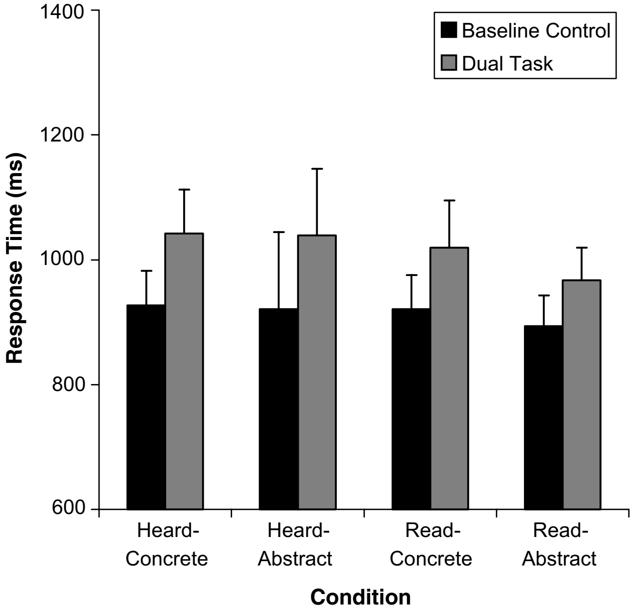

Fig. 4. Mean response times (ms) and standard errors for baseline control and dual task conditions in Experiment 3.

5. General discussion

It was hypothesized that verbal WM supports necessary processes in written language production, whereas visual WM supports optional processes associated with the planning of image-based conceptual content. Here, writing a definition to either a concrete or an abstract noun slowed the responses made to a concurrent verbal WM task. This outcome is consistent with the notion that grammatical, phonological, or orthographic encoding required the use of verbal WM.

As expected, only concrete nouns slowed the visual WM task. The planning of conceptual content prior to grammatical and phonological encoding was assumed to be sensitive to whether images are maintained in WM. Sadoski et al. (1997) concluded that concrete words activate both imaginal and verbal representations in writing, with the dual codes yielding richer, more detailed definitions. We replicated their results in three experiments and further showed that the image-based conceptual content disrupted the speed with which a concurrent visual WM task could be performed. The results add support to the dual coding theory of language production and memory proposed by Sadoski and Paivio (2001).

Our results on the role of spatial WM are less clear. It may be the case that the definition task studied here makes little, if any, demands on spatial WM. This tentative conclusion is contingent on further study with spatial tasks that take as long to respond to as the verbal and visual tasks that we examined. It is also important to examine whether writing extended, cohesive texts demands spatial WM (Hayes, 1996).

The present findings confirm the importance of verbal and, more selectively, visual WM in language production, as hypothesized by Kellogg (1996). Several studies now support the idea that verbal WM is used to maintain phonological representations during written language production (e.g., Chenoweth & Hayes, 2003; Kellogg, 2004; Levy & Marek, 1998; Ransdell et al., 2002). But these findings appear at odds with neurological case studies in which normal written as well as spoken language is found in patients with severe impairment in short-term verbal memory tasks (Gathercole & Baddeley, 1993). These cases imply that written production can succeed by direct retrieval from an orthographic lexicon when a phonologically based verbal WM component is damaged (Shelton & Caramazza, 1999). Thus, taken together the literature suggests that in a normal population language production typically uses a phonological pathway that depends on verbal WM; but it is too strong to conclude that phonological storage is necessary for fluent language production as proposed in Kellogg's (1996) model.

Identifying the one or more stages of language production affected by our manipulations is difficult. It is reasonable to suggest that the disruption in RT on the visual task by concrete nouns likely stemmed from the planning stage. Retrieving and maintaining an imaginal representation of a concrete noun ought to depend on the availability of visual WM. Presumably, semantic WM is also necessary for storing abstract prepositional representations. But once a conceptual representation, whether imaginal or propositional, is activated, grammatical, phonological, and orthographic encoding ought to follow in like manner for both concrete and abstract words. In Bock and Levelt's (1994) model, the representations retrieved during grammatical encoding (lemma) and phonological encoding (lexeme) are independent of the imaginal and prepositional representations at the conceptual level. Hence, it is unlikely that a selective interference effect for concrete nouns alone arose after the planning stage.

By contrast, assignment of the verbal task interference effect to phonological, orthographic, or grammatical encoding is premature. On the one hand, the outcome of Experiment 3 suggests that writing involves the temporary storage of words coded phonologically. The verbal interference effect was just as large when the syllable in the concurrent task was aurally instead of visually presented. If orthography were maintained in verbal WM, then one would expect a larger interference effect in the visual presentation condition. It is also known that apraxic patients who make phonemic errors in spoken language production also fail to show the usual phonemic similarity and word length effects characteristic of verbal WM tasks (Waters, Rochon, & Caplan, 1992). Thus, there is a link between difficulties in phonological encoding in speech production and deficiencies in verbal WM. One could argue, then, that the verbal interference effects observed here arise from storage of the output of the phonological encoding phase of language production (Bock & Levelt, 1994). These representations would serve as input to orthographic encoding in written production.

On the other hand, it is still uncertain whether cascaded stages of grammatical, phonological, and orthographic encoding best describe language production. Other models posit modality-specific lexical representations where grammatical information is embedded within both phonological and orthographic lexicons (Shelton & Caramazza, 1999). Connectionist models propose that grammatical, phonological, and orthographic encoding are interactive rather than cascaded stages of processing (Dell, 1988). From a connectionist perspective, then, it is likely that all three levels of representation depend on the computational resources of verbal WM. In any case, it is premature to conclude which specific aspect of linguistic encoding does or does not require the support of verbal WM.

Empirically, it is known that a concurrent load on verbal WM can disrupt grammatical encoding as evidenced by subject–verb agreement errors in written French (Fayol et al., 1994; Largy & Fayol, 2001). Further, subject–verb agreement in written French is facilitated when phonological cues help to resolve the correct verb inflection for a plural subject. When the inflection is silent, errors are more likely under a concurrent load than when phonological cues are available (Largy & Fayol, 2001). Resolving the correct spelling of a regular verb when multiple orthographic representations are active carries a cognitive cost. It is important in future research to determine the extent to which grammatical, phonological, and orthographic processing compete for the limited resources of verbal WM.

In conclusion, our findings suggest that the dual task method examined in the present experiments is a fruitful approach to studying the contributions of specific WM components to written language production. One stage, if not more stages, of linguistically encoding the conceptual content of a planned message requires the transient storage of phonological representations in verbal WM. Visual WM appears to only play a role when concrete language gives rise to imagery during the planning stage. Moreover, writing a series of definitions in longhand does not appear to interfere with a concurrent spatial WM for either concrete or abstract nouns, but further research on this issue is warranted.

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