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# Effects of working memory load on long-term word priming

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Three experiments assessed the role of verbal and visuo-spatial working memory in supporting long-term repetition priming for written words. In Experiment 1, two priming tasks (word stem completion and category-exemplar production) were included with three levels of load on working memory: (1) without memory load, (2) memory load that involved storing a string of six digits, and (3) memory load that involved storing a graphic shape. Experiments 2 and 3 compared the effects of a verbal (Experiment 2) or a visual (Experiment 3) working memory load at encoding on both an implicit (word stem completion) and an explicit test (cued recall). The results show no effect of memory load in any of the implicit memory tests, suggesting that priming does not rely on working memory resources. By contrast, loading working memory at encoding causes a significant disruptive effect on the explicit memory test for words when the load is verbal but not visual.

The term "working memory" refers to a system capable of holding and manipulating information while allowing subjects to perform other more complex tasks such as learning, comprehension, or reading (Baddeley, 1990). Although there are now many different models to explain working memory performance (see Miyake & Shah, 1999, for a recent review), the working memory model proposed by Baddeley and Hitch (1974) and developed during the last 25 years (Baddeley, 1986, 1999; Baddeley & Logie, 1999) has become one of the most widely used. In Baddeley and Hitch's (1974) working memory model, verbal and visuo-spatial information are manipulated by two different slave subsystems named the phonological loop and the visuo-spatial sketchpad. This fragmentation of working memory is supported by dissociations observed between verbal and visuo-spatial modalities in various neuropsychological (e.g., Basso, Spinnler, Vallar, & Zanobio, 1982), and behavioural (e.g., Logie, Zucco, & Baddeley, 1990) studies.

As in other models of short-term memory (e.g., Atkinson & Shiffrin, 1968), the short-term retention of information in working memory has been considered a basic step in the process of developing long-term memories (Baddeley, 1986). This assumption has received confirmatory empirical evidence from both neuropsychological and cognitive approaches. From neuropsychological studies it has been demonstrated that learning new words is impaired in patients with a reduced phonological short-term memory (Baddeley, 1993; Baddeley, Papagno, & Vallar, 1988). Similarly, it is possible to simulate reduced working memory capacity in non-memory-impaired individuals by using a dual-task technique where participants are required to remember a list of digits while they have to perform other cognitive tasks. For example, in Baddeley and Hitch (1974),

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an immediate or delayed free recall test for words was used with a preload or a concurrent load of zero, three, or six digits to be memorised before or during word presentation. In these experiments the percentage of recalled words declined significantly with an increased load of digits, both in the immediate and delayed tests. Baddeley and Hitch (1974) concluded that ‘‘a load of six items does impair the long-term component of free recall’’ (p. 72).

Comparable effects of learning impairment using a concurrent load have also been found in other tasks such as paired-associate learning (Baddeley, Lewis, Eldridge, & Thomson, 1984a) and retention of prose (Baddeley & Hitch, 1974). Another useful dual-task technique is articulatory suppression in which participants are required to repeat some words or statements (e.g., ‘‘the, the, the …’’) while encoding materials. Using this technique, recall of verbal material is reduced (Baddeley, Lewis, & Vallar, 1984b). By contrast, articulatory suppression did not interfere with the retention of non-verbal visual information (Brandimonte, Hitch, & Bishop, 1992).

Based on these findings it has been suggested that working memory not only serves as a backup system for the maintenance of information while it is processed, but also plays an important role in long-term memory acquisition (Baddeley, 1986, 1992, 1993).

More recently evidence has been reported for a close correspondence between specific types of working memory and specific forms of long-term learning. For example, Gathercole, Hitch, Service, and Martin (1997), using tasks of word learning with 5-year-old children, found that phonological short-term memory plays a significant role in the long-term learning of the sounds of new words. Romani and Martin (1999), examining the long-term memory of a patient with problems in phonological short-term memory for words, found that the long-term memory problems of that patient were specific for words. This patient was very impaired in memory tests involving learning of lists of words but not for coherent stories or non-verbal visual information. The authors concluded that the activation and maintenance of phonological codes in short-term memory is necessary to store this information in long-term memory.

It should be noted that the above studies considered the role of working in supporting direct measures of memory, such as recall or cued recall (Johnson & Hasher, 1987). Direct measures express a form of memory that can be described as explicit because the tasks instruct participants to use their intentional or conscious recollection of prior experiences (Graf & Masson, 1993; Roediger & McDermott, 1993). Thus explicit memory can be distinguished from various sorts of implicit memory, which reflects the influence of prior experiences on subsequent task performance in circumstances where intentional recollection of specific episodes is not required (Graf & Schacter, 1985).

