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The Impact of Storage on Processing: How Is Information Maintained in Working Memory?

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Working memory is typically defined as a system devoted to the simultaneous maintenance and processing of information. However, the interplay between these 2 functions is still a matter of debate in the literature, with views ranging from complete independence to complete dependence. The time-based resource-sharing model assumes that a central bottleneck constrains the 2 functions to alternate in such a way that maintenance activities postpone concurrent processing, with each additional piece of information to be maintained resulting in an additional postponement. Using different kinds of memoranda, we examined in a series of 7 experiments the effect of increasing memory load on different processing tasks. The results reveal that, insofar as attention is needed for maintenance, processing times linearly increase at a rate of about 50 ms per verbal or visuospatial memory item, suggesting a very fast refresh rate in working memory. Our results also show an asymmetry between verbal and spatial information, in that spatial information can solely rely on attention for its maintenance while verbal information can also rely on a domain-specific maintenance mechanism independent from attention. The implications for the functioning of working memory are discussed, with a specific focus on how information is maintained in working memory.

Keywords: working memory, memory load, processing time, refreshing, attention

Launched by the seminal work of Baddeley and Hitch (1974), the concept of working memory (WM) has become increasingly important in psychology. Usually defined as a system devoted to the simultaneous processing and maintenance of the information relevant for goal-directed activities, WM is considered as the keystone of cognitive architecture, the capacity of which is accordingly predictive of fluid intelligence, academic achievement, and performance in a series of high-level cognitive processes such as reasoning, problem solving, learning, and comprehension (Barrouillet, 1996; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Kane, Conway, Hambrick, & Engle, 2007; Kane et al., 2004; Kyllonen & Christal, 1990). Recent work established that WM is involved not only in high-level cognition but also in low-level basic processes often considered as automatic (Barrouillet, Lepine, & Camos, 2008), further reinforcing its pivotal role in cognition. The importance of WM for our understanding of human mind has elicited an impressive amount of empirical and theoretical contributions aiming at describing its structure and functioning.

Baddeley and Hitch (1974) conceived working memory as an interface capable of maintaining and processing information, as opposed to short-term memory only having storage capacity. The specific interplay and interdependence between storage and processing is, however, still a matter of considerable debate in the literature, mostly because it is central to understanding the core structure and functioning of WM. Understanding this interplay requires an assessment both of the impact of processing on maintenance activities and, conversely, of the impact of maintenance on processing. However, in sharp contrast to the increasing number of meticulous examinations of the effect of processing on maintenance, the impact of maintenance on processing remains largely underexplored. Consequently, the present study focused on the impact that the maintenance in WM of a variety of items has on the concurrent online processing of incoming information.

This investigation was conducted within the theoretical framework provided by the time-based resource-sharing (TBRS) model of WM (Barrouillet, Bernardin, & Camos, 2004; Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Barrouillet, Portrat, & Camos, 2011). After presenting this model and deriving its predictions concerning the impact of maintenance on processing, we review the relevant literature and show that no existing research has yet provided the necessary conditions to test our predictions. We then present a set of seven experiments showing that maintaining information active in WM postpones concurrent processing

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insofar as the information to be maintained relies on a domain-general attention-based mechanism of maintenance. Importantly, the postponement of processing is commensurate with the number of items to be maintained, and this relationship provides a direct way of assessing the time it takes to refresh one piece of information in WM through attentional focusing. Finally, a compelling asymmetry between the maintenance of verbal and spatial information is demonstrated.

The TBRS Model and the Impact of Processing on Maintenance

The TBRS model assumes that processing and maintenance rely on the same limited pool of attentional resources that must be shared between the two functions. Online processing is assumed to be goal directed and, as such, to involve the construction, selection, and transformation of representations for which it relies on attention. Maintenance, on the other hand, is proposed to rely on a process of activation and reactivation of memory traces through attentional focusing (see Cowan, 1995). Thus, online processing and maintenance are proposed to rely on the same central resource in WM. Following Pashler's (1998) conception of a central bottleneck, it is assumed that only one elementary cognitive step could take place at a time at the central level of WM. Thus, central processes such as processing and maintenance would take place in a sequential manner such that no attentional refreshing can take place when new incoming information is being processed and no new incoming information can be processed when memory traces are being refreshed. This sequential functioning at the central level is proposed to have far-reaching consequences for the interplay between processing and maintenance.

Concerning the effect of processing on concurrent maintenance activities, the TBRS model predicts that the detrimental effect on maintenance of a given concurrent task would be a function of the proportion of time during which this task occupies attention, preventing refreshing processes to take place. This proportion of time is conceptualized as the cognitive load the task involves. Because the activation of the memory traces in WM suffers from a time-related decay as soon as attention is switched away, the traces of the to-be-remembered items fade away when attention is occupied by a processing step. Refreshing these items through reactivation by attentional focusing is thus needed before their complete disappearance. The proposed sharing of attention would be achieved by a rapid and incessant switching of attention from processing to storage, occurring during short pauses that would be freed while concurrent processing is running.

Thus, one of the main predictions of the TBRS model concerning the impact of processing on maintenance is that there is a tradeoff between processing and maintenance, with the number of representations that can be maintained being a function of the cognitive load involved by concurrent activities. Importantly, because the resource shared between processing and storage activities is proposed to be domain general in nature, a detrimental effect of processing is predicted regardless of the domain involved in the processing and maintenance activities insofar as the concurrent processing task relies on attention for its execution. These predictions have been tested and confirmed in several studies showing a linear relationship between cognitive load and WM span across a wide range of memoranda and intervening tasks, as long as the intervening task involves attention (Barrouillet et al., 2004, 2007, 2011; Vergauwe, Barrouillet, & Camos, 2009, 2010; Vergauwe, Dewaele, Langerock, & Barrouillet 2012; see Barrouillet & Camos, 2012, for a review).

The Impact of Maintenance on Processing

The sequential functioning at the central level, as proposed by the TBRS model, implies not only that attentional refreshing cannot take place when new incoming information is being processed but also that new incoming information cannot be processed when memory traces are being refreshed. Thus, when processing and storage are performed concurrently, processing episodes are postponed by maintenance activities in the same way as maintenance activities are postponed by processing. As we have seen, the postponement of maintenance activities results in memory loss due to the temporal decay of memory traces. The postponement of processing by maintenance activities, on the other hand, might have a negligible effect on processing accuracy, provided that the stimuli to be processed are still available in the environment. However, the effect of maintenance on processing should appear in processing time.

Specifically, the sequential functioning of WM assumed by the TBRS model leads to the prediction that maintenance activities should postpone concurrent processing. Although attention-based maintenance activities were originally thought of as rethinking only of the just-activated item (e.g., Raye, Johnson, Mitchell, Reeder, & Greene, 2002), more recent studies have shown that attentional refreshing proceeds in a cumulative fashion, starting from the first list item and proceeding in forward order until the end (Loaiza & McCabe, 2012; McCabe, 2008). Because attentional maintenance proceeds in a cumulative fashion, maintenance-based postponement of processing should linearly increase with the number of items to be maintained. Moreover, the slope of this predicted linear function should be indicative of the time it takes to refresh one item through attentional focusing. Importantly, because the resource shared between processing and storage is assumed to be domain general in nature, this effect should be observed regardless of the domain involved in the processing and maintenance activities, insofar as these processing and maintenance rely on attention-based mechanisms.

Our previous studies of the effect of processing on storage suggest that while spatial information can solely rely on attention for its maintenance, verbal information can also rely on a domain-specific maintenance mechanism independent from attention (Camos, Lagner, & Barrouillet, 2009; Camos, Mora, & Barrouillet, in press; Vergauwe et al., 2010). This latter mechanism would be specific to the maintenance of verbal information, would rely on overt or covert vocalization in a sequential manner, and is often referred to as articulatory rehearsal, as opposed to attentional refreshing. Empirical evidence indicates that the two mechanisms can concur for maintaining verbal information and have independent and additive effects (Camos et al., 2009, in press; Camos, Mora, & Oberauer, 2011; Hudjetz & Oberauer, 2007; Mora & Camos, 2013). These behavioral findings and the resulting hypothesis of independence are corroborated by neurological investigations demonstrating that the two mechanisms involve different neural substrates (e.g., Raye, Johnson, Mitchell, Greene, & Johnson, 2007). When the use of articulatory rehearsal is prevented, we expect that any increase in the amount of verbal information to be maintained will postpone processing. However, when there is no restriction on the mechanisms used for maintenance of verbal material, we expect that increasing the amount of information to be maintained will only postpone processing when the capacity of the nonattentional mechanism is exceeded. Although an equivalent mechanism for visuospatial information has been hypothesized in some versions of the multiple-component model (Baddeley & Logie, 1999; see also Logie, 2011), several recent findings suggest that, unlike verbal material, spatial information has only an attention-based maintenance mechanism at its disposal. For example, we showed that, while verbal maintenance was more disrupted by verbal than visuospatial concurrent processing, visuospatial maintenance was disrupted to the same extent by verbal and visuospatial concurrent processing (Vergauwe et al., 2010). Similar asymmetries in cross-domain interference between verbal and visuospatial activities have been observed (e.g., Bayliss, Jarrold, Gunn, & Baddeley, 2003; Depoorter & Vandierendonck, 2009; Meiser & Klauer, 1999; Morey & Mall, 2012), supporting the idea of attentional refreshing being the sole mechanism for visuospatial maintenance. As a consequence, even the maintenance of a very small amount of visuospatial information should disrupt any kind of attention-demanding processing and lead to its postponement. Finally, recent findings suggest that there are some features that cannot be refreshed, even when attention is available to maintain their memory traces (Ricker & Cowan, 2010). For such kinds of information, postponement of concurrent processing as a function of memory load would not be observed.

Thus, three specific predictions can be derived. First, when information can only rely on attention for its maintenance (i.e., for visuospatial information or for verbal information when verbal rehearsal is prevented), we predict that any increase in the amount of information to be maintained will result in slower processing. Second, for information that, in addition to relying on attention, can also rely on a nonattentional mechanism for its maintenance (i.e., verbal rehearsal for the maintenance of verbal items), we predict that an increase in memory load will result in slower processing only when the capacity of the nonattentional mechanism is exceeded. Third, for information that cannot be maintained through the attention-based mechanism, we predict that the relation between the amount of information to be maintained and processing time will disappear.

Previous Research on the Impact of Maintenance on Processing

Although the impact of the maintenance activities on processing remains underexplored, some studies either explicitly tested this relationship or provided some insight on it (Baddeley & Hitch, 1974; Engle, Cantor, & Carullo, 1992; Friedman & Miyake, 2004; Jarrold, Tam, Baddeley, & Harvey, 2011; Maehara & Saito, 2007; Saito & Miyake, 2004; Towse, Hitch, & Hutton, 2000). However, they led to divergent findings. First, a subset of studies focusing on complex span tasks compared the response times (RTs) in the first and last processing episodes within a trial. Complex span tasks are tasks in which a series of items is presented for further recall (e.g., words), each item being preceded or followed by a processing episode (e.g., an equation to be verified). Thus, whereas the memory load during the first processing episode is of zero or one item, the last processing episode is performed under the maximum memory load, rendering the comparison between the first and last processing episodes relevant for examining the effects of maintenance on processing. Whereas Saito and Miyake (2004), as well as Maehara and Saito (2007), showed longer RTs in the last than in the first episode in a reading span task, such an increase was not observed by Towse et al. (2000) in reading and operation span tasks. Besides the fact that these studies failed to replicate each other though using the same paradigm, they cannot inform us about the exact nature of the relation between memory load and processing times due to the comparison of only two values. Other studies made comparisons across a larger range of memory loads, but they also led to divergent results (Engle et al., 1992; Friedman & Miyake, 2004; Jarrold et al., 2011). In Engle et al. (1992), while processing times increased with memory load in an operation span task, memory load had no effect in a reading span task. However, in a similar reading span task, Friedman and Miyake (2004) showed a significant linear increase of reading times across sentence positions. More recently, Jarrold et al. (2011) replicated this increase in processing times across positions in different complex span tasks varying the nature (verbal vs. nonverbal) of their processing component. But then again, no maintenance-related increase in processing times was observed when the same memory material (nouns) and processing activities were presented in a Brown-Peterson paradigm in which a single processing phase separates the presentation and recall of memory items.

To summarize, studies that explored the impact of maintenance activities on processing times proved inconsistent. These divergent findings do not seem to be linked to differences in paradigm or in the nature of memoranda and intervening activities because studies using the same tasks led to different results (e.g., Towse et al., 2000, vs. Maehara & Saito, 2007; Saito & Miyake, 2004), while studies differing in material showed similar effects (operation span task in Engle et al., 1992, vs. reading span task in Friedman & Miyake, 2004). One possible explanation of these divergences may rely on the fact that most of the studies omitted to verify the effectiveness of maintenance activities when assessing the effect of memory load on processing times. Indeed, if participants neglect or fail to maintain the memory load, no reliable impact on concurrent processing can be expected. The study by Baddeley and Hitch (1974) is a nice illustration of this prerequisite. They investigated the effect of memory load on reasoning by asking participants to verify sentences with or without a six-letter memory preload. In one group, which received equal stress on storage and processing, as is classically done in such experiments, the memory load induced no variation in verification times. By contrast, in a group in which storage was stressed, verification times strongly increased under memory load. It should be noted that the two groups largely differed on their recall performance, the former neglecting the memory task and exhibiting a lower mean recall performance (3.7 letters recalled) than the latter (5 letters). This result echoes Maehara and Saito's (2007) comment that "in imperfect trials it would be unclear whether participants had manipulated the processing tasks while holding memory items in their minds" (p. 220). As a matter of fact, Maehara and Saito's study is the only one that restricted processing times analyses to trials with lists perfectly recalled, and they observed longer reading times for the last versus the first episodes. Unfortunately, as we discussed above, they restricted their comparisons to the two extreme episodes and did not provide any detail about their skimming procedure. Analyzing processing times without any restriction as to recall performance can lead to situations in which the intended manipulation of memory load is illusory.

