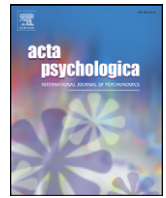




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Lapsed attention to elapsed time? Individual differences in working memory capacity and temporal reproduction

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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.

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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 & Buonomano, 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; Szegal, 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.

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

between “temporal resolution power” and psychometric intelligence in large-sample factor-analytic work. According to their *temporal resolution power hypothesis*, bottom-up neural efficiency leads both to higher WMC and psychometric intelligence because elementary mental operations are more likely to be completed before critical information is lost or distorted (see also Deary, 2000). Rammsayer and colleagues have argued that individual differences in neural properties underlying mental speed (e.g., rate of transmission, frequency of oscillations, phase synchrony) are best captured at a behavioral level by temporal judgment tasks. They have found much evidence consistent with this proposal.

For example, Helmbold and Rammsayer (2006) showed that temporal discrimination accounted for substantial variance in both speed and reasoning components of *gF*; much more so than e.g., Hick Reaction Time (RT) tasks (also supposed to measure “speed of information processing”). Some studies have also included measures of WMC (e.g., Rammsayer & Brandler, 2007) as part of psychometric intelligence batteries, but correlations among individual WMC tasks and timing tasks were not reported. Indeed, except for Troche and Rammsayer (2009) WMC has not been examined as a latent factor in relation to temporal processing, separately from *gF*. Thus Troche and Rammsayer (2009) correctly stated that theirs was “the first study on the interplay among TRP [temporal resolution power], WM capacity and psychometric intelligence” (p. 480). They reported moderate to strong correlations between temporal judgment and WMC (across the set of individual tasks, *r*s ranged from .24 to .52). Furthermore, structural equation modeling showed that WMC “completely mediated” relations between the latent variables for temporal judgment and intelligence (p. 484). In other words, whatever variance in *gF* was accounted for by temporal judgment, WMC accounted for that same variance and more. These results were reported to be “surprising” (p. 485), testifying to the relative novelty of such investigations, and strongly suggested that WMC would predict temporal reproductions in the present work, perhaps independently of shared relations with *gF*.

We sought to expand on this previous factor-analytic work in a few ways. Troche and Rammsayer (2009) did not assess timing with an “executive” (motor response) component such as the method of reproduction. Again temporal performance was not described in much detail beyond correlation coefficients. In contrast, we used the method of reproduction in the present work to further generalize relationships between WMC and timing, and examined performance in somewhat more detail than previously reported. Structural equation modeling work such as Troche and Rammsayer (2009) is exceedingly valuable as “macro-analysis” of individual differences. However, this approach is well-complemented by converging “micro-analysis,” obtained through measured-selection of individuals combined with experimental manipulations (Kane et al., 2007), as in the present work.

1. Present research

We sought to increase existing knowledge about individual differences in WMC in relation to time perception within the population of healthy younger adults, across different time scales, and in the absence (or presence) of concurrent mental tasks; also characterizing performance in somewhat more detail than previously reported. With scant existing evidence in this area, an extreme-groups’ design is justified for these goals (Preacher, Rucker, MacCallum, & Nicewander, 2005). Participants were classified as either high-WMC or low-WMC in a pre-screening session, in which two valid measures of WMC (for verbal and visual-spatial content) were administered.

In Experiment 1, high-WMC and low-WMC reproduced one of three target durations on each trial (500 ms, 1500 ms, or 2500 ms) by simply pressing, holding, and releasing a single key for the required length of time. In Experiment 2, high-WMC and low-WMC reproduced one of three target durations on each trial (500 ms, 1500 ms, or 2500 ms) and also made a non-temporal choice response to terminate reproductions.

A measure of *gF* was included as covariate. In Experiment 3, high-WMC and low-WMC reproduced one of five target durations on each trial (1500 ms, 2500 ms, 3500 ms, 4500 ms, or 5500 ms). We predicted generally that high-WMC observers would be more accurate (unbiased) and less variable at temporal reproductions than low-WMC. To provide additional context for interpretation, we generated the following hypotheses by speculatively combining assumptions from separate WMC and timing literatures.

1.1. Arousal

Within terms of clock-counter models, lower levels of arousal are associated with slower clock rates and consequent under-estimation of durations. With measures of pupil dilation, low-WMC individuals have shown lower baseline levels of arousal than high-WMC (Heitz, Schrock, Payne, & Engle, 2007). Therefore an *arousal hypothesis* predicts low-WMC reproductions to be consistently too short, and/or consistently shorter than high-WMC.