Implicit memory can be expressed in numerous ways, but long-term priming has been the most frequently studied example (e.g., Richardson-Klavehn & Bjork, 1988). Interest in priming has been fuelled by various dissociations observed between priming and explicit forms of memory, in particular recall and recognition tests. Thus, unlike these explicit memories, it is possible to find amnesic patients who show priming effects at levels quite similar to normals (see Shimamura, 1986, 1993, for reviews) and older adults can also show similar levels of priming to younger adults despite the decreased explicit performance of the elderly (see Light, 1991; Light & La Voie, 1993, for a review).

By contrast, the relation between working memory load and long-term priming remains unclear. The most relevant data come from studies that divide attention during the encoding phase of long-term priming experiments where the task used to divide attention requires the use of working memory resources. Procedures used to divide attention during the encoding phase of a priming task have been very different across studies. Some studies imposed few burdens on working memory, such as when participants decided whether a tone presented concurrently with the encoding phase was high, medium, or low (Parkin & Russo, 1990; Russo & Parkin, 1993; Schmitter-Edgecombe, 1996), or decided whether a digit presented auditorily was odd or even (Schmitter-Edgecombe, 1999a, 1999b). Because there is no need to maintain this information over time, from the perspective of the working memory model (e.g., Baddeley, 1986), we can expect that these concurrent tasks only make minimal demands on either the phonological loop or the central executive. However, other studies of divided attention during the encoding phase of a priming task have used concurrent tasks that impose a larger load on working memory resources. For example, in some of these experiments (Mulligan, 1997; Mulligan & Stone, 1999) participants were required to memorise a series of digits and letters (usually three or six items) before reading aloud the word presented as a prime in the study phase. Subsequently, subjects were asked to recall the series of digits and letters, and then complete the test phase of the experiment in which priming was measured.

Results concerning the effect of memory load on priming using this paradigm are controversial. While some studies have found an effect of digit load on priming (e.g., Mulligan, 1997; Mulligan & Stone, 1999) some others fail to find this effect (Mulligan & Stone, 1999, Experiment 1). Mulligan and colleagues (Mulligan, 1997; Mulligan & Stone, 1999) suggest that these inconsistencies may be due to the strength of interference of dividing attention, with reduced priming under strong but not mild interference conditions (Mulligan & Stone, 1999), or due to the type of implicit memory test used (conceptual vs perceptual), with reduced priming most notable for conceptual tasks (Mulligan, 1998). However the final cause of these inconsistencies is not obvious.

Determining the role of working memory in long-term priming has important theoretical implications. For example, as noted above, working memory resources play an important role in long-term learning for corresponding information (e.g., long-term phonological knowledge requires phonological short-term memory). Given that long-term priming is often thought to be a by-product of long-term learning within perceptual systems (e.g., Bowers, 1999), it might be expected that reducing working memory capacity in visual or phonological systems would impair visual or phonological long-term priming, respectively. The conclusions of Mulligan and colleagues would seem to pose a challenge to this view, but more research needs to be carried out before any firm conclusions are warranted.

In the present paper, we assessed long-term priming for visual words under two modalities of working memory load (phonological and visual) in order to investigate the role of working memory in long-term priming.

## EXPERIMENT 1

In this experiment both phonological and visual working memory were manipulated at the study phase of two priming tasks (perceptual and conceptual). A phonological working memory load was imposed by requiring participants to recall a string of six digits. A concurrent task of 6-digit serial recall has been found to produce a clear and significant decrement in performance in a wide range of learning tasks (Baddeley, 1986; Baddeley & Hitch, 1974). Visual working memory was loaded by presenting a geometrical shape simultaneously with the study words and requiring participants to memorise the shape and later to recognise it.

Given the claim that divided attention selectively affects conceptual priming (e.g., Mulligan, 1998), we also included perceptual and conceptual priming tasks (see Blaxton, 1989). The word stem completion task was used for the perceptual priming task (e.g., Bowers & Schacter, 1990; Graf & Schacter, 1985) and the category-exemplar production task was used as a conceptual test (e.g., Hamann, 1990; Mulligan & Stone, 1999). On the basis of previous studies suggesting that priming is sensitive to levels-of-processing manipulations, particularly for conceptual priming tasks (Roediger & McDermott, 1993; see Brown & Mitchell, 1994, for a review), two different incidental study procedures were used: (1) a structural decision task (Does the word include the letter E before A?) and (2) a conceptual decision task (Does the word refer to a living being?).

Finally, the issue of subject awareness and explicit memory contamination in the performance of implicit tests is always a concern. We used a procedure designed to reduce awareness by including many study words not repeated at test, and disguising the nature of the study and test phases of the experiment. In order to determine the success of these procedures, a post-test awareness questionnaire (Bowers & Schacter, 1990) was administered at the end of the experiment.

### Method

*Participants*. A total of 48 undergraduates (42 women and 6 men) at the University Autònoma de Barcelona (Spain), with an average age of 20 years and 3 months, participated voluntarily in this experiment.