The Present Study

The usual WM tasks such as complex span tasks focus on the detrimental effect of processing on recall performance, considered as a dependent variable (Barrouillet et al., 2004; Case, Kurland, & Goldberg, 1982; Daneman & Carpenter, 1980; Turner & Engle, 1989). Accordingly, in these tasks, the condition for a valid measure is that subjects give priority to the intervening activity without any pause or postponement. Indeed, neglecting the processing component to allocate all the available attention to the memoranda would distort the WM task and turn it into a simple span task. Investigating the effect of maintenance on processing requires reversing this logic. Performance on the processing component now becomes the dependent variable, while the demand of the memory component, which has to be prioritized by subjects, is manipulated. For this purpose, we used a Brown-Peterson paradigm in which participants were given a list of items for further recall and asked to perform an intervening task over a fixed retention interval prior to recall. However, they were instructed to perform this intervening activity in such a way that, though aiming at the best performance, they did not forget the memoranda. For example, participants were presented with series of zero to seven letters to be remembered and were asked during a 12-s retention interval to judge the parity of as many numbers as they could by pressing keys, each keypress displaying on screen a new number for judgment. Thus, in the current study, we adopted a participant-paced approach rather than an experimenter-paced approach since the aim is to examine the effect of maintenance on processing latencies rather than the effect of processing load on recall accuracy. We predicted that the aim of a perfect recall of the memoranda would lead participants to refresh them quickly before each processing episode, resulting in a linear increase of the processing times. Importantly, because testing this hypothesis requires having the assurance that participants effectively maintained the memoranda, processing time analyses were restricted to those trials in which participants achieved perfect recall.

Our predictions were tested in three series of experiments. The first series reports three experiments that studied the relationship between memory load and processing times by using memoranda for which it is assumed that only the attention-based mechanism for maintenance is available. For this purpose, we used series of locations (i.e., spatial information) and series of letters as memoranda, the latter being performed under concurrent articulation to prevent any involvement of nonattentional maintenance based on verbal rehearsal.

The second series of experiments examines the contribution of the peripheral maintenance mechanism of articulatory rehearsal for verbal material. If there is indeed a system that can store and maintain verbal information without relying on attention, then this kind of maintenance should not have an impact on concurrent attention-demanding processing. Thus, we released the constraint of concurrent articulation while maintaining letters (Experiment 4). To anticipate, results showed that when concurrent articulation was removed, responses in the processing task remained unaffected by concurrent maintenance up to four letters. It is only beyond this limit that storage activities postponed concurrent processing. In a following experiment (Experiment 5), we studied the nature of this limit by examining whether the number of items that can be maintained independently from attention would remain constant or, instead, would vary as a function of articulatory demands. Therefore, we used words to be maintained and varied the number of syllables in these words.

Finally, we tested the hypothesis that a direct relationship between processing and storage would only exist insofar as the information to be maintained relies on the attention-based mechanism of maintenance. As shown in the previous series of experiments, memory load only postpones concurrent processing when maintenance is actually relying on attention, that is, when peripheral maintenance is unavailable or its capacity is exceeded. Recent findings suggest that there are some features of stimuli that cannot be refreshed even when attention is available to maintain the memory traces (Ricker & Cowan, 2010). Ricker and Cowan (2010) proposed that this might be the case for information that does not form identifiable chunks in long-term memory. The TBRS model predicts that, for this kind of nonrefreshable feature, postponement of concurrent processing as a function of memory load would not be observed. We tested this hypothesis in a final series of experiments in which we used nonrefreshable features (i.e., fonts) as information to be maintained in our paradigm and combined it with either a parity judgment task or a visual discrimination task (Experiments 6 and 7, respectively).

The Effect of Attentional Refreshing on Processing

The first series of experiments studied the relationship between memory load and processing times using memoranda for which we assume that only the attention-based mechanism for maintenance is available. That is, we used as memoranda either spatial (series of locations) or verbal information (series of letters), the latter being maintained under concurrent articulation to prevent any involvement of nonattentional maintenance mechanism based on articulatory rehearsal. In all the experiments, memory items were successively presented on screen (from zero to five spatial locations and from zero to seven letters), followed by a 12-s delay during which participants had to perform an intervening task on stimuli that appeared successively on screen. Participants were asked to process correctly as many stimuli as they could. The maintenance of spatial locations was combined with a visuospatial concurrent task (i.e., a spatial fit task) in Experiment 1 and a parity judgment task in Experiment 2, while series of letters were combined with the parity judgment task in Experiment 3. In all the experiments, we predicted that memory load should lead to a postponement of the processing activity in such a way that RTs in the intervening task should linearly increase with the number of items to be remembered.

We stressed above the necessity to restrict processing time analyses to those trials in which participants achieved perfect recall. Moreover, reliable comparisons of RTs between different list lengths required a comparison across the same participants. However, this skimming procedure would lead to more and more participants being discarded as the list length increases. Thus, retaining only the participants able to reach perfect recall in all list lengths from zero to seven would lead to the analyses being restricted to a very small subset of high-span participants able to maintain seven letters while performing a concurrent task. Apart from the fact that the assessment of the memory load effect would be done in a too-restricted sample of participants, many studies have already shown that high-span adults have specific performance in many cognitive tasks (for a review, see Conway, Jarrold, Kane, Miyake, & Towse, 2007). For example, the data of Engle et al. (1992) suggested that high-span and low-span adults cope differently with dual-task situations that combine processing and storage. Thus, we had to reduce the range of list lengths involved in the analyses to preserve a sufficient number of participants. We chose to extend our analyses toward the longest list length at which two thirds of our sample were still able to achieve perfect recall in at least two trials to allow mean calculation.

Experiment 1

In the first experiment, participants were required to maintain series of locations while performing a spatial fit task during the retention interval prior to recall (see Figure 1, top panel).

Method

Participants and design. A total of 26 undergraduate psychology students (19 female, mean age = 22.34 years) enrolled at the University of Geneva (Geneva, Switzerland) participated for course credit.[1] All participants had normal or corrected-to-normal vision. Memory load, from zero to five locations, was manipulated within subjects.

Materials and procedure. Each experimental trial started with a screen that informed the participant about the number of locations to be maintained. After a fixation cross for 500 ms, participants saw a series of screens containing an array of 16 squares randomly displayed on screen with one square colored blue at a rate of one location/second. The presentation of the last location was followed by a 12-s processing phase during which participants performed a spatial fit task. For this task, we used the stimuli from Vergauwe et al. (2009, 2010, 2012), which consist of a set of 24 white boxes containing a black horizontal line and two black square dots (see Figure 1, top panel). The horizontal line was centrally displayed on screen, and the dots were positioned on the same horizontal plane as each other, either above or below the horizontal line. The line varied in length, and the distance between the dots was chosen in such a way that, for half of the boxes, the line could fit into the gap between the dots. Participants were instructed to decide whether or not the line could fit into the gap by pressing a right- or left-hand key on the keyboard for positive or negative responses, respectively. The 24 boxes were used approximately equally often throughout the experiment. Each box remained on screen until response, which triggered the appearance of the next box. When the 12 s had elapsed, recall was probed. The 16-square array was presented on screen, and participants had to use the mouse for recalling the locations of the blue squares by clicking on the corresponding locations in correct order. For this and all the following experiments, participants were instructed to perform the processing task in such a way that, though aiming at responding as fast and as accurately as possible, they did not forget the memoranda.

The experiment, administered using E-prime software (Psychology Software Tools, Inc., Pittsburgh, PA), consisted of six trials for each memory load (from zero to five), resulting in 36 trials presented in random order. Participants were asked to rest their index fingers on the two response keys from the fixation screen onward. In a training session, participants were first familiarized with the memory task (one series of three locations, one of one location, and one of five locations) before practicing the processing task (20 boxes to be judged). Finally, three practice trials combined the memory task with the processing task (one series of two locations, one series of four locations, and one series of zero locations).

Results

The data of six participants who probably did not pay sufficient attention to the task and had less than 50% of the series of locations correctly recalled were discarded from further analyses. Not surprisingly, for the remaining 20 participants, recall performance decreased as the list length increased (94%, 85%, 60%, 40%, and 33% of series correctly recalled for list lengths 1, 2, 3, 4, and 5, respectively). Following the skimming procedure explained above, we only kept the list lengths at which a minimum of two thirds of participants had a sufficient number of correctly recalled series (a minimum of two series per length). This procedure led to us taking into account performance up to list length 4 in 18 participants. The rate of correct responses on the spatial fit task in this sample decreased with list length (88%, 86%, 86%, 85%, and 82% of correct parity judgments for list lengths 0, 1, 2, 3, and 4, respectively) but remained high, testifying that participants paid attention to the task.

Concerning the RTs on the spatial fit task, only correct responses were analyzed. Furthermore, we distinguished between the very first and the remaining responses, as was done in previous studies (Engle et al., 1992; Friedman & Miyake, 2004; Jarrold et al., 2011). Indeed, for each list length, RTs were remarkably longer for the very first than for the remaining spatial fit judgments that did not considerably vary from the second to the last stimulus processed. This was true for the previous studies cited above as well as for all the reported experiments in this article (see Figure 2, which illustrates this phenomenon for the first series of experiments, and Table 1). Thus, for each trial, two dependent measures were taken: (a) the RT for the individual's first response in the processing phase, referred to as first processing times, and (b) the mean of all subsequent RTs in that processing phase, referred to as subsequent processing times.[2] While longer first processing times have been attributed to the consolidation of memory traces, longer

[1] The number of participants in Experiments 1–4 was determined by our aim of having, for each of these experiments, a data set comprising the data from 20 subjects after having discarded those participants who were unable recall at least 50% of the series correctly. This number was increased in Experiment 5 because the introduction of an extra variable (monosyllabic vs. bisyllabic words) decreased the number of observations per cell. Finally, for Experiments 6 and 7, a fixed number of 24 participants were tested.

[2] We analyzed mean RTs rather than median RTs or trimmed mean RTs because our hypothesis is essentially based on the additive-factor model by which, on a single trial, the hypothesized process durations add to yield the reaction time. "The median, however, is inappropriate for this purpose because it is not, in general, additive" (see Sternberg, 1969, p. 286). Our main hypothesis is concerned with the examination of linear relations between RT and memory load for which Ulrich and Miller (1994) showed that "using truncated RTs can seriously distort linear relations between RT and an independent variable" (p. 34).

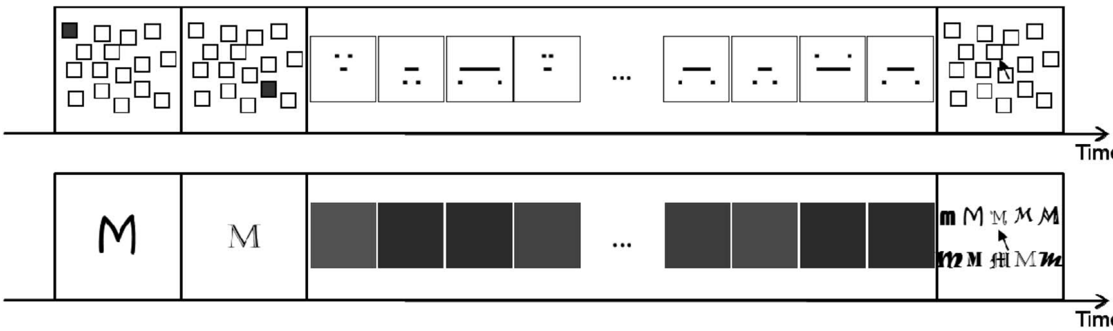

Figure 1. Illustration of the paradigm we used in the experiments reported in the present article. Examples of series of two memory items (i.e., memory load of two) are shown, the presentation of the memoranda being followed by a 12-s delay during which participants performed a self-paced processing task prior to recall. Upper panel: spatial memory for series of locations combined with the spatial fit judgment task (Experiment 1). Lower panel: visual memory for series of fonts combined with the visual color discrimination task (Experiment 7).

subsequent processing times are typically attributed to the maintenance of memory traces (e.g., Engle et al., 1992; Jarrold et al., 2011). This procedure for defining our dependent variables was applied in all the following experiments.

In a first step, we performed an analysis of variance (ANOVA) on first processing times with list length (from 0 to 4) as a within-subject factor. This revealed a significant effect of list length, $F(4, 68) = 11.61$, $p < .001$, $\eta_p^2 = .41$. First processing times on the spatial fit task linearly increased with the number of locations to be maintained, $F(1, 17) = 19.16$, $p < .001$, $\eta_p^2 = .53$, the linear trend accounting for 95% of the variance associated with the effect of list length (see Figure 3 and Table 1). The linear regression of the first processing times on list lengths revealed a slope of 236 ms.

In a second step, we performed the same ANOVA on subsequent processing times. As we predicted, subsequent processing times on the spatial fit task linearly increased with the number of locations to be maintained, $F(1, 17) = 11.43$, $p < .01$, $\eta_p^2 = .40$, the linear trend accounting for 88% of the variance associated with the effect of list length (see Figure 3 and Table 2). There were no significant higher order polynomial effects, $F(1, 17) = 3.96$, $p = .06$, for quadratic, $F(1, 17) = 2.67$, $p = .12$, for cubic, and $F(1, 17) = 1.03$, $p = .32$, for quartic effects.

