



## Consolidating working memory: Distinguishing the effects of consolidation, rehearsal and attentional refreshing in a working memory span task

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### ABSTRACT

In a series of experiments, we demonstrated that manipulating the opportunity that individuals had to consolidate each memory item produced systematic differences in working memory span performance. In young adults, presenting an unfilled delay interval immediately following the presentation of each to-be-remembered item and before the onset of a distractor processing activity produced enhanced working memory performance relative to when the same delay interval was presented after the processing activity. In addition, the beneficial effect of providing an opportunity for consolidation was unaffected by manipulations of processing difficulty (Experiment 1), processing pace (Experiment 2), and articulatory suppression (Experiment 3). Finally, we demonstrated that RT functions consistent with a process of short-term consolidation are evident at longer item presentation times more commonly associated with working memory span tasks (Experiment 4). Together, these results suggest that the process of consolidation is separable from articulatory rehearsal and attentional refreshing. Moreover, these results are difficult to account for in terms of cognitive load, temporal distinctiveness, and/or distractor removal and suggest that current models of working memory may need to be modified to take into account the temporal parameters associated with the initial consolidation of memory items.

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### Introduction

Working memory is thought to be responsible for the active maintenance and management of information required to complete current task goals (Baddeley, 1986), and is commonly measured using working memory span tasks that require both the maintenance of a series of to-be-remembered items and the completion of a concurrent processing activity (Daneman & Carpenter, 1980). The factors influencing the maintenance of information in

working memory have been the subject of extensive research in the 40 years since the seminal model of Baddeley and Hitch (1974) was first proposed. A central tenet of the Baddeley and Hitch model was that verbal information was maintained in working memory through a process of rehearsal (Baddeley, Lewis, & Vallar, 1984), and extensive research has been devoted to understanding this mechanism (Awh et al., 1996; Baddeley, 1986; Baddeley, Thomson, & Buchanan, 1975; Tam, Jarrold, Baddeley, & Sabatos-DeVito, 2010; Tan & Ward, 2008). However, more recent conceptualisations of working memory have begun to suggest that other processes in addition to rehearsal may be important for the successful maintenance of information in memory (Camos, Lagner,

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& Barrouillet, 2009; Cowan, 1999; Tam et al., 2010). In particular, a number of researchers have argued for a process of attentional refreshing that acts to maintain information stored in working memory by focusing domain-general attention on to-be-remembered items (Barrouillet, Bernardin, & Camos, 2004; Barrouillet, Portrat, & Camos, 2011; Johnson, 1992), with considerable evidence amassed to support this view (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Camos et al., 2009; Raye, Johnson, Mitchell, Greene, & Johnson, 2007; Raye, Johnson, Mitchell, Reeder, & Greene, 2002). Additionally, some recent investigations have suggested that the process of consolidating information into working memory may also play a role in determining performance (Nieuwenstein & Wyble, 2014; Ricker & Cowan, 2014; Vergauwe, Camos, & Barrouillet, 2014). However, the nature of the consolidation process in the context of working memory remains relatively underspecified and, importantly, little is known about how it relates to the more established processes of rehearsal and attentional refreshing. The current study aimed to address these issues by examining the effect of providing an opportunity for consolidation in a working memory span task, and differentiating this effect from those associated with attentional refreshing and articulatory rehearsal.

Short-term consolidation refers to the processing involved in transforming fragile, transient sensory input into more durable memory representations (Chun & Potter, 1995; Jolicoeur & Dell'Acqua, 1998) and has been distinguished from the more basic sensory and perceptual encoding involved in the detection and identification of a stimulus (Jolicoeur & Dell'Acqua, 1998; Nieuwenstein & Wyble, 2014; Ricker & Cowan, 2014). The transmission of information during sensory and perceptual encoding is thought to be fast and to occur in parallel, with representations formed during these stages subject to rapid forgetting unless they undergo a process of consolidation. In contrast, the process of consolidation, which is thought to occur after these basic encoding stages, is argued to be time-consuming and reliant on central attentional mechanisms (Jolicoeur & Dell'Acqua, 1998). Consolidated memory representations are thought to be available for later report in the absence of ongoing sensory input (Chun & Potter, 1995; Jolicoeur & Dell'Acqua, 1998), to be able to withstand interference from new information entering the system (Nieuwenstein & Wyble, 2014), and to be more resistant to forgetting (Ricker & Cowan, 2014). Ricker and Cowan (2014) have likened encoding to the sensory activation of features in long-term memory and consolidation to the entry of these features into Cowan's (1988, 1995) focus of attention. A number of frameworks have proposed a similar distinction between initial sensory encoding and the subsequent formation or consolidation of integrated representations in short-term memory (e.g., Chun & Potter, 1995; Jolicoeur & Dell'Acqua, 1998; Massaro, 1975; Nieuwenstein & Wyble, 2014) and we will follow suit in using this distinction and terminology. However, we remain open to the possibility that what we and others have termed consolidation may in fact reflect the operation of other post-encoding processes and will return to this issue in the General Discussion.

Jolicoeur and Dell'Acqua (1998) were one of the first to provide a systematic investigation of the process of short-term consolidation. They developed a paradigm for investigating the time course of consolidation by combining a visual memory task with an auditory forced-choice reaction time task. Participants were presented with a visual stimulus item (a letter or symbol) which was quickly masked, followed by the forced-choice reaction time task, which involved judging tones as being either high or low in pitch by making an appropriate keypress. Finally, participants were required to recall the initial visual memory stimulus. The time interval between the presentation of the initial memory stimulus and the onset of the tone was varied systematically. The hypothesis was that if the memory stimulus was still being consolidated when the tone was presented, reaction times to the tone would be slowed relative to a tone presented after consolidation had finished, when an individual's central attentional mechanisms would again be available. Results consistently showed that reaction times to the tone were slower when the interval between the initial memory stimulus and the tone was short, and became increasingly faster as this interval increased. This was taken as evidence of a process of consolidation. Jolicoeur and Dell'Acqua (1998) went on to demonstrate that this process of consolidation was under conscious control, by including a condition in which participants were still presented with the memory items, but were instructed to ignore these and to just respond to the choice reaction time task, as recall was not required at the end of each trial. For this condition, reaction times to the tone were unaffected by temporal proximity to the initial stimulus, suggesting that the slowed reaction times in the former condition were specifically associated with the need to remember information and not simply the perceptual characteristics of the task. Jolicoeur and Dell'Acqua (1998) concluded that consolidation is an important process involved in transferring information into short-term memory, and that it requires central processing resources.

Although considerable research has been devoted to establishing the basic parameters of the consolidation process (Jolicoeur, 1999; Jolicoeur & Dell'Acqua, 1999; Nieuwenstein & Wyble, 2014; Stevanovski & Jolicoeur, 2007, 2011), it is not currently known whether the process of consolidation is important for performance on a typical working memory span task. However, converging evidence from studies that have manipulated the time available for post-encoding processing in other paradigms suggests that it is likely to be a contributing factor. For example, a recent study by Barrouillet, Plancher, Guida, and Camos (2013) showed that increasing the time available for the encoding of memory items in a serial recall task, by presenting memory items at a slow (i.e., 5000 ms per item) rather than a fast (i.e., 500 ms per item) pace, led to better recall of the memory items. Moreover, recall of the memory items presented at a slow pace was more resistant to an increase in the number of distractors presented during retrieval, suggesting that the memory traces may have been protected to some extent from event-based interference, but were still affected by an increase in the attentional demand of the distractors. Barrouillet et al. (2013) attributed the difference between the fast and slow paced conditions to

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