*Design and materials*. Two priming tasks, one perceptual (word stem completion) and one conceptual (category-exemplar production) were included as a within-subject variable, as were memory load and type of encoding task. Memory load during study had three levels: (1) without memory load, (2) memory load of a string of six digits, and (3) memory load of visual stimuli (geometrical shapes). In addition, the encoding phase used two types of orienting tasks: structural (Does the word include the letter E before A?) and conceptual (Does the word refer to a living being?).

A PC Computer with a 14″ colour screen was used. The software for the stimuli presentation was written with QBASIC language.

For the stem completion task, 24 Spanish common nouns with a length of five to eight letters and with an absolute frequency between 5 and 50 per million (low and medium low frequency) in the FREC Spanish data base (Sebastián, Martí, Cuetos, & Carreiras, 1995) were used. All these words had different initial trigrams (stems). The number of words that could be generated from these stems was also controlled (more than 10 and less than 100 words). Of these words, 12 were presented at study (primed items) and 12 were not (baseline items used to compute priming scores), and all 24 items were presented at test. These two sets of words were counterbalanced between subjects.

For the category-exemplar production task 24 Spanish nouns from different semantic categories were used. These words were selected from the Pascual and Musitu (1980) Spanish categorical norms. Only one noun of each category was selected such that it was ranked from sixth to tenth in the list. As with the word stem completion task, half of these words were used as primes and the other half as new words.

An additional 210 words were used as distractors so that each target word was embedded with five distractor words during the encoding task. The distractor words were selected based on two constraints: none of these words had the same initial stem of any target word, and none of them corresponded to a category of those used in the category-exemplar production task.

The materials used to load working memory during the implicit memory task were as follows: For the digit serial recall task 30 different series of six digits were randomly generated, with the constraints that digits did not repeat (e.g., 607519), and that there were no forward or backwards natural series (e.g., 6, 7 or 7, 6). Geometric shapes for the visual recognition task consisted of 30 blue shapes with three regular sides of 14 cm each, and a fourth that could take on different configurations (see Appendix).

An awareness questionnaire (similar to that used in Bowers & Schacter, 1990) was administered in the post-test phase. The key questions were: (a) Do you think you have been using in the word production task words that appeared previously in the decision task? (b) How many of those words do you think you used? and (c) Did you try to memorise words during the decision tasks?

*Procedure*. Participants were tested individually, and all tasks were run on computer. Before the main experiment a training phase was administered. During this phase subjects were taught to perform the tasks of digit serial recall, recognition of geometrical shapes, the decision tasks of the study phase, and the tasks performed in the test phase, with the constraint that the study and test phases were presented as language tasks and unrelated.

The procedure used in the main experiment was different from the more usual long-term priming procedure. The experiment was organised into a set of study and test phases. In each study phase only one target word was presented with five distractor words, followed by a delay of 25 seconds, followed by a test phase in which participants generated three words for each of the two stimuli presented (one of which was previously studied). Thus, each study trial was followed by a test trial, rather than the more usual way of presenting all the study words in a block, followed by a block of test items.

The incidental study task for both structural and conceptual encoding involved typing ‘‘y’’ or ‘‘n’’ (yes/no) as fast as possible to the question that appeared at the top of the screen (‘‘Does the word include the letter E before A?’’ for the structural task or ‘‘Does the word refer to a living being?’’ for the conceptual task) for each of the six words presented (one target word and five distractor words). The target word could appear randomly in the third or fourth rank position of the set of six words. Participants’ response times were recorded. A word remained on the screen for 1 second when a participant’s reaction time was less than 1 second.

The test phase of the implicit memory task took place after a 25-second delay during which some blue dots randomly filled the screen. The test phase was either perceptual (word stem completion) or conceptual (category-exemplar production). For the perceptual task (word stem completion) three capital letters appeared as the initial stem of a word (e.g., FER–) and participants were asked to complete the stem three times as quickly as possible by typing the first three words that came to their mind. This procedure was repeated a second time using a different stem. In the category-exemplar production task the name of a semantic category was presented on the screen (e.g., FLOWERS) and participants were asked to type, as quickly as possible, the names of the first three exemplars of this category that came to their mind. On completion, a new semantic category was presented and participants generated three more words.

The study–test sequence was repeated four times for the structural encoding trials and four times for the conceptual encoding trials. Of these, two trials corresponded to word stem completion and two trials to category-exemplar production. When the processing at encoding or at retrieval changed, participants were informed beforehand and performed one trial of training. The order of presentation of the tasks both at encoding (structural and conceptual) and at test (word stem completion and category-exemplar production) was counterbalanced between subjects.

For the phonological memory load condition, one digit of the corresponding series appeared in front of the word (e.g., 3 – SARDINA). Participants were required to read aloud and memorise the digit, and at the same time type the key letter ''y'' or ''n'' to answer the corresponding question related to the word. When the first digit–word pair disappeared the next digit–word pair was presented. This procedure was repeated for the six digit–word pairs. When the last pair had faded from the screen, an empty six-cell box appeared and participants were required to fill the cells with the digits in the same order of presentation. Following a delay to complete the total 25 seconds between encoding and retrieval, the implicit test phase took place using the same procedure as for the implicit task without memory load.