To obtain an estimate of the time needed to refresh one location through attentional focusing, we calculated, for each individual, the slope of the function relating response latency on the spatial fit task (i.e., subsequent processing times) to the number of items that were to be remembered (i.e., list length). Importantly, in contrast to the aforementioned ANOVA that was constrained by a strict skimming procedure, the slopes of the individual memory load–response latency curves were calculated using a procedure that allowed us to include more data for analysis; all trials in which the individual exhibited perfect recall were now included. Thus, the memory loads included in the calculation of the slope varied between participants as a function of their individual memory performance. Following this procedure allowed us to include the data of all of the 20 participants who recalled at least 50% of the series correctly and resulted in a mean slope of 57 ms per additional location ($SD = 82$ ms) that differed significantly from zero, $t(19) = 3.11$, $p < .01$.

Analysis of the first processing times suggests that attention-demanding memory processes in the service of consolidation take about 230 ms per location. The direct relationship between memory load and subsequent processing times suggests strongly that processing and storage are not independent and that spatial locations are being maintained through an attention-based mechanism that competes with the processing activity. Moreover, refreshing seems to be a very fast process, only taking about 60 ms per location. However, one could argue that such a direct relationship between processing and storage was only observed because the processing and storage components in Experiment 1 both pertained to the spatial domain. According to the TBRS model, attentional refreshing should postpone all concurrent processing tasks insofar as it requires attention. Thus, in the next experiment, we replicated Experiment 1 but used a parity judgment task instead of the spatial fit task. According to the TBRS model, changing the nature of concurrent processing should not affect the observed relationship between memory load and processing times.

Experiment 2

In this second experiment, participants were required to maintain series of locations while performing a parity judgment task during the retention interval prior to recall.

Method

Participants and design. A total of 24 undergraduate psychology students (18 female, mean age = 21.38 years) enrolled at the University of Geneva participated for course credit. None of them took part in the previous experiment. All participants had normal or corrected-to-normal vision. Memory load, from zero to five locations, was manipulated within subjects.

Materials and procedure. Materials and procedure were the same as those used in the previous experiment except that participants performed a parity judgment task instead of the spatial fit task during the processing phase. Numbers from one to 10 were centrally displayed on screen (Courier New, 24 pt.) and participants were asked to press the right- or left-hand key for even or odd numbers, respectively. Throughout the experiment, all num-

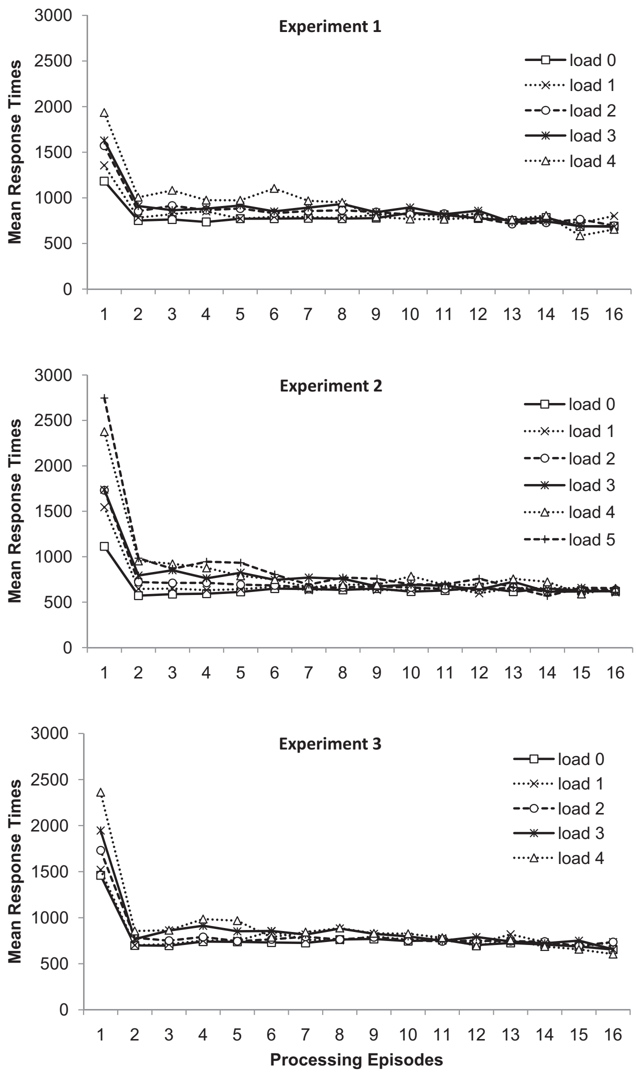

Figure 2. Mean response times in milliseconds as a function of the rank of the successive processing episodes and memory load for Experiment 1 (parity task while maintaining spatial locations), Experiment 2 (spatial fit task while maintaining spatial locations), and Experiment 3 (parity task while maintaining letters under articulatory suppression). Note that, for higher memory loads, response times for responses after the 10th processing episode only include participants who gave fast responses because only fast responders were able to fit a large number of responses into the fixed time window of 12 s.

bers were used approximately equally often. Numbers were presented in grey on a black background and remained on screen until response, which triggered the appearance of the next number. The experiment consisted of six trials for each memory load (from zero to five), resulting in 36 trials presented in random order.

Results

The data of four participants with less than 50% of the series of locations correctly recalled were discarded from further analyses. For the remaining 20 participants, recall performance decreased as the list length increased (92%, 80%, 57%, 53%, and 40% of lists correctly recalled for list lengths 1, 2, 3, 4, and 5, respectively). Using the same skimming procedure as in Experiment 1, we analyzed the data of 17 participants up to list length 5. The rate of correct responses on the parity task decreased with list length (89%, 88%, 87%, 87%, 86%, and 82% of correct parity judgments for list lengths 0, 1, 2, 3, 4, and 5, respectively) but remained high. First and subsequent processing times were calculated as in Experiment 1, and the same ANOVA was performed with list length (from 0 to 5) as a within-subject factor for both dependent variables.

The ANOVA for first processing times revealed a significant effect of list length, $F(5, 80) = 20.15$, $p < .01$, $\eta_p^2 = .56$. First processing times on the parity task linearly increased with the number of locations to be maintained, $F(1, 16) = 42.19$, $p < .01$, $\eta_p^2 = .73$ (see Figure 3 and Table 1). The linear regression of the first processing times on list lengths revealed an R^2 value of .94 with a slope of 294 ms.

As expected, even though we changed the nature of concurrent processing, we still observed a clear relationship between memory load and subsequent processing times as reflected in the linear increase in parity judgment times with the number of locations to be maintained, $F(1, 16) = 12.83$, $p < .01$, $\eta_p^2 = .45$ (see Figure 3 and Table 2), which explained 96% of the variance associated with the effect of list length, $F(5, 80) = 5.27$, $p < .001$, $\eta_p^2 = .25$. There were no significant higher order polynomial effects (all *F*s < 1) for quadratic, cubic, quartic, and quintic effects. To obtain an estimate of the time needed to refresh one location through attentional focusing, we used the same procedure as in Experiment 1 to calculate the slope of the function relating response latency on the parity task (i.e., subsequent processing times) to the number of items that were to be remembered (i.e., list length). Following this procedure allowed us to include the data of all of the 20 participants who recalled at least 50% of the series correctly and resulted in a mean slope of 55 ms per additional location ($SD = 71$ ms) that differed significantly from zero, $t(19) = 3.46$, $p < .01$. This estimate is very similar to the one obtained in Experiment 1 (57 ms/item).

Thus, for visuospatial memoranda, maintaining a concurrent memory load led participants to produce slower responses in the intervening task, a postponement that increased linearly with the number of items to be maintained, regardless of the nature of the intervening task. Also, analysis of the first processing times suggests that attention-demanding memory processes in the service of consolidation take about 290 ms per location. In the next experiment, we aimed to test whether the same relationship between memory load and processing times would be observed for verbal memoranda under concurrent articulation, that is, when only attention-based maintenance mechanisms are available for verbal material.

Experiment 3

In this third experiment, participants were required to maintain series of letters while performing the parity judgment task under concurrent articulation during the retention interval prior to recall.

Table 1
Mean Response Times in Milliseconds (and Standard Deviations) to the First Stimulus as a Function of the Experimental Condition and List Length

Experiment	List length 0	1	2	3	4	5	6
1 (spatial + spatial)	1,190 (330)	1,386 (502)	1,615 (763)	1,730 (890)	2,197 (1,048)		
2 (spatial + parity)	1,114 (315)	1,529 (662)	1,731 (1,000)	1,738 (972)	2,288 (1,107)	2,718 (1,228)	
3 (letters + parity + AS)	1,460 (404)	1,534 (431)	1,731 (606)	1,946 (557)	2,365 (977)		
4 (letters + parity)	967 (319)	896 (291)	839 (304)	825 (198)	1,014 (439)	1,110 (476)	1,444 (712)
5 (monosyllabic words + parity)	1,271 (524)	948 (290)	970 (357)	1,100 (435)	1,532 (883)		
5 (bisyllabic words + parity)	1,165 (422)	1,026 (309)	1,044 (528)	1,079 (682)	1,801 (1,210)		
6 (visual + parity + AS)	1,143 (285)	1,332 (437)	1,501 (674)	1,498 (749)			
7 (visual + visual + AS)	1,158 (324)	1,292 (429)	1,318 (406)	1,466 (651)			

Note. AS = articulatory suppression.

Method

Participants and design. A total of 24 undergraduate psychology students (22 female, mean age = 21.81 years) enrolled at the University of Geneva participated for course credit. None of them took part in the previous experiments. All participants had normal or corrected-to-normal vision. Memory load from zero to seven letters was manipulated within subjects.

Materials and procedure. The procedure was the same as in Experiment 2 with three exceptions. First, spatial locations were replaced by uppercase consonants (Courier New, 18 pt.) centrally displayed on screen in black on a white background at a rate of one letter/second. Second, during the parity judgment task, participants were required to utter the syllables *ba bi boo* continuously throughout the entire 12-s processing phase prior to recall. To remind the participant of this, these syllables were presented centrally on top of each screen displaying a number. Third, at recall, participants were invited to write down the letters on response sheets containing 48 lines of seven boxes.

The experiment consisted of six trials for each memory load (from zero to seven), resulting in 48 trials presented in a random order. In a training session, participants were first familiarized with the memory task (one series of three letters, one series of five letters, and one series of one letter) before practicing the parity task (20 numbers to be judged while uttering the syllables *ba bi boo*). Finally, three practice trials combined the memory task with the processing task (one series of two letters, one series of six letters, and one series of zero letters).

Results

The data of four participants with less than 50% of the series of letters correctly recalled were discarded from further analyses. For the remaining 20 participants, recall performance decreased as the list length increased (96%, 87%, 80%, 60%, 37%, 24%, and 12% of lists correctly recalled for list lengths of 1, 2, 3, 4, 5, 6, and 7, respectively). The skimming procedure led to us analyzing the data of 20 participants up to list length 4. The rate of correct responses on the parity task decreased with list length (85%, 84%, 85%, 83%, and 81% of correct parity judgments for list lengths 0, 1, 2, 3, and 4, respectively) but again remained high.

The ANOVA for first processing times revealed a significant effect of list length, $F(4, 76) = 10.68$, $p < .01$, $\eta_p^2 = .36$. First processing times on the parity task linearly increased with the number of letters to be maintained, $F(1, 19) = 16.91$, $p < .01$, $\eta_p^2 = .47$ (see Figure 3 and Table 1); the linear effect explained 93% of the variance associated with the effect of list length. The linear regression of the first processing times on list lengths revealed a slope of 222 ms.

Subsequent processing times increased with list length, as testified by a significant linear trend, $F(1, 19) = 11.82$, $p < .01$, $\eta_p^2 = .38$ (see Figure 3 and Table 2). There was no quadratic or cubic significant effect, $F(1, 19) = 3.00$, $p = .10$, and $F < 1$, respectively. While there was a significant quartic effect, $F(1, 19) = 9.81$, $p = .005$, it only accounted for 3% of the variance associated with the main effect of list length, as opposed to the linear effect explaining 90% of the variance associated with the main effect of list length. Using the aforementioned procedure, we estimated the time needed to refresh one letter through attentional focusing by calculating the slope of the function relating response latency on the parity task (i.e., subsequent processing times) to the number of items that were to be remembered (i.e., list length). Following this procedure allowed us to include the data of the 20 participants who recalled at least 50% of the series correctly and resulted in a mean slope of 43 ms per additional letter ($SD = 49$ ms) that differed significantly from zero, $t(19) = 3.93$, $p < .001$.

Thus, when only attention is available for maintaining verbal information by rendering unavailable the domain-specific mechanism of maintenance through concurrent articulation, increasing the number of items to be maintained slows down concurrent processing, the postponement in processing being a direct function of the number of items to be maintained. Analysis of the first processing times suggests that attention-demanding memory processes in the service of consolidation take about 220 ms per letter, while attention-demanding memory processes in the service of maintenance take about 40 ms per letter.