1.2. Lapsed attention

Directing attention away from elapsed time is generally predicted to lead to shortened time estimates. Low-WMC individuals are more prone to lapses of attention than high-WMC (Unsworth et al., 2010). Like the arousal hypothesis, a *strong lapsed attention hypothesis* predicts low-WMC reproductions to be consistently too short and/or consistently shorter than high-WMC. However, lapsed or divided attention does not necessarily result in shortened time estimates: Sometimes they are just made more variable (Brown, 1997, 2006). Therefore a *weak lapsed attention hypothesis* predicts low-WMC reproductions to be more variable than high-WMC.

1.3. Temporal resolution power

Rammsayer and colleagues proposed a *temporal resolution power hypothesis* to explain individual differences in psychometric intelligence (Rammsayer & Brandler, 2002), and recently extended this account to explain individual differences in WMC (Troche & Rammsayer, 2009). According to this theory, greater bottom-up neural efficiency leads to higher WMC and higher psychometric intelligence, because elementary mental operations are thereby more likely to be completed before critical information is lost or distorted (see also Deary, 2000). Assuming that low-WMC individuals process information more slowly, a *strong temporal resolution power hypothesis* predicts low-WMC to consistently under-estimate time (and more so than high-WMC), perhaps due to a slower rate of sampling. However, neural processing may be not only slower for low-WMC (and lower-intelligence) individuals: It may be also less well-coordinated. Therefore a *weak temporal resolution power hypothesis* predicts that if low-WMC reproductions are not exclusively too short, they will be at least more variable.

1.4. Cognitively controlled timing

Lewis and Miall (2003, 2006) identified three criteria that may determine whether temporal judgment depends more on brain areas associated with lower-level automatic processes versus higher-level cognitively mediated processes. The present temporal reproduction tasks might be classified accordingly as follows: 1) some time scales were sub-second (automatic) and some were supra-second (cognitively controlled), 2) performance depended on motor responses (automatic), and 3) performance concerned timing of discrete events (cognitively controlled); however, participants executed a continuous series of reproductions of the same target duration within short blocks (potentially automatic, especially for sub-second durations). In sum, the present temporal judgment tasks might be classified as eliciting automatic timing for sub-second durations, and cognitively controlled timing for supra-

second durations. WMC generally distinguishes performance that depends on higher-level, cognitively controlled processes, not on lower-level, automatic ones (Kane et al., 2007). Therefore, a *cognitively controlled timing* hypothesis predicts WMC to differentiate temporal reproductions selectively for durations exceeding about 1 s.

1.5. Memory mixing

In a study of Parkinson's disease effects on interval timing (Malapani et al., 1998), temporal reproductions by off-medication patients were too long for relatively short intervals (8 s) and too short for relatively long intervals (21 s) when these were tested together in the same session. In contrast, on-medication patients accurately estimated both short and long intervals. The pattern shown by off-medication patients is called *Vierordt's Law* (Lejeune & Wearden, 2009), but was aptly described as a "migration effect" by the authors (p. 316). They ascribed this effect to improperly mixing reference memory distributions ("coupled temporal memories"). In other words, Parkinsonian temporal judgments "migrated" incorrectly toward the mean of a combined distribution of times, instead of tending correctly toward separate means for distinct distributions. Malapani et al. showed this effect to be dependent on testing a mixture of relatively short and long intervals in a single session: Patients accurately reproduced both when these were tested in separate sessions.

These findings were later replicated by Koch et al. (2008) in tasks more like those in the present work, mixing both sub-second short (about 500 ms) and supra-second long (about 2000 ms) target durations (similar to present Experiments 1 and 2). Parkinson's patients again showed the migration effect/*Vierordt's Law* when both short and long intervals were tested in the same session, but not when these were tested in separate sessions. Temporal judgment and WMC both depend on an intact dopaminergic system (Lustig, Matell, & Meck, 2005). A *memory mixing* hypothesis predicts low-WMC reproductions to show the migration effect/*Vierordt's Law* to a greater extent than high-WMC. Specifically, low-WMC reproductions should be consistently too long for relatively short durations, and too short for relatively long durations, in a context-dependent manner; while high-WMC should be more accurate (unbiased). The memory mixing hypothesis necessarily implies greater variability for low-WMC reproductions versus high-WMC.