For the visual memory load condition a blue figure shaped as those described in the materials section appeared on the screen during the study task. Participants were asked to respond using the keyboard to the question proposed to each word while at the same time they memorised the shape of the background graphic. After the incidental encoding task six graphics labelled with the letters A to F appeared on the screen (see Appendix) and participants had to recognise the shape recently presented by pressing the corresponding key (from A to F). Following a delay of the remaining portion of the 25 seconds, the implicit test phase took place. For the non-memory load condition neither numbers nor geometric figures were presented along with the words.

When all the experimental tasks were completed, the awareness questionnaire was administered. The entire experiment took approximately 1 hour.

## Results

Before performance on the priming task was assessed, performance in the incidental encoding task was checked in order to ensure that participants were paying attention to the task. Percentage of correct answers in the decision task (typing ''y'' or ''n'') was found to be very high (93%), indicating that participants performed the task correctly.

The proportion of target words produced at test was calculated for both old (previously presented) and new words. Priming scores, in both word stem completion (Table 1) and category-exemplar production (Table 2), were computed by subtracting the proportion of generated new words from the proportion of generated old words.

A repeated measures analysis of variance with two factors (memory load and type of encoding) was carried out on the priming scores for both word stem completion and category-exemplar production.

For the word stem completion task no effect of memory load was found, $F(2, 94) = 0.650$, $MSe = 0.124$, $p = .524$, indicating that priming was unaffected by working memory load. By contrast, significant effects were obtained for encoding type

**TABLE 1**
Mean proportion correct (and SD) on the word stem completion task as a function of study status, memory load, and type of encoding

| *Memory load condition* | *Study status* Old | *Study status* New | *Priming (Old–New)* |
|---|---|---|---|
| *Without memory load* | | | |
| Structural encoding | .49 (.36) | .10 (.20) | .39 (.42) |
| Conceptual encoding | .65 (.33) | .11 (.24) | .54 (.39) |
| *Concurrent digit serial recall* | | | |
| Structural | .40 (.34) | .12 (.21) | .28 (.32) |
| Conceptual | .63 (.35) | .10 (.20) | .53 (.43) |
| *Concurrent recognition of shapes* | | | |
| Structural | .50 (.39) | .08 (.21) | .42 (.44) |
| Conceptual | .58 (.34) | .14 (.27) | .44 (.46) |

**TABLE 2**
Mean proportion correct (and SD) on the category-exemplar production task as a function of study status, memory load, and type of encoding

| *Memory load condition* | *Study status* | | *Priming (Old–New)* |
|---|---|---|---|
| | *Old* | *New* | |
| *Without memory load* | | | |
| Structural encoding | .37 (.35) | .17 (.26) | .20 (.43) |
| Conceptual encoding | .41 (.34) | .08 (.18) | .33 (.37) |
| *Concurrent digit serial recall* | | | |
| Structural | .31 (.32) | .16 (.28) | .15 (.39) |
| Conceptual | .42 (.34) | .10 (.20) | .32 (.43) |
| *Concurrent recognition of shapes* | | | |
| Structural | .32 (.31) | .19 (.26) | .13 (.39) |
| Conceptual | .40 (.38) | .11 (.21) | .29 (.43) |

$F(1, 47) = 7.220$, $MSe = 0.202$, $p = .010$. In contrast with some previous results where a small or null effect of level-of-processing was found in perceptual priming, we found a clear effect of this variable reflecting larger priming following conceptual study (see Table 1). More precisely, the proportion of priming due to conceptual encoding was statistically larger than the proportion of priming following structural encoding in both the non-memory load and memory load with digit serial recall. In the condition memory load with visual recognition the tendency was the same but the results were not statistically different. Moreover, in the analysis of variance for the two factors, the interaction of memory load by encoding type was not statistically significant ($p = .204$).

For the category-exemplar production task, again no effect of memory load was found, $F(2, 94) = 0.429$, $MSe = 0.154$, $p = .652$, while significant effects were obtained for encoding type, with more priming following conceptual encoding, $F(1, 47) = 7.843$, $MSe = 0.224$, $p = .007$. The interaction of memory load by encoding type was not statistically significant ($p = .939$).

In order to assess the awareness of participants during the experiment the post-test quetionnaire was analysed. Responses to the post-test questionnaire showed that none of the participants expressed intentionality for the test phase of the implicit memory task. However, 34 participants (70%) thought that they were aware of having unintentionally used at some point some word presented in the encoding task (that is, they were categorised as aware but unintentional). An analysis of awareness as a between-subjects variable did not show any effect on priming, neither on word stem completion, $F(1, 46) = 0.054$, $MSe = 0.206$, $p = .817$, nor on category-exemplar production, $F(1, 46) = 0.960$, $MSe = 0.160$, $p = .332$. Therefore the level of awareness of participants was similar to previous experiments concerning long-term word priming when an incidental encoding task is used.