Discussion: Experiments 1–3

In these first three experiments that used memoranda for which we assumed that participants had only attention-based mechanisms of maintenance at their disposal, maintaining a concurrent memory load led to the production of slower subsequent responses in the intervening task, a postponement that increased linearly with the number of items to be maintained. Thus, for both verbal material under concurrent articulatory suppression and spatial material, a

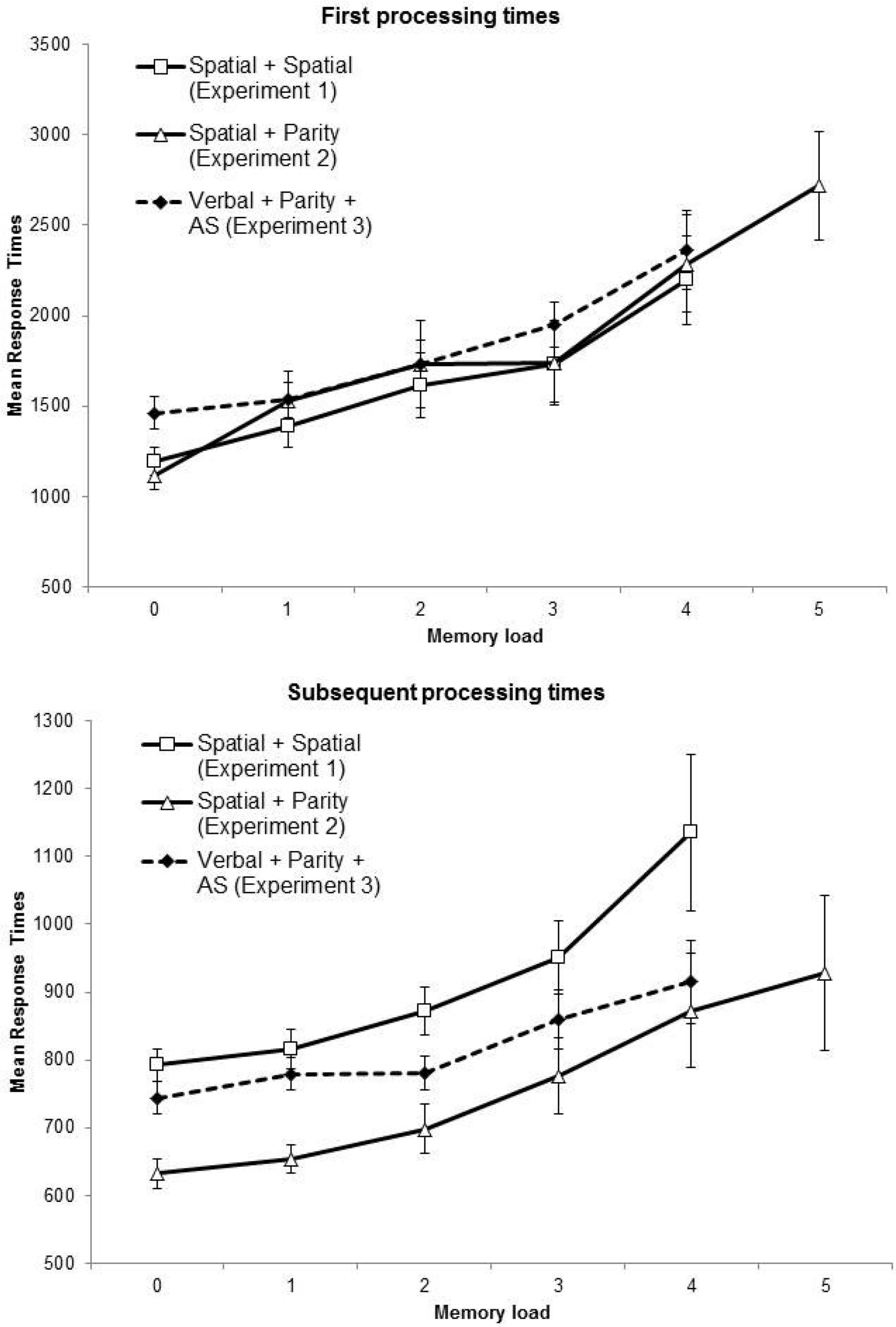

Figure 3. Mean processing times (first processing times in upper panel, subsequent processing times in lower panel) in milliseconds as a function of memory load for the spatial fit task while maintaining spatial locations (Spatial + Spatial, Experiment 1), for the parity task while maintaining spatial locations (Spatial + Parity, Experiment 2), and for the parity task while maintaining letters under AS (Verbal + Parity + AS, Experiment 3). Error bars represent standard error. AS = articulatory suppression.

direct relationship was observed between processing and maintenance activities. This suggests that the maintenance of memory traces involves a central mechanism of maintenance able to hold verbal as well as visuospatial information. Moreover, we found that this mechanism disrupts concurrent processing activities, whatever their domain or nature, indicating that it competes with these activities for a general-purpose limited resource. Thus, our first series of experiments supports the proposal that processing

Table 2
Mean Processing Times in Milliseconds (and Standard Deviations) to the Subsequent Stimuli as a Function of List Length in Experiments 1–7

	List length						
Experiment	0	1	2	3	4	5	6
1 (spatial + spatial)	792 (102)	816 (127)	872 (153)	951 (231)	1,135 (486)		
2 (spatial + parity)	632 (94)	654 (89)	698 (148)	776 (232)	873 (350)	928 (475)	
3 (letters + parity + AS)	744 (108)	779 (105)	780 (110)	859 (193)	915 (274)		
4 (letters + parity)	627 (86)	635 (77)	630 (87)	637 (91)	649 (106)	685 (132)	719 (231)
5 (monosyllabic words + parity)	617 (65)	633 (67)	634 (86)	652 (96)	759 (191)		
5 (bisyllabic words + parity)	607 (73)	642 (76)	651 (80)	672 (124)	729 (129)		
6 (visual + parity + AS)	689 (107)	681 (103)	708 (123)	702 (149)			
7 (visual + visual + AS)	663 (83)	665 (90)	662 (77)	672 (94)			

Note. AS = articulatory suppression.

and storage are dependent functions of WM. Moreover, our results support the existence of the process of attentional refreshing postulated by the TBRS model (see also Cowan, 1995) and identified at the cerebral level by Raye et al. (2007). Indeed, the linear increase in subsequent processing times with the number of memory items supports the hypothesis that maintenance of verbal information under concurrent articulation and of spatial information is carried out by an attentional system that is in charge for both processing and storage activities on any type of WM representation.

Interestingly, individual slope analyses revealed strikingly converging estimates with slopes around 50 ms for refreshing one item (57 ms and 55 ms for spatial locations in two experiments and 43 ms for letters).[3] These values are very close to the covert retrieval process described by Cowan, Saults, and Elliott (2002), who estimated the time needed to reactivate a verbal item at about 40 ms. These values are also very close to the serial memory scanning process proposed by Sternberg (1966), who showed that the process takes 38 ms longer for each additional item in memory. It seems then that attentional refreshing is a very fast process, potentially closely related to serial memory scanning.

A closer look to Figure 2, however, seems to suggest that the effect of memory load on response latency in the concurrent processing task might be confined to the first 10 processing episodes. Indeed, after about 10 processing items, the effect is no longer visibly present in Figure 2. Might this suggest that attentional refreshing only operates in the first half of the retention interval rather than throughout the whole processing window? Baddeley and Hitch (1974) indicated that, in procedures like the one we have used here, participants might perform maintenance-related activities at the beginning of the processing phase and, by the end of that processing phase, they might have successfully transferred that information into long-term memory. If this is the case, one would expect the effect of memory load to disappear for later processing episodes. It is, however, important to note that, on average, participants responded to about 15 items when there was no memory load (14 in Experiment 1, 17 in Experiment 2, and 14 in Experiment 3), whereas they responded to only about 10 items for the highest memory load under consideration in our analysis (10 for a memory load of four in Experiment 1, 11 for a memory load of five in Experiment 2, and 11 for a memory load of four in Experiment 3). As such, when considering higher memory loads, RTs for responses after the 10th processing episode only include participants who gave fast responses because only fast responders were able to fit a large number of responses into the fixed time window of 12 s.

To test the idea of refreshing being confined to the first part of the processing phase, we calculated subsequent processing times again, this time only including the RTs of the subsequent responses of Processing Episodes 2–10. Using the same procedure to calculate individual slopes as mentioned before, slope estimates based on this processing period were almost identical to the ones that were based on all subsequent processing episodes: 59 ms in Experiment 1 (compared to 57 ms when all subsequent responses were included), 55 ms in Experiment 2 (compared to 55 ms when all subsequent responses were included), and 44 ms in Experiment 3 (compared to 43 ms when all subsequent responses were included). Thus, the effect of memory load on response latency does not seem to be confined to the first part of the processing phase. Instead, the current data suggest that participants are refreshing the memory items quickly throughout the entire processing phase. Theoretical and practical implications of such fast refreshing process are discussed in the General Discussion.

Interestingly, we not only observed a direct relationship between memory load and subsequent processing times; first processing times also increased as a linear function of the number of items to be maintained. While postponement of subsequent responses has typically been attributed to maintenance-related activities, longer first processing times have been attributed to the consolidation of memory traces (e.g., Engle et al., 1992; Jarrold et al., 2011). In line with the findings of Jolicœur and Dell'Acqua (1998), who showed that the process of short-term consolidation requires central processing mechanisms, the current results suggest that consolidation is attention demanding. Moreover, the present results suggest that attention-demanding consolidation takes about 250 ms per item.

[3] The different intercepts in Figure 3 are most probably reflecting longer RTs for spatial fit judgments (Experiment 1) than for parity judgments (Experiments 2 and 3) and longer RTs for parity judgments under articulatory suppression (Experiment 3) than for parity judgments without articulatory suppression (Experiment 2). Similarly, the different intercepts in Figure 4 are most probably reflecting longer RTs for parity judgments under articulatory suppression (Experiment 3) than for parity judgments without articulatory suppression (Experiment 4).

This value is close to the time needed to consolidate a memory target in the imaginal module postulated by Taatgen, Juvina, Schipper, Borst, and Martens (2009), which can be seen as the equivalent within the Adaptive Control of Thought–Rational framework of Baddeley's (2000) episodic buffer. The authors estimated that this consolidation takes 250 ms on average (see Shapiro, Raymond, & Arnell, 1994, for a similar estimate).

The results of the first series of experiments are also relevant for the problem of WM capacity. We applied to our results a procedure for evaluating WM spans that we used in several previous studies (Barrouillet et al., 2004, 2007, 2011; see also Kemps, De Rammelaere, & Desmet, 2000; Smyth & Scholey, 1992, for the same procedure), which consists in crediting each series correctly recalled with one sixth (there were six series of each length) and adding up the resulting sixths. Mean spans were computed on the entire sample of participants who paid sufficient attention to the task and recalled more than half of the series. The mean span for the letters was 3.95, very close to the four chunks that can be maintained in the focus of attention according to Cowan (2001; Chen & Cowan, 2009; Saults & Cowan, 2007). The mean spans for spatial locations in the two experiments with the spatial fit task and the parity task during retention interval were very close to each other (3.12 and 3.21, respectively) but lower than for letters. The small advantage in span for letters compared with spatial locations could result from the supplementary involvement of some long-term memory component, as suggested by Cowan, Rouder, Blume, and Saults (2012). Still, these values are very much in line with the work of Cowan (2001) demonstrating a limit at about three to four items in WM. Thus, we provide here additional support for the idea that only about three to four items can be maintained at the central level of WM.

However, as we mentioned before, studies have shown that verbal material has an additional maintenance mechanism at its disposal, a mechanism that is not attention based (Baddeley, 1986; Baddeley & Hitch, 1974; Baddeley & Logie, 1999; Camos et al., 2009; Hudjetz & Oberauer, 2007). Thus, while there seems to be a domain-general system that permits the maintenance of four items in WM, a domain-specific mechanism of maintenance for verbal material could possibly supplement this. This domain-specific contribution to verbal maintenance, in addition to the domain-general attentional mechanism identified in the first series of experiments, was studied in a second series of experiments.

The Effect of Storage Through Articulatory Rehearsal on Processing

The second series of experiments aimed at examining the contribution of the peripheral maintenance mechanism of articulatory rehearsal for verbal material. If there is indeed a peripheral system that can store and maintain verbal information without relying on attentional refreshing (Camos et al., 2009: Hudjetz & Oberauer, 2007), then this kind of maintenance should not have an impact on concurrent central processes that do need attention, such as online processing of new incoming information. Thus, in Experiment 4, we released the constraint of concurrent articulation for verbal memoranda while keeping unchanged the other characteristics of the task used in Experiment 3. Comparing these two experiments would allow us to estimate directly the proper contribution of any mechanism specialized in the maintenance of verbal information and its relationship with the central attention-based system. Thus, participants were asked to perform the parity task while maintaining lists of letters but without any concurrent articulation.

We expected that, when verbal material has both attentional and nonattentional mechanisms available, an increase in the amount of information to be maintained will only result in slower processing when the capacity of the nonattentional mechanism is exceeded. Based on the results of Baddeley and Hitch (1974) showing that concurrently maintaining six digits resulted in slower reasoning while the maintenance of three digits did not, we expected the peripheral capacity limit to be situated somewhere between three and six items. Chen and Cowan (2009) observed that increasing memory load caused a significant accuracy decrement on a concurrent speeded reaction time task only when the list exceeded three or four verbal items. Thus, we expected that any increase in the amount of information to be maintained beyond that limit would result in slower processing.

Experiment 4

Method

A total of 20 undergraduate psychology students (17 female, mean age = 22.34 years) enrolled at the University of Geneva participated for course credit. Memory load, from zero to seven letters, was manipulated within subjects. None of the participants took part in the previous experiments. All participants had normal or corrected-to-normal vision. Materials and procedure were exactly the same as those used in Experiment 3 except that there was no concurrent articulatory suppression and thus the syllables *ba bi boo* were no longer presented onscreen.