1.6. Summary

From the preceding arguments, four relatively distinct hypotheses concerning WMC and temporal reproduction can be tested. One group of explanations, including the so-called *arousal*, *strong lapsed attention*, and *strong temporal resolution power* hypotheses, predicts low-WMC reproductions to be 1) *consistently too short and/or shorter* than high-WMC. Another group of explanations, including the so-called *memory mixing*, *weak lapsed attention*, and *weak temporal resolution power* hypotheses, predicts low-WMC reproductions to be 2) *more variable* than high-WMC. Among these, the memory mixing hypothesis is most direct in predicting low-WMC reproductions to show 3) the *migration effect/Vierordt's Law* to a greater extent than high-WMC. [Note that outcomes (2) and (3) are non-independent, because over the long run there are more opportunities for a more variable system to "over-shoot" short durations and "under-shoot" long durations.] The so-called *cognitively controlled timing* hypothesis uniquely predicts WMC to distinguish temporal reproductions for 4) *supra-second but not sub-second* time scales.

2. General method

2.1. Participants

Participants were recruited for the present experiments if they were classified as either high-WMC or low-WMC during prior testing,

as described below. Participants in all experiments were recruited from the community or undergraduate research pool, were between the ages of 18 and 35 years (Experiment 1, $M = 24.4$, $SD = 4.5$; Experiment 2, $M = 23.6$, $SD = 3.9$; Experiment 3, $M = 22.7$, $SD = 4.4$), gave written informed consent, and were compensated with pay or partial course credit.

2.2. Procedure

Participants were recruited after first visiting the lab for WMC measurement, in a pre-screening session lasting approximately 60 min. Participants performed computer-administered tasks seated at a comfortable distance from the monitor, alone in a sound-attenuated room. Participants were made aware they would be monitored for compliance with general instructions via closed-circuit cameras when the researcher was absent from the room. All tasks were programmed in e-prime experimental software, with presentation timing accurate to 1 ms (Schneider, Eschman, & Zuccolotto, 2002). The WMC tasks administered in the pre-screening session have been extensively validated as measures of domain-general WMC and executive control (Conway et al., 2005).

Operation Span is a test of WMC for verbal material. Participants solved simple math equations, in between encoding to-be-remembered letters presented sequentially in the center of the screen (from the set: F, H, J, K, L, N, P, Q, R, S, T, and Y). Participants were prompted to report the presented letters in order after 3–7 equation–letter events (set-size; randomly determined on each trial), by clicking with the mouse on their choices from a 4×3 grid presenting the complete set of 12 letters that could have been shown. In order to maintain correct serial position in the response sequence for recalled letters, participants were instructed to click a "blank" option for any letters they could not recall. Additional details are reported in Unsworth, Heitz, Schrock, and Engle (2005).

Symmetry Span is a test of WMC for visual–spatial material. Participants judged whether black-and-white images were symmetrical, in between encoding the location in which a red square sequentially appeared in a 4×4 grid. Participants were prompted to report the square locations in order after 2–5 symmetry–square events (set-size; randomly determined on each trial), by clicking on their choices in the cells of an empty 4×4 grid. In order to maintain correct serial position in the response sequence for recalled square locations, participants were instructed to click a "blank" option for any square locations they could not recall. Additional details are reported in Unsworth et al. (2009).

There were three trials for each set-size in each WMC task. Scoring was done automatically by the computer program. One point was assigned for each item correctly reported in correct serial position. "Strict" serial position scoring was applied, i.e., if the letters *JRKT* were to be reported, the response "JRK" would be assigned 3 points, the response "blank RKT" would be assigned 3 points, but the response "RKT" would be assigned 0 point. This scoring method has been shown to yield WMC scores with good reliability and validity (Conway et al., 2005). The ranges of possible scores were (0, 75) for *Operation Span* and (0, 42) for *Symmetry Span*.