Performance on the working memory tasks was also assessed in order to ensure that they were sufficiently difficult to reduce working memory capacity devoted to the study words. Proportion of correct responses was lower for the digit serial recall and the visual recognition of shapes tasks when performed as concurrent tasks compared to the baseline condition ($p$ values $< .01$). Nevertheless, performance in both working memory tasks in the memory load conditions was above the chance level (61% correct was the mean proportion in the digit serial recall task and 45% correct was the mean proportion in the visual recognition of shapes).

## Discussion

The working memory resources of the phonological loop and the visuo-spatial sketchpad were manipulated at study in two types of priming tasks, one perceptual (word stem completion) and one conceptual (category-exemplar production). Results show that neither memory load condition reduced stem completion or category-generation priming. Thus it appears that working memory resources do not play an important role in long-term word priming, be the priming task perceptual or conceptual.

One possible concern with these results is that participants avoided the demanding working memory task and simply focused in the incidental encoding task, effectively treating the working memory tasks as a secondary task. However, we would argue that this is unlikely. Not only were the participants explicitly encouraged to memorise the information presented in the working memory tasks, but their performance in these tasks was also well above chance in all of memory load conditions. Indeed, performance on the digit serial recall task was comparable with previous results. For example, Baddeley and Hitch (1974) reported a 61% accuracy rate when a six-digit load was used as a concurrent task. Furthermore, in response to the post-test questionnaire, none of the participants claimed that they attempted to memorise the prime words, consistent with the view that working memory resources were directed to the concurrent tasks.

Another possible concern is that the effect of working memory load was only assessed on the implicit memory tests. The detrimental effect of loading working memory by concurrent tasks at encoding on subsequent explicit memory tests was inferred from previous studies (e.g., Baddeley & Hitch, 1974; see Baddeley, 1986, for a review) but not directly assessed.

## EXPERIMENT 2

The results of Experiment 1 suggest that a load on working memory during encoding does not reduce priming, whereas past studies have found explicit memory to be reduced under comparable conditions. However, in order to provide a more direct comparison of the role of working memory in supporting priming and explicit memory, two additional experiments were carried out. In the new experiments, a cued recall task was used as a measure of explicit memory while priming was measured by means of a word stem completion task. Experiment 2 manipulated the resources of the phonological loop with a concurrent digit serial recall task during the encoding phase.

To reduce the likelihood that participants relied on explicit memory when performing the stem completion task, the cued recall task was performed in the last stage of the experiment. Due to this, the study–test procedure employed in Experiment 1 was replaced by the traditional procedure in which all the study words are presented in one block followed by one test block.

### Method

*Participants*. A total of 48 undergraduates (45 women and 3 men) at the University Autònoma de Barcelona (Spain), with an average age of 20 years and 8 months, participated voluntarily in this experiment.

*Design and materials*. Retrieval task (word stem completion and cued recall) and memory load (without memory load and digit serial recall) were both manipulated as within-subject variables. Type of encoding (structural or conceptual) was manipulated between subjects.

A total of 36 words with the same attributes as those of the stem completion task in Experiment 1 were used in Experiment 2. From these words a set of 12 was used for the cued recall task and the remaining 24 for the word stem completion task (12 as old words and 12 as new words). The sets of words were counterbalanced in the experiment so that each set appeared the same number of times in each of the three conditions. The six series of six digits for the digit serial recall task were taken from Experiment 1. The post-test questionnaire of Experiment 1 was also used.

*Procedure*. Materials were presented on the same computer as in Experiment 1. Each word appeared on the centre of the screen and participants were asked to press either "y" (yes) or "n" (no) on the keyboard in response to the posed question depending on the between-subjects condition (structural or conceptual). Both questions were the same as in Experiment 1. The 24 words appeared in blocks of 6 alternating a block of words alone with a block of words plus digits. When a word plus digit was presented the digit appeared at the beginning of the word (e.g., 3 – CABAÑA) and both disappeared when a key (y or n) was pressed on the keyboard. After the presentation of a word plus digit set, an empty six-cell box appeared on the screen and participants were required to fill the boxes by typing the six digits presented before. Half of the participants started the experiment with a block of only words and the other half with a block of word plus digit.

After a delay of 25 seconds the word stem completion task was performed. A trigram appeared on the screen and participants were asked to complete the trigram in order to create the first word that came to mind. Of the 24 trigrams, 12 corresponded to words previously presented (old words) and the other 12 to new words. Old and new words were alternated during the task. The cued recall task took place immediately after the stem completion task. A trigram appearred on the screen and participants were required to complete the trigram in order to form a word that had been presented in the study phase. When a word was retrieved participants were asked to type a number (from 0 to 5) indicating the degree of confidence on the recalled word. When participants were unable to recall a word, a new trigram was presented. After the presentation of the 12 trigrams for the cued recall task the post-test questionnaire was administered.