Results

No participant exhibited less than 50% of the series of letters correctly recalled. Recall performance decreased as the list length increased (96%, 97%, 97%, 91%, 77%, 46%, and 33% of lists correctly recalled for list lengths of 1, 2, 3, 4, 5, 6, and 7, respectively). Using the skimming procedure described above, we analyzed the data of 17 participants up to list length 6. The rate of correct responses on the parity task was high and remained stable across list lengths (88%, 87%, 89%, 88%, 88%, 88%, and 88% of correct parity judgments for list lengths 0, 1, 2, 3, 4, 5, and 6, respectively).

The ANOVA for first processing times revealed a significant effect of memory load, $F(6, 96) = 8.70$, $p < .01$, $\eta_p^2 = .35$ (see Table 1). However, as can be seen in Figure 4, first processing times remained unaffected and even tended to decrease slightly between list length 0 and list length 3, $F(1, 16) = 4.05$, $p = .06$, and then linearly increased from list length 3 to list length 6. An ANOVA with experiment (Experiments 3 and 4, with and without articulatory suppression, respectively) as between-subject factor and list length from zero to three as within-subject factor revealed a significant interaction between experiment and list length, $F(3, 105) = 8.34$, $p < .001$, $\eta_p^2 = .19$. Whereas, under articulatory suppression, there is a significant effect of memory load on first processing times between list length 0 and list length 3, $F(3, 33) = 6.76$, $p < .01$, this effect disappeared when concurrent articulation was removed in Experiment 4 ($F < 1$). Thus, when concurrent

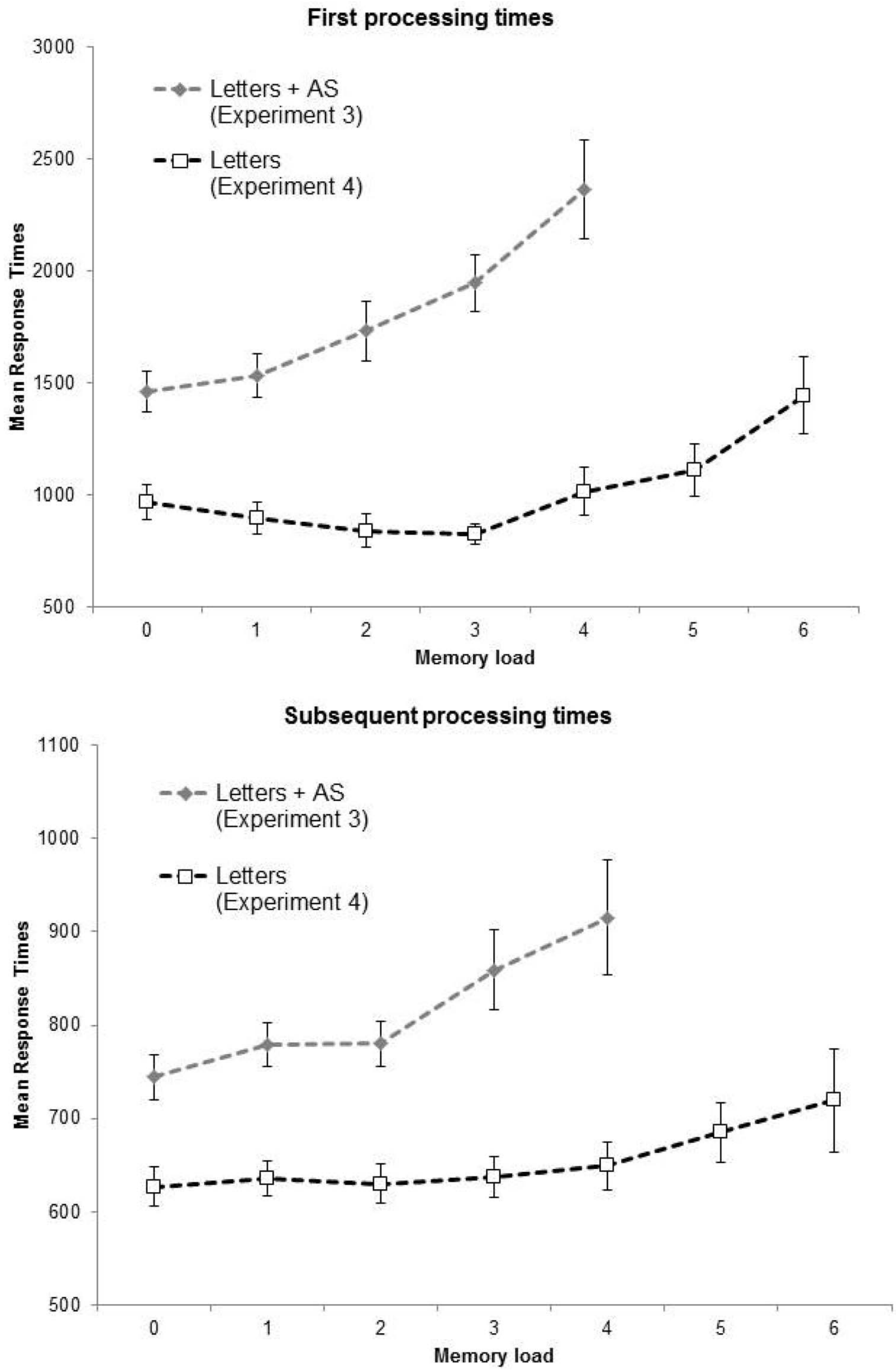

Figure 4. Mean processing times (first processing times in upper panel, subsequent processing times in lower panel) in milliseconds for letters as a function of memory load depending on the presence (Letters + AS, Experiment 3) or absence (Letters, Experiment 4) of AS. Error bars represent standard error. AS = articulatory suppression.

articulation was removed, first response latencies on the parity task remained unaffected by the concurrent maintenance of up to three letters. This suggests that up to three letters could be maintained without any evidence of attention-demanding consolidation processes.

The ANOVA for subsequent processing times also revealed a significant effect of memory load, $F(6, 96) = 3.34$, $p < .01$, $\eta_p^2 = .17$. As can be seen in Figure 4, subsequent processing times remained unaffected between list length 0 and list length 4 ($F < 1$), linearly increasing only from list length 4 to list length 6. An ANOVA with experiment (Experiments 3 and 4, with and without articulatory suppression, respectively) as between-subject factor and list length from zero to four as within-subject factor revealed a significant interaction between experiment and list length, $F(4, 140) = 5.41$, $p < .001$, $\eta_p^2 = .13$. Whereas, under articulatory suppression, maintaining four letters involved a substantial increase in processing times (from 744 ms to 915 ms with zero and four letters to be maintained, respectively), $F(1, 35) = 20.82$, $p < .001$, $\eta_p^2 = .37$, this difference disappeared when concurrent articulation was removed in Experiment 4. At list length 4, processing times did not differ significantly from what was observed without any memory load (627 ms and 649 ms with zero and four letters to be maintained, respectively; $F < 1$; see Figure 4 and Table 2). Thus, when concurrent articulation was removed, subsequent response latencies on the parity task remained unaffected by the concurrent maintenance of up to four letters. It is only beyond this limit that storage activities postponed concurrent processing.[4] While mean subsequent processing times exhibited a small increase of 22 ms for the first four letters to be maintained (from 627 ms to 649 ms for list lengths 0 to 4), adding a fifth and a sixth letter elicited an increase of 70 ms (from 649 ms to 719 ms from list lengths 4 to 6). Using the same procedure as in the previous experiments, we calculated the individual slopes of the function relating processing times to memory loads as from four items on. This was done for the 19 participants who had mean subsequent processing times beyond list length 4. This analysis revealed a mean slope of 54 ms ($SD = 84$ ms) that differed significantly from zero, $t(18) = 2.80$, $p < .02$.

These findings strongly suggest that, as surmised by Baddeley and Hitch (1974), there exists a mechanism of maintenance of phonological information based on verbal rehearsal that is independent from the central system. Participants were able to maintain up to four letters with no effect on concurrent processing after the very first processing item, the very first processing time being unaffected up to three letters. Moreover, our results indicate that this mechanism is capacity limited. When more than four letters have to be maintained, at least a part of maintenance activities is taken in charge by the central attentional system as testified by the longer processing times on the intervening task observed with memory loads as from four items on. The mean slope of 54 ms, very close to those observed in the previous experiments, strongly suggests the intervention of the same central mechanism used for maintaining spatial information or verbal items under articulatory suppression. This echoes one of the first proposals put forward by Baddeley and Hitch (1974) and subsequently abandoned (Baddeley, 1986), according to which the central executive would have some storage capacity that could be used when the capacity of the phonological loop is exhausted. Our paradigm reveals that this theoretical view might have been abandoned prematurely.

The fact that subsequent processing times remained unaffected by a concurrent load up till four letters when the constraint of concurrent articulation was released indicates that the phonological loop can store and maintain active through verbal rehearsal up to four letters without any interference with a concurrent attention-demanding task. The fact that a similar pattern was observed for first processing times suggests that these items are also not subject to the time-consuming attention-demanding process of consolidation. This raises the question of the nature of this limitation. A limit of four is of course reminiscent of the size of the focus of attention, as described by Cowan (2001), and the number of representations that the central attentional system can hold, as we observed in our first series of experiments, but this convergence could also be simply coincidental. If the observed limit at four letters results from limitations in the peripheral domain-specific maintenance device for verbal material, then the limit should result from limitations in the articulatory mechanism and not from a limited number of slots or chunks. As a consequence, the number of verbal items that the peripheral device can maintain should not be constant but should vary with articulation demands such as those resulting from word length. We tested this hypothesis by running a fifth experiment with the same design as the previous one except that we replaced letters by either monosyllabic or bisyllabic words.

Experiment 5

Method

Participants and design. A total of 28 native French-speaking undergraduate psychology students (24 female, mean age = 20.64 years) enrolled at the University of Geneva participated for course credit. None of them took part in the previous experiments. All participants had normal or corrected-to-normal vision. Memory load (from zero to seven words) and type of words (monosyllabic vs. bisyllabic) were manipulated within subjects.

Materials and procedure. The materials and procedure were the same as in Experiment 4 except that the series to be maintained consisted of either monosyllabic or bisyllabic French words instead of letters. A pool of 19 monosyllabic words and a pool of 19 bisyllabic words were selected from the French Brulex database (Content, Mousty, & Radeaux, 1990) and matched on their frequency in books ($M = 180.79$ for monosyllabic words and 179.63 for bisyllabic words, $p = .98$) and on their orthographic neighborhood ($M = 5.26$ for monosyllabic words and 5.32 for bisyllabic words, $p = .97$). The experiment consisted of six trials for each memory load (from zero to seven), three of them with monosyllabic words and three with bisyllabic words, resulting in 48 trials presented in random order.

Results

The data of two participants with less than 50% of the series of words correctly recalled were discarded from further analyses. For the remaining 26 participants, recall performance decreased as the list length increased (97%, 99%, 99%, 85%, 41%, 26%, and 6% of

[4] See footnote 3.

lists correctly recalled for list lengths 1, 2, 3, 4, 5, 6, and 7, respectively). All 26 participants achieved correct recall of at least one third of monosyllabic and bisyllabic word lists up to list length 4. The rate of correct responses on the parity task remained high and stable over list lengths (86%, 87%, 87%, 87%, and 84% of correct parity judgments for list lengths 0, 1, 2, 3, and 4, respectively).

We performed an ANOVA on first processing times with list length (from zero to four) and type of words (monosyllabic vs. bisyllabic) as within-subject factors. This revealed no significant effect of type of words, $F(1, 25) = 2.11$, $p = .16$, and a significant effect of list length, $F(4, 100) = 10.82$, $p < .001$, $\eta_p^2 = .30$, that interacted significantly with type of words, $F(4, 100) = 2.55$, $p < .05$, $\eta_p^2 = .09$ (see Table 1). Figure 5 reveals that first processing times strongly increased for both types of words between list lengths 3 and 4, an effect that tended to be larger for bisyllabic words, $F(1, 25) = 4.07$, $p = .05$.

We performed an ANOVA on subsequent processing times with list length (from zero to four) and type of words (monosyllabic vs. bisyllabic) as within-subject factors. This revealed no effect of type of words ($F < 1$) and a significant effect of list length, $F(4, 100) = 14.62$, $p < .001$, $\eta_p^2 = .37$, that did not significantly interact with type of words, $F(4, 100) = 1.79$, $p > .12$, $\eta_p^2 = .07$ (see Table 2). Figure 5 reveals that subsequent processing times strongly increased for both types of words between list lengths 3 and 4. Planned comparisons revealed that for monosyllabic words, processing times already differed from list length 0 at list length 3, $F(1, 25) = 6.41$, $p < .02$, $\eta_p^2 = .20$, but not at list length 2, $F(1, 25) = 1.49$, $p > .20$, $\eta_p^2 = .06$. On the contrary, processing times for bisyllabic words exhibited a steady increase from list length 1 onward, all the differences between immediately successive values of list length reaching significance (ps $< .02$). Nonetheless, the slopes remained moderate between list lengths 0 and 3, with 11 ms and 20 ms for mono- and bisyllabic words, respectively.