Scores for each WMC task were converted to z-scores in reference to a distribution of scores obtained over a period of several years of testing student and community volunteers (ages 18 to 35 years). At the time the present studies were conducted there were approximately 2000 scores in the reference distributions for the two WMC tasks, arguably qualifying these distributions as "normative." The z-scores for the two WMC tasks were averaged to form a composite z-score. Individuals were classified as high-WMC (low-WMC) if their composite z-score fell within the upper (lower) quartile of the reference distribution for these composite z-scores. Summary statistics for the reference distributions that were used to classify individuals as high- or low-WMC in the present work were the following (in raw scores): *Operation Span*: $M = 57.87$, $SD = 13.27$, *Symmetry Span*: $M = 27.89$, $SD = 8.67$. The

Table 1

Means (standard deviations) for median absolute reproduction errors (ms) by high-WMC and low-WMC in Experiments 1, 2, and 3. Positive values indicate that reproductions tended to be longer than the target duration and negative values indicate that reproductions tended to be shorter.

Experiment 1					
	500 ms		1500 ms		2500 ms
High	+ 1.76 (17.28)		– 8.34 (38.58)		– 52.62 (65.45)
Low	+ 31.92 (43.25)		– 33.29 (111.27)		– 158.19 (185.53)
Experiment 2					
	500 ms		1500 ms		2500 ms
High	+ 11.55 (52.78)		+ 0.68 (84.56)		– 68.66 (100.25)
Low	+ 124.64 (213.13)		– 19.80 (179.00)		– 298.11 (546.21)
Experiment 3					
	1500 ms	2500 ms	3500 ms	4500 ms	5500 ms
High	+ 12.35 (67.79)	+ 27.38 (92.62)	+ 13.43 (103.46)	– 25.25 (120.34)	– 100.68 (139.44)
Low	+ 54.79 (116.10)	+ 35.53 (130.25)	– 2.36 (106.05)	– 123.36 (350.69)	– 158.84 (328.98)

correlation between individual WMC measures was statistically reliable in the reference distribution, $r = .56$, $p < .001$.

Because participants were classified as high-WMC or low-WMC based on extreme z-scores located in upper or lower tails of a normative distribution, it is trivial that WMC groups in the present work were statistically different from each other (in terms of measured WMC). However, such information is reported for each experiment, for the sake of completeness.

3. Experiment 1: Method

3.1. Participants

A total of 52 individuals (25 high-WMC, 17 women; 27 low-WMC, 20 women) participated in Experiment 1. Measured WMC was statistically different between groups in Experiment 1, $t(50) = -19.38$, $p < .001$ (high-WMC $M = .875$, $SD = .186$; low-WMC $M = -1.08$, $SD = .448$)¹.

3.2. Procedure

3.2.1. Temporal reproduction task

Participants returned to the lab to perform the temporal reproduction task in a session lasting approximately 60 min. Participants pressed the 'Enter' key to initiate each trial. After a central fixation cross appeared for 250 ms, a green dot appeared centrally on the screen to demonstrate the target duration (500 ms, 1500 ms, or 2500 ms). These time scales were chosen to assess temporal judgment over a range thought to be within the so-called "specious present" (Grondin, 2010; James, 1890/1950). We wanted to explore the lower and upper ends of this range. For this purpose 500 ms was selected as the lowest feasible value: Longer than typical latencies for simple RT and in the neighborhood for choice RT (Luce, 1986). Furthermore the range of 500 ms to 2500 ms covers much of the time scale at which short-term/WM processes are thought to be critical to ongoing cognition and action (Jonides et al., 2008).

Participants pressed the 'Enter' key to proceed to the reproduction phase. Participants were instructed to press and hold the 'space' bar for the same length of time that the stimulus had appeared, and to release the 'space' bar at the appropriate time to terminate reproductions. A blue dot appeared centrally on the screen during reproductions. Using a key-release response to record temporal reproductions (instead of e.g., two successive key-presses) was intended to minimize unreliability due to keyboard error, as well as variability in motor skills/RT. Similarly,

¹ WMC score statistics are reported in z-score units.

allowing participants to control transitions between trials (and between demonstration and reproduction phases within trials) was intended to ensure that participants were paying attention to the task at the onsets of demonstrated and reproduced durations.

Reproductions within a time window bounded by $\pm 10\%$ of the target duration were followed by a feedback message "correct." Reproductions outside that time window were followed by messages "too short" or "too long" as appropriate. Feedback was intended to control within-group variability and thus facilitate observing statistically reliable between-group effects and interactions. The same duration was demonstrated and reproduced for 10 consecutive trials within a block. There were 10 blocks per duration and order of blocks was randomly determined. Self-paced breaks were offered between blocks.