Prior to the experiment a training phase was run in which the encoding and the word stem completion task were presented as tests of speed of language processing and unrelated. Nothing was said about the cued recall task.

## Results

Priming was computed in the same way as in Experiment 1. Table 3 shows the mean number of target words completed in each condition and the amount of priming in both encoding conditions. An analysis of variance with memory load as a within-subject factor and type of encoding as a between-subjects factor was carried out on the priming scores. The effect of memory load was found to be not significant, $F(1, 46) = 0.143$, $MSe = 1.162$, $p = .707$, while the effect of type of encoding was significant, $F(1, 46) = 6.888$, $MSe = 2.184$, $p < .01$, showing that conceptual encoding provided more priming than the structural encoding did. No statistical effect of interaction of load by encoding was found ($p > .09$).

Table 4 shows the mean number of words correctly recalled in the cued recall task for both types of encoding. The same analysis of variance was carried out on the cued recall scores. The effect of memory load was significant for the cued recall task, $F(1, 46) = 14.845$, $MSe = 0.909$, $p < .001$, showing that a working memory load of six digits during encoding produced a decrease in the number of words recalled. The effect of type of encoding was also statistically significant, $F(1, 46) = 39.665$, $MSe = 2.420$, $p < .001$. Conceptual encoding resulted in a better performance for words than the structural encoding did. In fact, structural encoding resulted in quite poor memory for words. As in the word stem completion task, no interaction of load by encoding was found ($p > .09$).

Responses to the post-test questionnaire showed that none of the participants intentionally retrieved study words in the word stem completion task. However, 16 subjects (33%) thought that they unintentionally retrieved some of the study words.

**TABLE 3**
Mean number of correct words (and SD) on the stem completion task as a function of study status, memory load, and type of encoding

| *Memory load condition* | *Study status* *Old* | *New* | *Priming (Old–New)* |
|---|---|---|---|
| *Without memory load* | | | |
| Structural encoding | 1.46 (.88) | .38 (.58) | 1.08 (1.06) |
| Conceptual encoding | 2.79 (1.47) | .54 (.83) | 2.25 (1.70) |
| *Concurrent digit serial recall* | | | |
| Structural | 1.50 (1.10) | .13 (.34) | 1.38 (1.10) |
| Conceptual | 2.17 (1.05) | .38 (.65) | 1.79 (1.22) |

**TABLE 4**
Mean number of words correct (and SD) on the cued recall task as a function of memory load and type of encoding

| *Memory load condition* | *Encoding* *Structural* | *Conceptual* |
|---|---|---|
| Without memory load | 1.13 (1.15) | 3.46 (1.67) |
| Concurrent digit serial recall | 0.71 (0.69) | 2.38 (1.44) |

## Discussion

The results of Experiment 2 confirm those of Experiment 1 regarding the absence of an effect of verbal memory load during encoding on word stem completion priming. In addition, this later experiment revealed a different pattern of results in a cued recall task. The words presented under the concurrent task of digit serial recall were less likely to be recalled than those words presented when the working memory resources were free. The results of the cued recall task confirm those found in previous studies where phonological working memory was manipulated with a concurrent task of digit serial recall (e.g., Baddeley & Hitch, 1974).

In addition, more priming was obtained following conceptual compared to structural encoding. These results confirm those of Experiment 1 and are consistent with some other findings that have observed levels-of-processing effects on implicit tests, particularly on conceptual priming but sometimes on perceptual priming as well (Roediger & McDermott, 1993; see Brown & Mitchell, 1994, for a review). These effects are not attributable to explicit memory contamination, as shown by the responses to the post-test questionnaire.

## EXPERIMENT 3

Experiment 2 provided further evidence that priming does not rely heavily on working memory resources, but it focused strictly on the role of the phonological loop. In Experiment 3 we focused on the visuo-spatial sketchpad of working memory. A task of recognising Japanese characters (katakana) was used to load the working memory of the visuo-spatial sketchpad while participants were encoding words. Katakana characters were chosen as visual stimuli because participants did not have any knowledge of these scripts, making it difficult for them to recode these characters into a verbal representation (and thus circumventing the use of visual working memory). For the sake of simplicity, we only included the conceptual encoding condition.

## Method

*Participants*. A total of 24 undergraduates (23 women and 1 man) at the University Autònoma de Barcelona (Spain), with an average age of 20 years and 9 months, participated voluntarily in this experiment.

*Design and materials*. The same design and materials of Experiment 2 were used on Experiment 3 with the difference that in this case the number of words was increased to 72 (three sets of 24 words each). The new words shared the same features of those in Experiment 2. For the visual recognition task six series of four Japanese katakana characters each were used.