Discussion: Experiments 4 and 5

Together, the results of Experiments 4 and 5 support our prediction that memory load only postpones concurrent processing when maintenance is actually relying on attention, that is, when the capacity of peripheral maintenance is exceeded. These results also support the proposal of two independent mechanisms for the maintenance of verbal information (Camos et al., 2009, 2011, in press; Mora & Camos, 2013). One mechanism, which interferes with concurrent processing, probably relies on attentional refreshing and is located at the central level of WM. The other, based on articulatory rehearsal, is independent from attention and as such is probably located at a peripheral level of WM, echoing the slave systems described by Baddeley's multiple-component model. In line with the original, but subsequently abandoned, proposal of Baddeley and Hitch (1974), our findings suggest that once the capacity of this peripheral system is exhausted, attention-based refreshing comes into play for maintaining some additional items, resulting in postponement of concurrent processing. This corroborates previous observations indicating that the two mechanisms of maintenance are independent, operate jointly for maintaining verbal information (Camos et al., 2009, in press), and can be strategically used depending on the constraints of the ongoing task. Camos et al. (2011) observed that individuals rely on the low-demanding verbal rehearsal strategy when performing an attention demanding concurrent task. This is what occurs here. The completion of the demanding parity judgment task drives participants to privilege verbal rehearsal for maintaining letters, as long as this strategy is possible. The similarity of the slopes relating processing times to memory load in Experiments 3 and 4 suggests that, when the capacity of verbal rehearsal is exceeded, the two mechanisms work jointly to achieve maintenance of long series of items. Interestingly, the operation of two independent maintenance mechanisms was observed not only in subsequent response latencies but also in first response latencies, which might suggest that only those items that are maintained through attentional refreshing at the central level of working memory undergo attention-demanding consolidation.

Concerning the limitation of the peripheral domain-specific system for verbal material, our findings suggest that it might not be conceived in terms of a fixed number of items or chunks. This limit was found to vary as a function of the articulatory demand of the memoranda, with higher demand resulting in fewer items that can be maintained in the phonological loop without any implication of the central system. The phonological loop seemed able to maintain up to four letters without interference with processing but only three monosyllabic words that involve a slightly higher articulatory demand (mean of 2.74 phonemes per monosyllabic word compared with 2.11 for letters). When the articulatory demand strongly increased (bisyllabic words involved a mean of 4.53 phonemes), maintenance seemed to rely on at least sporadic interventions of the central level even when there were fewer than three items to be maintained, as testified by the moderate but not negligible slope of 20 ms per item.

Taken together, the results of the first two series of experiments reveal a direct impact of memory load on subsequent processing times when (a) spatial material is to be maintained (Experiments 1 and 2), (b) verbal material is to be maintained under concurrent articulation (Experiment 3), and (c) the capacity of the phonological loop is exceeded (Experiments 4 and 5). That is, we have observed a direct relationship between processing and storage insofar as attention is needed to achieve maintenance. In a final series of experiments, we directly addressed this issue by examining the relationship between memory load and processing times for memoranda that cannot be maintained attentionally. In that case, the TBRS model predicts that the direct relationship between memory load and processing speed, as established in the previous experiments, should no longer be observed.

The Effect of Storage of Nonrefreshable Features on Processing

One of the main tenets of the TBRS model is that processing and storage interfere with each other insofar as both functions rely on the same attentional resource. For example, Barrouillet et al. (2007) demonstrated in a variety of situations that processing had a detrimental effect on WM spans as long as this processing involved attention. Thus, increasing the cognitive load involved by an attention-demanding choice reaction time task had a strong detrimental effect on concurrent maintenance, but varying the pace at which a simple reaction time task was performed had no effect at all. In the same way, the previous experiments confirmed that storage has an impact on processing insofar as mechanisms of

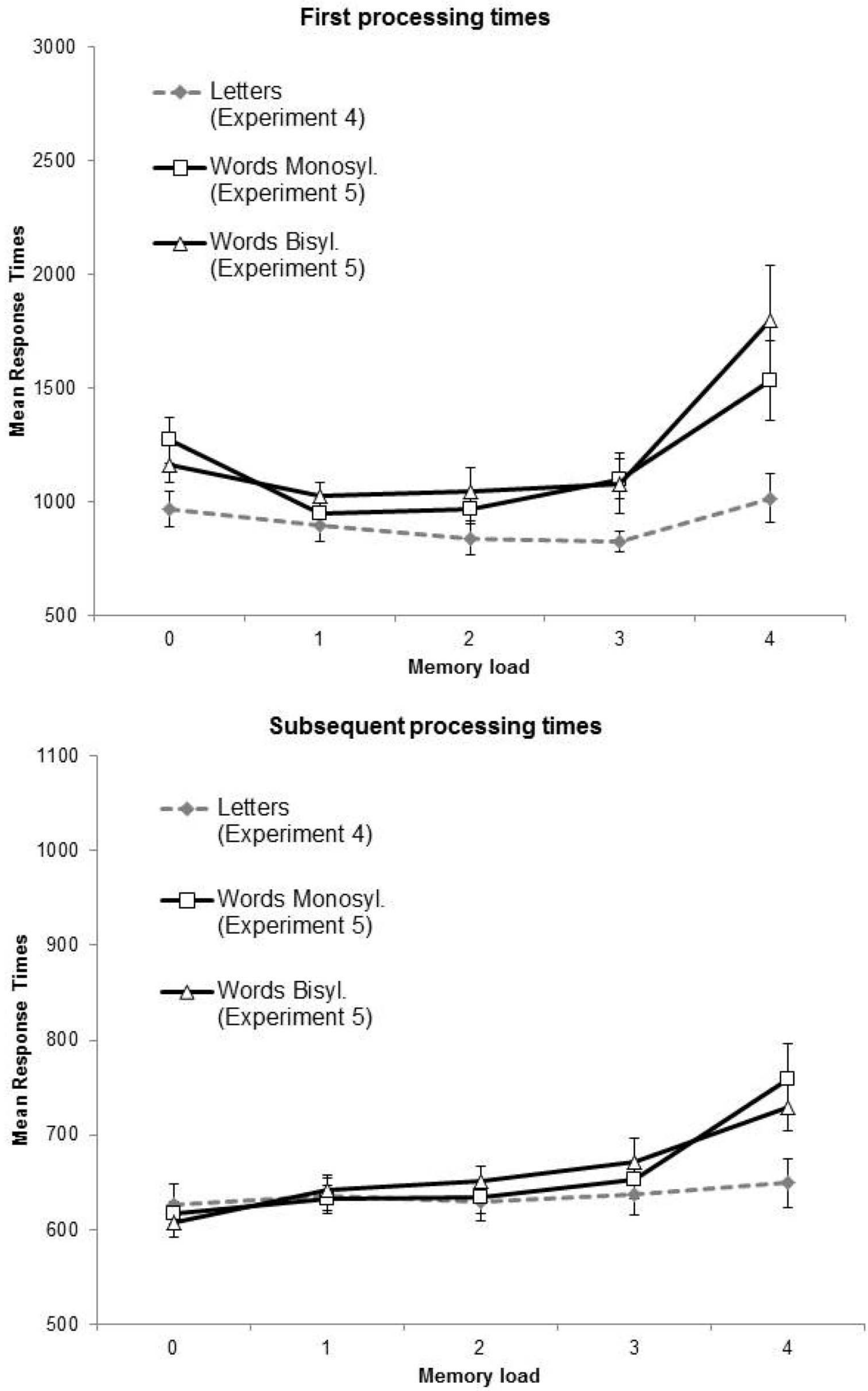

Figure 5. Mean processing times (first processing times in upper panel, subsequent processing times in lower panel) in milliseconds as a function of memory load for monosyllabic (Words Monosyl.) and bisyllabic words (Words Bisyl.) in Experiment 5, with a reminder as to what was observed with letters in Experiment 4 (Letters, in gray). Error bars represent standard error.

maintenance rely on attention. Although several studies have shown that verbal (e.g., Barrouillet et al., 2004, 2007, 2011; Camos et al., 2009; Chen & Cowan, 2009; Morey & Cowan, 2004, 2005; Vergauwe et al., 2010, 2012), visual (e.g., Morey & Cowan, 2004, 2005; Stevanovski & Jolicœur, 2007; Vergauwe et al., 2009), and spatial (e.g., Klauer & Stegmaier, 1997; Vergauwe et al., 2009, 2010) information have attention-based maintenance mechanisms at their disposal, recent findings suggest that there are some features that cannot be attentionally refreshed, even when attention is available. For example, Ricker and Cowan (2010) observed the loss of visual characters within seconds, even when attention was available. They asked participants to maintain unconventional visual characters that cannot be retained through verbal rehearsal for varying retention intervals up to 6 s during which they either performed a parity task or did not perform any distracting task. The authors observed dramatic forgetting even across the unfilled retention interval. The fact that memory for these unconventional characters deteriorates over time even when attention is available led Ricker and Cowan to suggest that they contain some nonrefreshable features that inescapably decay with time.

The TBRS model predicts that, for such kinds of information for which there is no attention-based mechanism of maintenance available, storage should not have any impact on concurrent processing. No postponement should be observed, and subsequent processing times should remain insensitive to variations in memory load. We established in a pretest (see the Appendix) that fonts undergo the same inescapable forgetting as the unconventional characters used by Ricker and Cowan (2010). In a final series of experiments, we used these fonts as memoranda in our paradigm (see Darling, Della Sala, & Logie, 2009, for a similar memory task using fonts) and combined it with a parity judgment task (Experiment 6) and with a visual discrimination task (Experiment 7; see also Figure 1, lower panel). As in Experiment 3, a concurrent articulation was added to the processing task during the retention interval in order to prevent the use of any verbal maintenance of the fonts.

Experiment 6

Method

Participants and design. A total of 24 undergraduate psychology students (21 female, mean age = 20.45 years) enrolled at the University of Geneva participated for course credit. None of them took part in the previous experiments, and all had normal or corrected-to-normal vision. Memory load, from zero to five letters, was manipulated within subjects.

Materials and procedure. The materials and procedure were the same as in Experiment 3 (remembering series of letters while performing a parity task under concurrent articulation) except that, for each trial, the same letter was used throughout the whole series, each time presented in a different font. That letter varied across trials by randomly selecting one out of the same pool of 15 letters used in the pretest. The different fonts to be remembered were on each trial chosen randomly without replacement out of the same pool of 18 distinct fonts used in the pretest. After the 12 s of parity task, recall was probed. The same letter was presented in 10 different fonts in two rows of five on screen. The different fonts included all those that were to be remembered, supplemented with additional fonts randomly picked out of our pool of fonts. Participants had to use the mouse for recalling the fonts of the letter by clicking on the corresponding fonts in correct order.

The experiment consisted of six trials for each memory load (from zero to five), resulting in 36 trials presented in random order. In a training session, participants were first familiarized with the memory task (one series of three fonts, one series of one font, and one series of five fonts) before practicing the processing task (20 digits to be judged). Finally, three practice trials combined the memory task with the processing task (one series of two fonts, one series of four fonts, and one series of zero fonts).

Results

The data of eight participants with less than 50% of the series of fonts correctly recalled were discarded from further analyses. One participant performed at chance level in the parity task, and these data were discarded too. For the remaining 15 participants, recall performance decreased as the list length increased (98%, 74%, 49%, 25%, and 11% of correct recall for list lengths 1, 2, 3, 4, and 5, respectively). After the skimming procedure, the data of the 15 participants were analyzed up to list length 3. The rate of correct responses on the parity task remained high and stable across list length (87%, 87%, 86%, and 87% of correct parity judgments for list lengths 0, 1, 2, and 3, respectively). The ANOVA on first processing times revealed a significant effect of memory load, $F(3, 42) = 3.56$, $p < .05$, $\eta_p^2 = .20$ (see Table 1). First processing times on the parity task tended to increase linearly with the number of letters to be maintained, $F(1, 14) = 4.52$, $p = .05$ (see Figure 6). The linear regression of the first processing times on list lengths revealed an R^2 value of .88 with a slope of 124 ms.

As can be seen in Figure 6 and in sharp contrast with the first series of experiments (see Figure 4), subsequent processing times did not vary as a function of list length, as reflected in the absence of any linear trend, $F(1, 14) = 1.40$, $p = .26$, $\eta_p^2 = .12$ (see Table 2). Thus, unlike locations, letters, or words, increasing the number of fonts to be maintained did not postpone concurrent processing after the first processing item. This was expected because our pretest suggested that fonts do not rely on attention-based mechanisms to be maintained. It could be argued that the flat line observed in Figure 6 is similar to the flat portion of the curve for letters without concurrent articulation in Figure 4, suggesting that fonts are being maintained verbally. However, participants maintained fonts under concurrent articulation, which makes it unlikely for fonts to be maintained in the phonological loop. Another explanation could be that, as for verbal material, visual material has a peripheral domain-specific maintenance mechanism at its disposal that operates independently from attention. Thus, in the following Experiment 7, the parity judgment task was replaced by a visual task aimed at hindering maintenance in some domain-specific visual system. We used for this purpose a visual color discrimination task under concurrent articulation (see Figure 1, lower panel).