4. Experiment 1: Results

4.1. Temporal reproduction accuracy (bias)

We located the median reproduction for each individual for each target duration.² Data from one low-WMC individual were discarded due to an apparent failure to follow instructions. Means and standard deviations for median reproduction absolute errors across target durations are presented in Table 1. It is useful to further examine reproduction accuracy (bias) as the ratio of the reproduced duration to the target duration. This allows performance to be compared across a range of durations using a common metric. A reproduction ratio greater than unity indicates that the reproduction was too long and a ratio less than unity indicates that it was too short. Theoretically, a reproduction ratio equal to unity indicates a perfectly accurate (unbiased) reproduction, although in practice no reproduction can be perfect or exactly equal to unity.

Temporal reproductions for a set of shortest, intermediate, and longest target durations (500 ms, 1500 ms, and 2500 ms, respectively) showed the following pattern (and a template for results in subsequent experiments). Low-WMC reproductions were consistently too long for the shortest duration (but high-WMC were fairly unbiased), and were too short for the longest (but high-WMC were fairly unbiased); both WMC groups were equally unbiased for the intermediate. See Fig. 1 (A)³. A 3 (Target Duration: 500 ms, 1500 ms, and 2500 ms) \times 2 (WMC: High and Low) mixed-model ANOVA⁴ on the mean of median ratios revealed

² Median reproductions for each individual were examined in order to be conservative when comparing WMC groups in terms of reproduction accuracy (bias). Analyses based on individual mean reproduction ratios did not alter any conclusions.

³ The most salient indicator of accuracy (lack of consistent bias) is not the height of the bars per se, but their proximity to "1" (as indicated by confidence intervals).

⁴ Statistics were Huynh-Feldt-corrected as necessary for violations of sphericity.

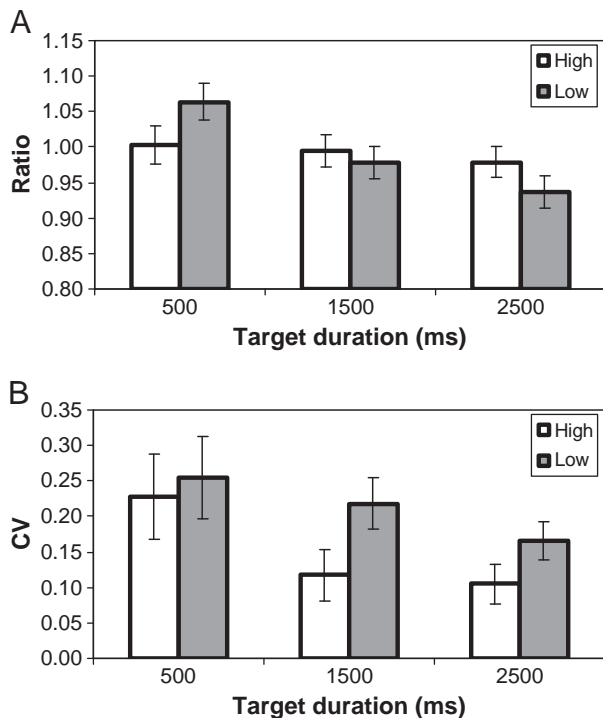


Fig. 1. Experiment 1: (A) Means of median reproduction ratios. (B) Means of reproduction coefficients of variation. Error bars represent 95% confidence intervals. Legends refer to WMC groups.

a statistically significant main effect of target duration, $F(2, 48) = 26.49$, $p < .001$, $\eta_p^2 = .351$. The main effect of WMC was not significant, $F < 1$, but the interaction was, $F(2, 48) = 12.84$, $p < .001$, $\eta_p^2 = .208$.

Pair-wise comparisons⁵ for the effect of target duration indicated that reproduction ratios for the shortest were greater than those for the longest, $p < .001$, and from those for the intermediate, $p = .001$; also ratios for the intermediate duration were greater than those for the longest, $p < .001$. Overall, reproduction ratios were monotonically decreasing as target durations increased. To clarify the interaction between WMC and target duration, independent sample t-tests indicated that low-WMC reproduction ratios were significantly greater than high-WMC for the shortest, $t(49) = 3.29$, $p = .006$, and less than high-WMC for the longest, $t(49) = -2.68$, $p = .030$; ratios did not differ between WMC groups for the intermediate, $t(49) = -1.06$, $p = .882$.