*Procedure*. The procedure was the same of Experiment 2 except for the fact that words appeared in blocks of four instead of six. Half of the blocks of four words were presented with a Japanese character at the beginning (e.g., ネ – VALVULA) and the remaining half without Japanese characters. After the presentation of a set of four words plus Japanese characters a visual recognition task took place where eight Japanese characters were shown on the screen and participants were required to point out the characters previously presented.

Once the 48 words had been encoded and before the word stem completion task took place, a distractor task was performed. This task required the recognition of Japanese characters, similar to the concurrent task used as memory load during the encoding of words. This provided a useful baseline measure in order to compare the results of the visual recognition test when used as a concurrent task or alone. The distractor task took approximately 2 minutes.

The word stem completion task, the cued recall task and the administration of the post-test questionnaire were designed in a similar way as in Experiment 2.

## Results

Table 5 shows the mean number of target words produced in each condition and the measure of priming (after subtracting new words from old words) in the word stem completion task. The mean number of words correctly recalled on the cued recall task for both encoding conditions (with and without visual memory load) are shown in Table 6.

A series of *t*-tests indicated an absence of effect of memory load for both priming, $t(23) = 0.110$, $p > .91$, and cued recall, $t(23) = 0.000$, $p = 1$. We were expecting that a load on visual working memory at encoding would impair performance on the cued recall task when compared with a condition of free working memory resources at encoding. Because the results were far from our prediction we were concerned with the possibility that the visual recognition task had only imposed a small demand on the visual working memory. To assess this possibility we analysed performance on the visual

**TABLE 5**
Mean number of correct words (and SD) on the stem completion task as a function of study status and memory load

| *Memory load condition* | *Study status* | | *Priming (Old–New)* |
|---|---|---|---|
| | *Old* | *New* | |
| Without memory load | 2.21 (1.53) | 0.83 (0.92) | 1.38 (1.79) |
| Concurrent recognition Japanese characters | 2.00 (1.18) | 0.67 (0.92) | 1.33 (1.46) |

**TABLE 6**
Mean number of words correct (and SD) on the cued recall task as a function of memory load

| *Memory load condition* | |
|---|---|
| Without memory load | 3.63 (1.64) |
| Concurrent recognition Japanese characters | 3.63 (1.91) |

recognition task when used as a concurrent task or alone. The mean percentage of Japanese characters correctly recognised was found to be 75% in the condition of the concurrent task (words plus Japanese characters) and 88% in the baseline condition (distractor task). The difference between both means was statistically significant, $t(23) = 3.747$, $p < .001$.

## Discussion

The results of Experiment 3 are consistent with those of Experiment 1, suggesting that a visual working memory load during the study phase does not affect priming. This result suggests that when participants are able to identify the words correctly, further visual working memory resources are not needed to form an implicit memory for words.

However, the cued recall results of Experiment 3 were unexpected. The words presented at the study phase under the condition of a concurrent memory task for visual stimuli were subsequently recalled at a same level as words presented without a concurrent task. One possible explanation for these results is that the visual recognition task was not sufficiently demanding to cause interference on the visuo-spatial sketchpad of the working memory. However the results for the visual task show that it was not so simple: Participants were only correct on average 88% of the time when they concentrated only on the shapes of the Japanese characters, and 75% correct when they performed the task simultaneously with the study of words (with chance at 50%). Thus, it is unlikely that the subjects had not dedicated their efforts to memorising the shapes of the Japanese characters.

Given that visual working memory resources were indeed employed, how can the good explicit memory performance be explained? One possibility is that participants converted the orthographic representations of words to their phonological forms, and relied on phonological memory in order to complete the explicit memory task. This is consistent with the view that there are different visual and verbal working memory systems. According to the working memory system (Baddeley, 1992; Baddeley & Hitch, 1974) the two coding systems (verbal and visual) are independent. The separability of visual from verbal working memory resources has been also inferred from neuropsychological studies (Basso et al., 1982) from PET studies (Smith & Jonides, 1997), and from experimental studies. For example, Brandimonte et al. (1992) (Experiment 2) showed that articulatory suppression during the encoding of visual stimuli did not affect performance on a visual task. The differential disruptive effect of a secondary task depending on the working memory code system has been analysed in other studies. For example, Logie et al. (1990) used a secondary task of visualising digit patterns on a three by five square matrix while performing either a visual or a letter span task. The results showed that the secondary imaging task had a large disruptive effect on the visual span task but only a small effect on the letter span task. As pointed out by Logie (1995), "the results are highly consistent with the use of a specialised verbal short-term memory store for the letter span task and a specialised visual short-term memory store for the visual span task" (p. 60).

However it has to be noticed that Logie et al. (1990) did find a small effect of the visual secondary task on the letter span task, whereas in Experiment 3 this effect was not found. It is important to point out that in a task of visualising digits such as the one used in Logie et al. the visual information might be easily recoded into a verbal code (a digit) and because of that some phonological working memory resources may have been used, resulting in some interference within the phonological loop with the letter span task. By contrast, a recoding strategy from visual into verbal codes is less likely in the case of unknown Japanese characters. Thus, by this view, recall of the words was mediated by phonological memory, so that loading visual working memory with Japanese characters, which cannot be converted to phonological forms, could not impair the functioning of phonological working and long-term memory. Whatever the proper explanation, the key finding is that loading the visual working memory system did not impair visual word priming.