Experiment 7

Method

Participants and design. A total of 24 undergraduate psychology students (19 female, mean age = 21.46 years) enrolled at

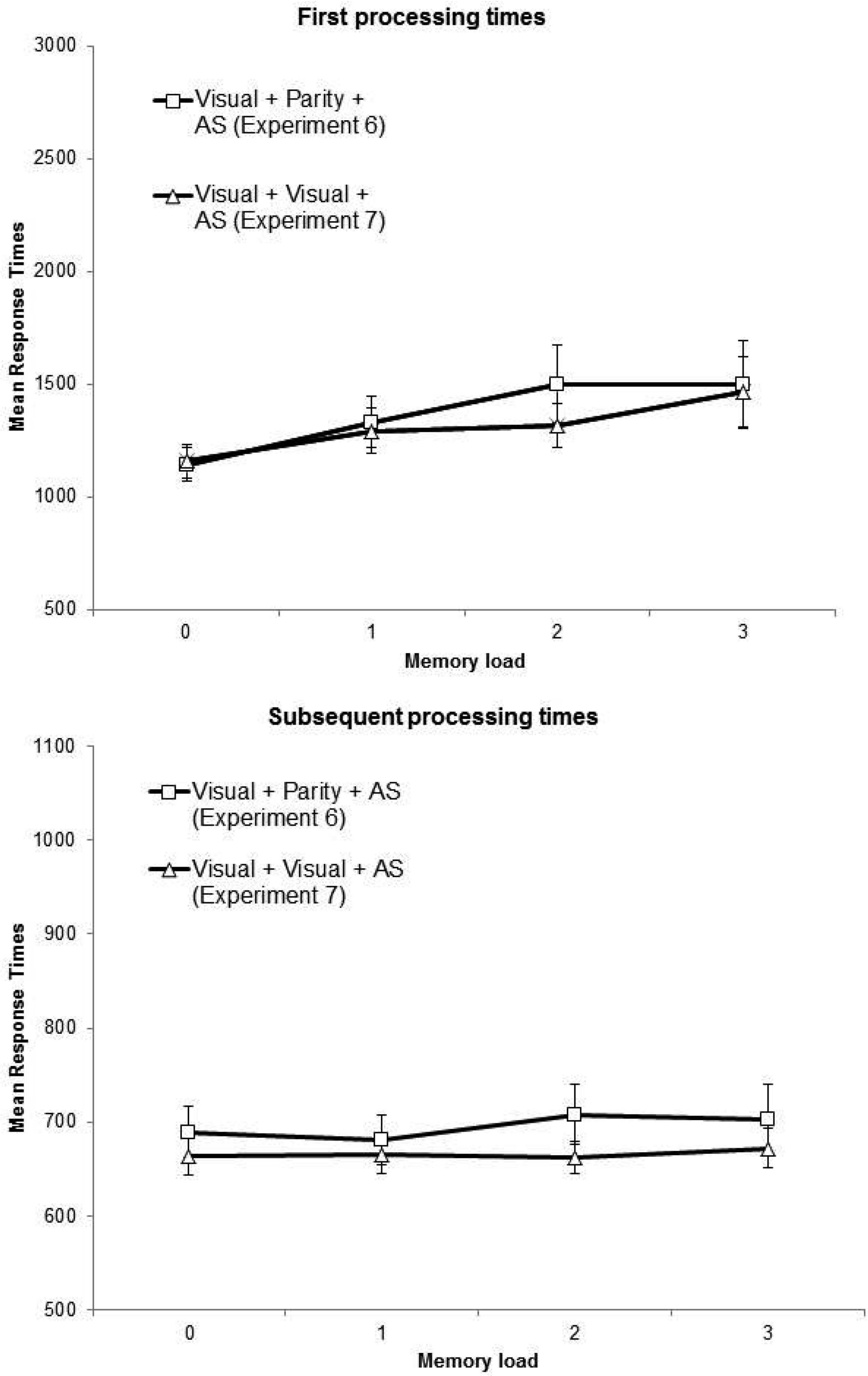

Figure 6. Mean processing times (first processing times in upper panel, subsequent processing times in lower panel) in milliseconds as a function of memory load for the parity task while maintaining visual fonts under concurrent articulation (Visual + Parity + AS, Experiment 6) and for the visual discrimination task while maintaining visual fonts under concurrent articulation (Visual + Visual + AS, Experiment 7). Error bars represent standard error. AS = articulatory suppression.

the University of Geneva participated for course credit. None of them took part in the previous experiments, and all had normal or corrected-to-normal vision. Memory load, from zero to five letters, was manipulated within subjects.

Materials and procedure. Materials and procedure were the same as those used in the previous experiment except that the presentation of the last font was followed by a 12-s processing phase during which participants performed a visual discrimination task. For this task, we used the stimuli of Vergauwe et al. (2009), which consist of 28 monochromatic displays that filled the entire screen. Half of the displays could objectively be categorized as in the red family and the other half as in the blue family. Participants were asked to press the right-hand key of the keyboard when the presented color was more red than blue and the left-hand key when it was more blue than red. Throughout the experiment, all colors were used approximately equally often and remained on screen until a response was given, which triggered the appearance of the next color.

Results

The data of three participants with less than 50% of the series of fonts correctly recalled were discarded from further analyses. One participant performed at chance level in the visual discrimination task, and these data were discarded too. For the remaining 20 participants, recall performance decreased as the list length increased (96%, 79%, 67%, 37%, and 21% of list correctly recalled for lengths 1, 2, 3, 4, and 5, respectively). Using the same skimming procedure as before, we analyzed the data of 19 participants up to list length 3. The rate of correct responses on the visual discrimination task decreased slightly with increasing list length (82%, 80%, 81%, and 80% of correct judgments for list lengths 0, 1, 2, and 3, respectively). The ANOVA on first processing times[5] showed an effect of memory load that failed to reach significance, $F(3, 51) = 2.75$, $p = .05$ (see Table 1). Further analysis showed a significant linear relationship between the number of letters to be maintained and first processing times, $F(1, 17) = 4.71$, $p < .05$, $\eta_p^2 = .22$ (see Figure 6). The linear regression of the first processing times on list lengths revealed an R^2 value of .94 with a slope of 95 ms.

As can be seen in Figure 6 and like in Experiment 6, subsequent processing times did not vary as a function of list length, with a nonsignificant linear trend ($F < 1$, $\eta_p^2 = .007$; see Table 2). Thus, increasing the number of fonts to be maintained did not postpone concurrent processing after the first processing item, even when concurrent processing pertained to the same visual domain.

Discussion: Experiments 6 and 7

As we predicted, increasing the amount of information to be maintained does not postpone concurrent processing when this information cannot be maintained through attentional refreshing. The fact that such postponement of subsequent responses is only observed insofar as maintenance actually relies on attention provides strong support to our idea that it is due to attentional refreshing. As we have mentioned before, the lack of an effect of memory load on processing times cannot be attributed to peripheral maintenance of the fonts in the phonological loop, as the tasks were performed under concurrent articulation.

Our results suggest that fonts are not being maintained through either attentional refreshing or verbal rehearsal. However, participants were able to recognize up to three fonts in correct order. How were they able to do so? A possibility could be that there is some kind of visual buffer where images can be stored independently from other WM resources such as attention or the phonological loop. This could be what Logie (1995) referred to as the visual cache. However, one would then have expected a dramatic decrease in recall performance between Experiments 6 and 7 due to the use of visual discrimination as secondary task, but this was not observed. Importantly, though, one should not take these results as showing that visual material in general cannot be maintained through attentional refreshing. Indeed, previous studies have shown that there are visual stimuli that do rely on attention for maintenance (e.g., Morey & Bieler, 2013; Stevanovski & Jolicœur, 2007; Vergauwe et al., 2009).

Furthermore, in contrast to subsequent RTs, first RTs did increase with the number of memory items. This suggests that, even though the fonts were not being maintained through attentional refreshing, they underwent some kind of attention-demanding consolidation. The consolidation times observed for fonts were, however, substantially shorter than the ones observed for letters and locations (124 ms and 95 ms, compared to about 250 ms). More research will be needed to elucidate this point. We think it might reflect the fact that fonts have less information in long-term memory that can be used during consolidation to create a durable memory trace, resulting in a more shallow process of consolidation. The lack of long-term information associations might also be key to understanding why this kind of information cannot be refreshed. The precise mechanism by which participants were able to recognize up to three fonts certainly deserves further investigation. However, the present study aimed not at deciphering this point but at testing the TBRS prediction that when memoranda do not require attention for their maintenance, they should not impact concurrent processing. What can be concluded from the present results is that in the same way as varying the rate at which a non-attention-demanding processing is performed has no effect on concurrent storage (Barrouillet et al., 2007, Experiment 7), varying the memory load induced by the memorization of nonrefreshable items has no effect on concurrent processing. Processing and storage interfere with each other as long as they rely on the same resource, attention.

General Discussion

The present study explored the effect that storage has on concurrent processing within WM. In line with the predictions of the TBRS model, which assumes that both functions compete for a common resource in a time-based way, maintaining information by keeping it active in WM postpones concurrent processing. These observations are in line with most studies that have examined processing times as a function of the serial position of the processing episode in complex span tasks (e.g., Engle et al., 1992, Experiment 1; Friedman & Miyake, 2004; Jarrold et al., 2011;

[5] One of the 19 participants who remained after our skimming procedure for subsequent processing times did not have enough data points to be included in the analysis of first processing phase. Hence, the data of 18 participants were included in this analysis.

Maehara & Saito, 2007; Saito & Miyake, 2004; but see Towse et al., 2000, as well as Engle et al., 1992, Experiment 2). However, they are in sharp contrast with the sole study using a Brown-Peterson paradigm, conducted by Jarrold et al. (2011), who failed to find a relation between memory load and processing times though using a preload technique similar to the one used in our study. To account for the different findings observed between the complex span and the Brown-Peterson paradigms, the authors interpreted this absence of effect as reflecting the fact that individuals did not try to refresh information during the processing phase that preceded recall. The findings of Baddeley and Hitch (1974) shed light on this phenomenon. As noted in the introduction, Baddeley and Hitch observed that reasoning was slowed down by memory load only when memory performance was stressed. An important feature of our study is that we designed our paradigm in such a way that maintenance activities were prioritized and we studied processing times only for those series with perfect recall. Although this led to discarding some of the collected data, these conditions are crucial when aiming at studying the impact of increased memory load. Indeed, it is difficult to study the influence of maintenance if one cannot ascertain that subjects are engaging in maintenance activities. For example, in the Jarrold et al. study, it can be computed that participants recalled only an average of 65% of items in lists of four to seven nouns (i.e., a mean of about 3.6 nouns recalled per trial).

Thus, our findings demonstrate that the use of mechanisms of maintenance is not restricted to a specific paradigm (e.g., complex span task) but extends to situations in which memory requirements have to be met while performing concurrent activities. Whatever the paradigm used, maintenance activities inescapably postpone processing. Moreover, comparing large ranges of memory loads revealed that this postponement is commensurate with the number of items to be maintained. In line with our predictions, we identified two exceptions to this dependency. When articulatory rehearsal is available, some verbal items can be maintained without any disruptive effect on concurrent processing. The same is observed when the memoranda consist of nonrefreshable features. These findings have implications for our understanding of how information is maintained and consolidated in WM. These are discussed before discussing implications for WM functioning.

Maintenance Mechanisms in WM

Across the first three experiments, we showed a direct impact of maintenance activities on processing times. Increasing the amount of information to be maintained resulted in a correlative slowing of processing of about 50 ms per item. Jarrold et al. (2011) reported a similar slowing of 41 ms in complex span tasks involving verbal maintenance. The present study reveals that changing the nature of the items to be remembered (visuospatial vs. verbal in Experiments 2 and 3, respectively) does not change this relationship between storage and processing, nor does changing the nature of the processing task (compare Experiments 1 and 2). We interpret this as evidence for the existence of a domain-general mechanism for maintaining information in WM that is attention based. Indeed, maintenance was observed to postpone concurrent processing across different domains of WM and when peripheral maintenance was ruled out. To our knowledge, the only resource in WM that is, across different theories of WM, proposed to be central, domain general, and taxed heavily by online processing of information is attention.

Our paradigm allowed us to evaluate the capacity of this central attention-based system at about three or four elements, echoing the capacity of the focus of attention described by Cowan (2005), the region of direct access in Oberauer's (2002) theory, and also the capacity of the general-purpose system postulated by Halford (1993). The present examination of the effects of storage on processing confirms one of the main assumptions of the TBRS model, previously investigated through the effect of processing on maintenance (Barrouillet et al., 2004, 2007; Vergauwe et al., 2010, 2012). Both streams of studies point toward the interdependence between processing and storage through a domain-general time-based resource sharing at the central level of WM.

Besides this central domain-general mechanism, our results suggest the existence of a domain-specific system that can maintain up to three or four verbal items without any interference with concurrent processing. The fact that concurrent articulation abolishes this capacity and that varying articulatory demands of verbal material to be maintained results in changes in this capacity supports the idea that the nonattentional maintenance mechanism for verbal material relies on articulatory rehearsal. As such, this system is akin to the phonological loop described in the different versions of the multiple-component model (Baddeley, 1986, 2000; Baddeley & Hitch, 1974; Baddeley & Logie, 1999). Interestingly, this phonological loop operates as an auxiliary system, independent from the central system but able to supplement it. When verbal information has to be maintained, we observed that the central system intervenes when the phonological loop is unavailable due to concurrent articulation as in Experiment 3 or when its capacity is exhausted as in Experiments 4 and 5, in which case the maintenance of additional items results in processing postponement. Note that these findings are entirely in line with the extended TBRS model as proposed by Camos et al. (2009) according to which a domain-general mechanism of maintenance through attentional refreshing is supplemented with a domain-specific mechanism of articulatory rehearsal for maintenance of verbal material. The present findings support this assumed coexistence of two independent mechanisms for maintaining verbal information in WM. The current observation that only a small number of items can be held by the phonological loop is in line with other studies suggesting that rehearsal can only maintain a rather small number of verbal memoranda (e.g., Jarrold, et al., 2011; Tan & Ward, 2008).This could also shed light on the limitation of immediate memory proposed by Miller (1956) at about seven items. Indeed, Miller based his famous estimate on data from simple verbal spans in which the central system and the phonological loop, both able to hold three or four items each, can operate jointly.