Pair-wise comparisons indicated that low-WMC reproduction ratios for the shortest duration were significantly greater than for the intermediate, $p = .002$, and greater than for the longest, $p < .001$; low-WMC ratios for the intermediate were significantly greater than for the longest, $p < .001$. In contrast, high-WMC reproduction ratios for the shortest were not different from those for the intermediate, $p = .672$, but were greater than those for the longest, $p = .023$; high-WMC ratios for the intermediate were not statistically different from those for the longest, $p = .054$.

Thus, low-WMC reproductions were monotonically decreasing as target durations increased. In contrast, high-WMC reproductions were about the same for the shortest and intermediate durations; but like low-WMC, high-WMC reproductions were too short for the longest duration, although to a lesser extent. 19 (out of 26) low-WMC and 9 (out of 25) high-WMC individually over-estimated the shortest and under-estimated the longest durations. This association was statistically significant, $\chi^2(1) = 5.66$, $p = .018$. This suggests that

⁵ In all post-hoc tests, including independent samples t-tests, the reported p-values have been Bonferroni-corrected for multiple comparisons and are compared to $\alpha = .05$.

WMC distinguished temporal reproductions qualitatively as well as quantitatively, according to the tendency to show the migration effect/Vierordt's Law.

4.2. Temporal reproduction variability

Temporal reproduction variability was calculated as the coefficient of variation (CV). For each individual the standard deviation of reproductions was divided by the mean. Larger CVs indicate greater variability. Low-WMC reproductions were more variable than high-WMC. See Fig. 1 (B). A 3 (Target Duration: 500 ms, 1500 ms, and 2500 ms) \times 2 (WMC: High and Low) mixed-model ANOVA on mean CV revealed statistically significant main effects of WMC, $F(1, 49) = 8.03$, $p = .007$, $\eta_p^2 = .141$ and target duration, $F(2, 48) = 18.06$, $p < .001$, $\eta_p^2 = .269$. The interaction of WMC with target duration was not significant, $F(2, 48) = 2.10$, $p = .147$, $\eta_p^2 = .041$. Pair-wise comparisons for the effect of target duration indicated that reproduction variability for the shortest duration was greater than that for the longest, $p < .001$, and greater than that for the intermediate, $p = .004$; also reproduction variability for the intermediate duration was greater than that for the longest, $p = .002$. Reproduction variability for both WMC groups was monotonically decreasing as target durations increased. Low-WMC reproductions were more variable than high-WMC.

5. Experiment 1: Discussion

Low-WMC reproductions tended to be consistently too long for the shortest duration (500 ms), but high-WMC were more accurate (unbiased). Low-WMC reproductions tended to be too short for the longest duration (2500 ms), but high-WMC were again more accurate (unbiased). Both groups accurately estimated the intermediate duration (1500 ms). Thus low-WMC reproductions showed the migration effect/Vierordt's Law to a greater extent than high-WMC, in the present range of durations. Additionally high-WMC reproductions were less variable than low-WMC. We had generated four relatively distinct hypotheses to facilitate interpretation. Results are not very consistent with the so-called *arousal*, *strong lapsed attention*, and *strong temporal resolution power hypotheses*. These predicted low-WMC reproductions to be 1) *consistently too short and/or shorter* than high-WMC. Results are most consistent with the so-called *memory mixing*, *weak lapsed attention*, and *weak temporal resolution power hypotheses*. These predicted low-WMC reproductions to be 2) *more variable* than high-WMC. The memory mixing hypothesis was most direct about correctly predicting low-WMC to show the 3) *migration effect/Vierordt's Law* more than high-WMC.

The so-called *cognitively controlled timing* hypothesis uniquely predicted WMC to distinguish reproductions at 4) *supra-second not sub-second* durations. However, high-WMC and low-WMC reproductions differed in the sub-second range. Assuming that individual differences in WMC primarily reflect individual differences in cognitive control, results suggest that the transition point between automatic/pre-attentive timing and cognitively controlled timing may not be fixed at 1 s (see also Grondin, 2010; Macar & Vidal, 2009). However sub-second and supra-second time durations were confounded with "shortest" and "longest" in the present task. This raises concern about extraneous influences from motor skills/RT. We addressed this specific confound in Experiment 3.