# GENERAL DISCUSSION

The aim of this study was to assess whether or not a reduced working memory capacity would reduce long-term word priming. Taken together, the results of the three experiments support the conclusion that long-term word priming is not diminished by concurrent verbal or visual working memory tasks performed simultaneously during the study phase. Therefore it can be concluded that minimal working memory resources are required for long-term repetition priming if the information is adequately processed during the study phase. It is important to emphasise, however, that there are many forms of implicit memory other than long-term repetition (Richardson-Klavehn & Bjork, 1988; Roediger & McDermott, 1993). It is unclear whether the same results will be found using other implicit memory tasks.

To our knowledge, this is the first study to directly focus on the contribution of working memory in supporting long-term word priming. Nevertheless, as noted above, there are related studies that have examined the effect of dividing attention on priming where the tasks used to divide attention made high requirements on working memory—for example using serial recall of digits or letters as a concurrent task. The present findings agree with these studies regarding the general conclusion that priming in perceptual implicit tests (e.g., word stem completion) is unaffected by dividing attention (Mulligan, 1998; Mulligan & Hartman, 1996; Schmitter-Edgecombe, 1996).

However, our finding that priming in a conceptual task is also undiminished by a working memory load conflicts with the majority of studies that have reported a reduction in conceptual priming following divided attention using serial recall as attentional interfering task (Mulligan, 1997, 1998; Mulligan & Hartman, 1996; Mulligan & Stone, 1999, Experiments 2 and 4; Schmitter-Edgecombe, 1996, 1999b), although there are some results that parallel our own (e.g., Mulligan & Stone, 1999, Experiments 1 and 3). Discrepancies between our results and the common finding of reduced priming in conceptual tests are difficult to explain at present because the methods used in the studies differ in a number of ways. Specific differences can be found in the selection of the target words, number of study–test blocks, procedure used in the study phase, number of exemplars per category, and the study instructions given to the subjects, among others.

However, it is necessary to emphasise that the crucial point for us is not division of attention during encoding but the load of information to be retained in the working memory. Our interest was to investigate the effect of holding information in working memory during a long-term priming task, not the amount of attentional resources used or where were they oriented. Indeed, because both incidental tasks used at encoding were highly attentionally demanding, we presented each word for at least 1 second in order to ensure that the items were perfectly identified.

In contrast with our conclusion that working memory resources are unnecessary for long-term repetition priming for words, a variety of evidence suggests that working memory is necessary for learning words. For example, poor working memory in children is correlated with poor vocabulary acquisition (Baddeley, Gathercole, & Papagno, 1998). Thus, the present findings might appear to pose a problem for the view that long-term priming is an incidental by-product of long-term learning (e.g., Bowers, 1999).

Before accepting this conclusion, however, it is worth noting that working memory resources appear to be particularly important in learning new information. For example, in two case reports of patients with phonological memory impairments, both P.V. and S.R. showed considerable impairment in learning foreign words, but relatively normal abilities in learning new associates between familiar words (Baddeley, 1993; Baddeley et al., 1988). That is, working memory appears to play a larger role in learning new phonological forms (and perhaps orthographic forms) than learning (or strengthening) pre-existing word forms. Thus, our finding that priming extends to familiar words under working memory load is not inconsistent with the claim that priming is a by-product of learning. What would be more problematic for this view would be the finding that working memory resources are irrelevant to long-term priming of novel words—a prediction we are currently testing.

Finally, our results speak to the question of level-of-processing effects on priming. Consistent with recent accounts (Brown & Mitchell, 1994; Roediger & McDermott, 1993) we have found that conceptual processing at encoding provides more facilitation than structural processing on both perceptual and conceptual priming tasks. These results are difficult to accommodate from a transfer-appropriate-processing account, according to which priming should be greatest when the study and test processes overlap (Roediger, Weldon & Challis, 1989). On this perspective, perceptual priming should have been greatest following structural study conditions.

In sum, we have obtained evidence that long-term repetition priming for familiar written words does not rely heavily on working memory capacity, be it phonological or visual-spatial working memory capacity. Our results with the stem completion task are consistent with a number of previous findings which have also found little or no reduction in priming in data-driven tasks when dividing attention at study employing conditions that load working memory (Mulligan, 1998; Mulligan & Hartman, 1996). However, our findings conflict with studies that have found that dividing attention with a memory task during the study phase of a conceptual priming task reduces the effect of priming (Mulligan, 1997; Mulligan & Stone, 1999). Clearly, additional work needs to be carried out in order to make sense of these conflicting findings, as well as to determine the role that working memory plays in other forms of implicit memory.

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## APPENDIX