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Lapsed attention to elapsed time? Individual differences in working memory capacity and temporal reproduction

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ABSTRACT

Working memory capacity (WMC) predicts individual differences in a wide range of mental abilities. In three experiments we examined whether WMC would predict temporal judgment. Low-WMC temporal reproductions were consistently too long for the shortest duration and too short for the longest, but were accurate (unbiased) for the intermediate. In contrast, high-WMC temporal reproductions were more accurate (unbiased) across the range. Thus low-WMC showed a classic "migration effect" (Vierordt's Law) to a greater extent than high-WMC. Furthermore reproduction errors depended more on *temporal context* than the absolute durations of "shortest," "longest," and "intermediate." Low-WMC reproductions were overall more variable than high-WMC. General fluid intelligence (*gF*) was also related to temporal bias and variability. However, WMC-related timing differences were only attenuated and not eliminated with *gF* as covariate. Results are discussed in terms of attention, memory, and other psychological constructs.

Working memory (WM) is a theoretical system for maintaining, manipulating, and accessing mental representations as needed during ongoing cognition and action. WM contributes to executive control of cognition and action through attention. For example, the contents of WM can bias attention to select only task-relevant perceptual stimuli for representation and evaluation (Cowan, 1995; Heitz & Engle, 2007; Soto, Hodsell, Rotshtein, & Humphreys, 2008). Conversely, attention can gate access to WM, in order to protect its contents in limited-capacity storage from interference (Cowan, 1995; Engle, 2002; Vogel, McCollough, & Machizawa, 2005). WM capacity (WMC) refers to a domain-general ability to coordinate attention and WM, in order to control cognition and action. WMC can vary within individuals across changing internal states and external circumstances, or between individuals as a relatively enduring personal characteristic (Kane, Conway, Hambrick, & Engle, 2007).

As an individual-differences variable, WMC is strongly predictive of both higher-order and lower-order mental abilities (for a review, see e.g., Kane et al., 2007). For example, WMC reliably accounts for large portions of variance in complex reasoning and general fluid intelligence (*gF*; Ackerman, Beier, & Boyle, 2005; Broadway & Engle, 2010; Deary, 2000; Engle, Tuholski, Laughlin, & Conway, 1999; Oberauer, Süß, Wilhelm, & Wittmann, 2003; Troche & Rammsayer, 2009; Unsworth, Redick, Heitz, Broadway, & Engle, 2009). WMC also predicts the accuracy and latency of simple decisions, particularly when strong interference is present. For example, there are numerous dissociations in the WMC literature between: (a) interfering situations (in which WMC-related individual differences are often observed), such as *looking away* from a sudden-onset stimulus in an antisaccade task, or naming the ink-color of an *incongruent color-word* in a Stroop task, and (b) non- interfering situations (in which WMC-related individual differences are not often observed), such as *looking toward* a sudden-onset stimulus in a prosaccade task, or naming the ink-color of a *congruent color-word* in a Stroop task (Kane & Engle, 2003; Unsworth, Schrock, & Engle, 2004).

Because WMC distinguishes performance in situations demanding attentional control (even without heavy memory load), such findings provide strong support for an "executive attention view" in which WMC is not strictly about memory, but about control of cognition (Engle, 2002; Kane et al., 2007). According to this theory, it is the ability to exert top-down control over cognition that is responsible for better performance in WM tasks; and also in a wide range of tasks that require cognitive control (but without heavy WM load). Furthermore, it is the ability to control attention in the face of interference that accounts for strong relationships between WMC and *gF* (Kane et al., 2007). However, detailed understanding of the internal structure and extent of the WMC construct is still incomplete.

Specifically, *interfering conditions are not always sufficient or necessary* to observe WMC-related individual differences in lower-level mental abilities. In some notable examples, WMC did not

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distinguish performance in the strongly interfering case of visual search for "conjunction targets" among highly similar distractors (Kane, Poole, Tuholski, & Engle, 2006). In contrast, WMC distinguished performance the non-interfering cases of enumerating a small set of objects (Barrouillet, Lepine, & Camos, 2008; Tuholski, Engle, & Baylis, 2001) and maintaining psychomotor vigilance (Unsworth, Redick, Lakey, & Young, 2010). In the present work we examined whether WMC would predict another lower-level mental ability (even without strongly interfering conditions): Judging temporal durations.

Interval timing is a basic ability shared across species that is important for organized behavior and survival (Gallistel, 1989). In three experiments we examined whether WMC would predict individual differences in temporal judgment in the milliseconds-to-seconds range, using the method of reproduction. On each trial observers viewed a stimulus defining a temporal interval (target duration), and subsequently tried to reproduce the target duration by timed manual response (s). Why might WMC be necessary to perform temporal reproduction tasks? Basically, a person would need to dynamically encode and maintain access to two distinct representations of elapsed time, for comparison and temporal judgment. Furthermore, the quality of these representations would depend on how consistently attention was directed to time. We outline a more detailed rationale in the following.