Interestingly, while creating a situation in which participants are entirely free to choose what mechanism they use for maintaining verbal material led us to show that up to about three or four items can be maintained before attention-based mechanisms kick in (Experiments 4 and 5), creating similar situations for spatial material shows that attention-based mechanisms are used from the first memory item onward (Experiments 1 and 2). Indeed, maintaining a single spatial location resulted in postponing concurrent processing even though we did not constrain in any way the use of nonattentional maintenance mechanisms for spatial information. This suggests that attention is crucially involved in spatial maintenance and that it might be impossible to maintain spatial information in WM without relying on attention. These findings confirm our hypothesis of an asymmetry between verbal and visuospatial domains because of the absence of a domain-specific mechanism of maintenance for visuospatial information.

While our data point to a domain-general mechanism of attention-based maintenance supplemented with only a domain-specific maintenance mechanism for verbal material, they also confirm the suggestion of Ricker and Cowan (2010) of there being features that cannot be refreshed attentionally and that inevitably get lost over time. Indeed, in sharp contrast to maintaining spatial locations or letters under concurrent articulation, memorizing up to three fonts did not have any effect on concurrent processing after the very first processing item. As our pretest showed that fonts cannot be refreshed attentionally, no effect of maintenance on processing was expected because, according to the TBRS model, processing and storage are interdependent only insofar as they rely on attention to be achieved. This was confirmed. Participants were, however, able to recognize up to three fonts in correct order. How were they able to do so? Based on the current results, we can discard attentional refreshing, verbal rehearsal, and a domain-specific visual mechanism as potential WM processes underlying the memorization of fonts. To our knowledge, no other active maintenance mechanisms have been proposed in WM that can easily be applied to visual features such as fonts. Therefore, it must be admitted that recognition of fonts was not underpinned by WM processes but by passive maintenance in long-term memory. This finding confirms the possible implication of a long-term memory component in WM performance, as suggested by Cowan et al. (2012) or in Unsworth and Engle's (2007) model of WM. The TBRS model would need some extension to accommodate this implication of long-term memory in WM.

In summary, the present findings point to a central domain-general mechanism for maintenance in WM. Additionally, some verbal items can be maintained through a domain-specific maintenance mechanism that is independent from attention. Interestingly, in line with our prediction of an asymmetry between verbal and spatial memoranda, while we have found clear evidence for a peripheral nonattentional mechanism for maintaining verbal material, spatial material was observed to be completely dependent on attention for its maintenance. Nonetheless, when only attention-based mechanisms are available for maintenance, it takes about the same time to refresh one verbal or one visuospatial item. Implications of this finding for WM functioning are discussed below.

WM Functioning

The main finding issuing from the present series of experiments is that maintaining information in WM without any recourse to auxiliary systems results in the postponement of concurrent processing. Moreover, the postponement of concurrent processing increases linearly with the number of items that are maintained. In particular, our results suggest that it takes about 50 ms to refresh one memory item through attentional focusing, suggesting a very fast speed of refreshing in WM. This estimated speed of refreshing indicates that WM functions in a very dynamic way and that time plays a crucial but very subtle role in the interplay between processing and storage. An important practical implication of such a fast refreshing rate is that it might be almost impossible to prevent any refreshing from taking place in WM tasks. Importantly, our observation of a very fast refresh rate in WM sheds light on four theoretical proposals concerned with WM functioning.

First, the fact that memory items can be refreshed very quickly is entirely in line with the dynamic WM functioning through rapid switching between processing and maintenance as proposed in the TBRS model (Barrouillet et al., 2004, 2011). Second, the fast refresh rate might reflect a rapidly rotating single-item focus of attention, as proposed by Cowan (2011). In an attempt to reconcile the two views on the capacity of the focus of attention (i.e., the single- vs. multiple-item views), Cowan proposed that such a rapidly rotating focus of attention could (re)activate several items quickly one after another on a temporal microscale, resulting in concurrent retention of several items on a temporal macroscale. Third and perhaps in close relation to the previous point, our results show that attentional refreshing proceeds in a cumulative fashion (Loaiza & McCabe, 2012; McCabe, 2008), rather than operating only on the just-activated item (Raye et al., 2002). Finally, the present estimation of the time needed to refresh one item through attentional focusing of about 50 ms per item is very close to the estimation of the time needed to covertly retrieve one item during serial recall as observed by Cowan et al. (2002). It is also close to the memory scanning rate observed by Sternberg (1966). Although this might be a simple coincidence, it might also suggest that the rates of refreshing, covert retrieval, and memory scanning reflect a common limitation, possibly related to the operation of the focus of attention. Such limitation could be that of very rapid serial processing in the focus of attention resulting in the central bottleneck put forward in the TBRS model (Barrouillet et al., 2004, 2007, 2011).

Additionally, we have observed that, like subsequent processing times, first processing times increase as a direct function of the number of items to maintain. While postponement of subsequent processing times is typically considered to reflect the operation of maintenance-related activities, postponement of first processing times can be considered as more closely related to consolidation-related activities. Ricker and Cowan (2013) recently showed that consolidation time is important for the stability of representations over time. In line with the idea that different processes are being assessed by first versus subsequent processing times, we observed a clear difference in the duration of each of these processes. While refreshing takes about 50 ms per item, consolidation seems to take about 250 ms for items that can only rely on attention-based maintenance (222 ms for letters under articulatory rehearsal, 236 ms and 294 ms for spatial locations). As we noted before, this estimate is in line with previous estimations of consolidation duration (i.e., 250 ms; Shapiro et al., 1994; Taatgen et al., 2009). Interestingly, our data suggest that about three to four letters or words might be maintained in WM without being associated with a consolidation cost. Indeed, in Experiments 4 and 5, we did not find evidence for attention-demanding time-consuming consolidation activities for very short series of letters and words. It might be that a limited number of verbal items can be maintained in the phonological loop and that these items do not undergo the process of consolidation because they remain at the peripheral level of working memory. It goes without saying that this is only a tentative interpretation of the current results that needs to be tested explicitly in future experiments. In the same way, future research will need to address the question of how the attention-demanding processes of refreshing and consolidation are related to each other and how they relate to WM performance.

A pending question concerns the way the two systems of maintenance for verbal information interact. Our results suggest that the central system is able to supplement the peripheral verbal system when its capacity is exhausted. Camos et al. (2011) observed that individuals are able to strategically select one or the other of the two systems as a function of task demands and the nature of the memoranda. Our results confirm these observations, participants favoring rehearsal when maintaining letters or words while performing an attention-demanding concurrent task. However, do the two systems hold distinct representations of the same memory item, or do they operate on distinct features of the same representation? How do the two systems collaborate to jointly maintain a series of items, and how are possibly different memory traces integrated at recall? These are among the many questions that remain to be answered.

Conclusion

This series of experiments lends strong support to the hypothesis that the two functions of WM, storage and processing, compete for a unique resource shared in a time-based way, storage leading to processing postponement. Our main findings are new in that they (a) show that processing and maintenance are dependent by showing a linear relationship between maintenance demands and processing times, (b) demonstrate explicitly the existence of a domain-general attention-based mechanism that can maintain and refresh up to three or four simple verbal memory items such as letters or simple spatial memory items such as locations at a very similar and fast rate of about 50ms/item, and (c) uncover a clear and predicted asymmetry between maintaining verbal and spatial material with a system being able to maintain some verbal items without attentional involvement while maintaining even a single spatial location heavily relies on attention.

Our findings also raise important questions for future research. Among them are the constancy of the observed refreshing rate across different domains and types of memory traces; whether the observed similarity in rates of attentional refreshing, covert retrieval, and memory search is a real theoretical issue or a mere coincidence; and how the different mechanisms available for verbal maintenance operate together. Although fundamental questions concerning the structure and functioning of WM remain unanswered, we believe that the present research considerably advances our understanding by showing that WM comprises an attention-based mechanism for maintenance that operates at a fast rate across its different domains.

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Appendix

Pretest for Experiments 6 and 7

This pretest aimed at testing the nonrefreshable nature of fonts. For this purpose, we used the same recognition paradigm as in Ricker and Cowan's (2010) second experiment in which participants were presented with an array of three unconventional visual characters for further recognition. Retention intervals varied in duration and were filled, or not, with an auditory parity task. Unlike for letters, the authors observed dramatic forgetting of unconventional characters even when attention was available for refreshing, with the percentage of correct rejections (i.e., correct "no-change" responses) dropping from 83% to 66% when the duration of the unfilled interval increased from 1,500 ms to 6,000 ms. The current pretest used this paradigm to demonstrate the same kind of forgetting for fonts even when attention is available for refreshing.

Method

Participants and Design

A total of 29 undergraduate psychology students (27 female, mean age = 20.68 years) enrolled at the University of Geneva participated for course credit. None of them took part in the experiments reported in the main text. All participants had normal or corrected-to-normal vision. The duration of the retention interval (RI: 1,500, 3,000, or 6,000 ms) and the presence of a secondary task (parity judgment vs. no-task) were manipulated within subjects, resulting in six experimental conditions per subject.

Materials and Procedure

A dual-task design was used consisting of a visual array memory task and an auditory secondary task that was performed during the retention interval prior to testing memory. Our method was based on Ricker and Cowan's (2010) Experiment 2. Besides the fact that three fonts were to be maintained instead of three unconventional characters, there were three minor changes. In our experiment, across trials, memoranda were presented at three fixed locations on screen instead of at randomly varying locations, the array was presented for 1,000 ms instead of 750 ms, and trials of the six different experimental conditions were presented randomly intermixed instead of blocked.

(*Appendix continues*)

Concerning the visual stimuli, they were letters presented in different fonts, using point size 24. That is, for a given trial, the same letter was presented in uppercase using three different fonts (e.g., P P P), and that letter varied across trials by randomly selecting one out of a pool of 15 letters for which the different fonts gave rise to sufficiently different visual input. These letters were A, B, E, F, G, H, K, M, P, R, S, V, W, Y, and Z. On each trial, three different fonts were chosen randomly without replacement out of a pool of 18 distinct fonts. These fonts were Curlz MT, Viner Hand ITC, Jokerman, Blackadder ITC, Kristen ITC, Ravie, Algerian, Castellar, Comic Sans MS, Old English Text MT, Arial, Courier New, Stencil, Rockwell, Magneto, Bauhaus 93, Bodoni MT, and Script. These were selected because they were not spontaneously namable by the authors and judged to result in sufficiently different visual output for each of the letters. All the letters were presented in black on a grey background within three invisible squares on screen, one just above and left to the center of the screen, one just above and right to the center of the screen, and one just below the center. For the auditory stimuli, the numbers between one and 10 were used and presented in a male voice, digitally recorded and played at a comfortable listening volume.

Each trial started with a fixation cross displayed in the middle of the screen for 1,000 ms. Next, an array of three fonts appeared on screen for 1,000 ms, followed by a blank screen for 250 ms, and then a visual mask that remained for 100 ms. After the mask, a blank screen was displayed for a variable duration of 1,400 ms, 2,900 ms, or 5,900 ms. As such, together with the mask display duration, we obtained retention intervals of 1,500 ms, 3,000 ms, and 6,000 ms, respectively. In the parity judgment conditions, participants heard spoken digits through headphones at a rate of one digit every 1,500 ms during these intervals (i.e., one, two, and four digits were presented during retention intervals of 1,500 ms, 3,000 ms, and 6,000 ms, respectively). Parity judgments were to be performed out loud and as quickly as possible after hearing each digit. The experimenter monitored compliance. During no-load conditions, participants did not hear any digit. Participants were informed that this occurred in half of the trials. After the retention interval, a single font was displayed in the center of the screen. On any given trial, the same letter was used here as the one used in the study array, again using point size 24. Participants entered a response by pressing the right-hand key of the keyboard if they thought the single font was one of the three fonts presented in the study array (which was true for half of the trials of every experimental condition) or the left-hand key of the keyboard if they thought that the single font was not one of the three fonts presented in the study array. When a different item was presented, the font of the letter was sampled from the 15 remaining fonts in our pool of distinct fonts. The order of same/different trials was random.

The experiment started with six-array practice trials with no secondary task, followed by six-array practice trials with parity judgment. For both sets of practice trials, there were two trials for each of the three RI durations. The same stimuli as in the experimental trials were used here. Participants completed 72 experimental trials (i.e., 12 trials per experimental condition).

Results

The data of two participants were discarded from further analyses because they demonstrated at-chance performance in the memory task. Correct rejections (i.e., correctly responding that there was no change) were analyzed by performing an analysis of variance on these percentages with RI duration (1,500 ms, 3,000 ms, or 6,000 ms) and presence of secondary task (no-task vs. parity) as within-subject factors. Like Ricker and Cowan (2010), we observed a significant effect of adding a secondary task, $F(1, 26) = 4.97$, $p < .05$, $\eta_p^2 = .16$, and a significant effect of the duration of RI, $F(2, 52) = 10.41$, $p < .001$, $\eta_p^2 = .29$, with no interaction ($F < 1$). Importantly, as we expected, a planned comparison showed that fonts were inevitably lost over time, even when attention was available for refreshing, as demonstrated by the significant effect of RI duration when there was no concurrent task, $F(2, 26) = 7.53$, $p < .01$, with 84%, 70%, and 68% of observed correct rejections for delays of 1,500 ms, 3,000 ms, and 6,000 ms, respectively. Upon this finding, we decided to use fonts as memoranda in Experiments 6 and 7, which aimed at examining the relation between processing and storage for memoranda that do not have attention-based maintenance mechanisms at their disposal.

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