Many theories of timing are described as clock–counter models (or pacemaker–accumulator models; e.g., Gibbon, Church, & Meck, 1984; for discussion of alternatives see e.g., Buhusi & Meck, 2005; Ivry & Schlerf, 2008; Mauk & Buonamano, 2004; Staddon, 2005). A prominent example is *scalar expectancy theory* (Gibbon et al., 1984); originally developed to explain temporal properties of conditioned learning in animals, in the seconds-to-minutes range. Clock–counter models assume that event timing is accomplished through the cooperation of internal clock, memory, and decision-making components. The clock is an endogenous oscillator continuously emitting pulses that are transmitted to a counter (or accumulator). Arousal is assumed to affect the pulse rate, and attention is assumed to affect the number of pulses reaching the accumulator: When attention is directed to time, a gate between the clock and counter is opened and pulses are allowed to accumulate (Zakay & Block, 1997). More elapsed time is represented by more pulses in the accumulator. The current pulse count is continuously transferred to WM and compared to one sampled from a distribution stored in "reference memory" (long-term memory). A temporal decision is made when the outcome of the comparison between the current pulse-count and the remembered one exceeds a threshold. Intuitively, the prominent roles allotted to attention and memory systems in time estimation suggest that WMC would distinguish temporal reproductions (even without strongly interfering conditions).

Experimental studies show that the accuracy of time estimation is affected by attentional and WM loads in concurrent tasks (Block, Hancock, & Zakay, 2010; Brown, 1997, 2006; Fortin, Bedard, & Champagne, 2005; Fortin, Champagne, & Poirier, 2007; Gaudreault, Fortin, & Macar, 2010). Sharing attention with non-temporal processing generally causes time estimates to be too short and/or more variable. Shortened time estimates are consistent with fewer "clock ticks" accumulating due to switching attention away from timing. Some researchers have concluded further that temporal and non-temporal forms of information processing are supported by a common pool of attentional resources and/or executive functions (Brown, 1997; 2006). In sum, a large number of experimental studies have investigated relations among attention, WM, and timing by manipulating concurrent non-temporal loads. Few studies have sought converging evidence, by using naturally occurring individual differences in WMC to "mimic" load manipulations. In the present work we sought to provide such converging evidence. Next we consider relations between WMC and timing with more focus on individual differences.

Outside of developmental or neurological contexts, very few studies have focused on individual differences in WMC in relation to temporal processing. A large literature suggests common deficits in these abilities in special populations such as *older adults* (Baudouin, Vanneste, Pouthas, & Isingrini, 2006; Block, Zakay, & Hancock, 1998), *young children* (Droit-Volet, 2010; McCormack, Brown, Smith, & Brock, 2004; Szelag, Kowalska, Rymarczyk, & Pöppel, 2002), patients with *schizophrenia* (Elvevåg, Brown, McCormack, & Vousden, 2004), and patients with *Parkinson's disease* (Koch et al., 2008; Malapani, Deweer, & Gibbon, 2002; Malapani et al., 1998). Consistent with these findings, neuroimaging evidence further suggests that attention, WMC, and temporal processing are sub-served by partly overlapping neurotransmitter systems and/or brain circuits (Nobre, 2001). In sum, a variety of developmental and neurological states differing between individuals are associated with both WMC and temporal processing disorders. However, better understanding of these joint deficits *within* the population of healthy younger adults is clearly warranted. The few studies published to date addressing this question are described next (in chronological order).

Saito (2001) found that memory for auditory rhythmic sequences accounted for unique variance in visual digit span, even after statistically controlling for several measures of phonological processing. Saito (2001) took this as evidence for a common timing mechanism subserving short-term memory for both verbal and temporal information, independently of phonological/articulatory control processes. In the present work we sought to further generalize the hypothesized relation between WMC and timing. Saito (2001) was primarily interested in phonological/articulatory control processes in relation to WMC and timing. Appropriate to this interest, WMC was assessed by digit span tasks. Additionally, temporal performance was not reported in much detail beyond correlation coefficients. Furthermore, relationships appear limited to the special case of complex rhythm perception and reproduction. In contrast, the present work used measures of WMC more related to central executive than to phonological/articulatory WM systems (Conway et al., 2005) and examined the more basic task of interval timing (in somewhat more detail than correlation coefficients).

Dutke (2005; Experiment 4) examined whether WMC would interact with effects from increasing the "coordinative demands" of a concurrent task. Participants under-estimated target durations in both low-load and high-load conditions, but more so in high-load. This result is consistent with the idea that fewer clock-ticks accumulated while attention was switched away from timing. Also, low-WMC under-estimated durations to a greater extent than high-WMC in *both* load conditions. This is consistent with the idea that low-WMC are less able to maintain attentional focus on timing, at least while performing a concurrent task. Note that effects of load and WMC were additive, not interactive. We sought to expand on a few features of this study in ways that could further generalize the hypothesized relationship between WMC and timing.

Specifically, in Dutke (2005; Experiment 4) the extreme-groups of high-WMC and low-WMC participants were formed by post-hoc median-split on the sample, measuring WMC with a task that was nearly identical to the task used to assess temporal reproduction. There was no "no load" condition, and only a single duration was tested (which apparently varied across participants depending on how long it took them to perform the concurrent task). Regrettably, temporal performance was not examined in much detail. In contrast, the tasks used to measure WMC in the present work bore little surface similarity to those used to assess temporal judgment. We pre-selected participants based on an independent distribution of WMC scores that could qualify as "normative," containing approximately 2000 scores from a diverse sample, to better ensure that extreme-groups were "truly different" with respect to WMC. We additionally assessed temporal processing across a range of durations, in the absence (as well as the presence) of a concurrent task, and examined performance in somewhat more detail than previously reported. We also included measured a prominent "comorbid variable" (*gF*) to better isolate influences of WMC on timing.

Rammsayer and colleagues (e.g., Helmbold & Rammsayer, 2006; Troche & Rammsayer, 2009) have extensively examined relationships