Both groups were more variable at reproducing the shortest compared to the longest durations. This shows a common transgression of the "scalar property" (Weber's Law applied to timing), that predicts reproduction variability to remain a constant proportion of the target duration over a range of intervals. (Conformity to Weber's Law would have been observed as constant CV across target durations.) Such transgressions are commonly observed in timing (Grondin, 2010) and psychophysical studies generally (often involving the smallest magnitude in a range; Gescheider, 1997; as in the present experiment). Here

the effect may be plausibly attributed to motor skills/RT, especially for reproductions of the shortest/sub-second duration (500 ms) versus longer/supra-second ones (1500 ms and 2500 ms). This raises concern that the selective over-estimation of the shortest duration by low-WMC was perhaps due to motor skills/RT and not to cognitively mediated “time perception.” Specifically, perhaps low-WMC reproductions were selectively too long for the shortest duration because they were (selectively) more variable for the shortest. However, this argument might be countered by noting that low-WMC reproductions were selectively too long but *not* selectively more variable for the shortest duration. Reproductions by both WMC groups were more variable for the shortest versus longest durations. Furthermore, low-WMC reproductions were more variable than high-WMC for the intermediate duration – but here WMC groups were equally accurate (unbiased). We cannot totally discount contributions from motor skills/RT, especially given the dependence of temporal reproductions on timed motor responses. In subsequent experiments we sought to further isolate timing effects due to WMC from those possibly due to motor skills/RT.

To summarize, Experiment 1 demonstrated substantial WMC-related differences in temporal judgment using the method of reproduction. However, showing that individuals who differ in WMC also differ in temporal judgment does not imply that the latter function depends on the former. In the following experiment we addressed two prominent alternatives to WMC: motor skills/RT and *gF*.

6. Experiment 2

In Experiment 2 we examined whether WMC-related differences in temporal reproduction would be much altered with more complex response requirements and a concurrent non-temporal task. Temporal reproduction involves a degree of motor control unrelated to “time perception” per se. For example, Droit-Volet (2010) argued that temporal reproduction errors for short durations are influenced by slower latencies to initiate responses terminating reproductions. Recall that our procedure in Experiment 1 was expressly designed to minimize such concerns. Observers had only to press, hold, and release a single key to initiate, maintain, and terminate reproductions, respectively. (As noted earlier this procedure was intended to limit variability unrelated to temporal judgment per se, such as keyboard unreliability, inattention, and motor skills/RT.) Notably in Experiment 1 reproductions by both WMC groups were on average within the bounds of $\pm 10\%$ of the target duration, i.e., the criterion for “correct” feedback (see again Table 1 or Fig. 1A). This suggests that the key-release procedure was fairly effective for its purposes. Still WMC-related differences in motor skills/RT may have contributed to certain critical results, e.g., the selective over-estimation by low-WMC reproductions for the sub-second/shortest target duration (500 ms).

After finding WMC-related differences in a task that already presents minimal interference, one immediate follow-up strategy is to impose additional task requirements to divide attention. Thus high-WMC participants might be induced to perform more like low-WMC under conditions of increased interference (cf. Kane & Engle, 2000). Experimental work has shown that time estimation is less accurate when attention must be shared between processing temporal and non-temporal information (see e.g., Block et al., 2010). Furthermore, WMC is sensitive to response complexity in choice RT tasks (Schmiedek, Oberauer, Wilhelm, Süß, & Wittmann, 2007). Therefore, in Experiment 2 we required participants to make a non-temporal choice concurrently with temporal reproductions.

WMC, *gF*, and temporal processing are strongly inter-related (Troche & Rammsayer, 2009). This raises a concern that the apparent WMC-related effects on temporal reproduction in Experiment 1 were spuriously due to shared relations with *gF*. Therefore in Experiment 2 we assessed contributions from *gF* (known also to correlate strongly with simple and choice RT; Jensen, 1993). Following the work by Troche and Rammsayer (2009), we expected *gF* to account for substantial

variance in temporal reproduction in common with WMC, but that WMC would still show relationships to timing over and above contributions from *gF*.

7. Experiment 2: Method

7.1. Participants

A total of 52 individuals (27 high-WMC, 15 women; 25 low-WMC, 16 women) participated in Experiment 2. None had participated in Experiment 1. We had *gF* measures for 44 of these participants (high-WMC, $n=22$; low-WMC, $n=22$) from their participation in other studies. We report results from only these 44 participants so *gF* could be included as a covariate in ANCOVA (ANOVA results from the full sample were similar to those from the reduced sample). WMC measurement and recruitment procedures were the same as Experiment 1. Participants returned to the lab to perform the temporal reproduction task in Experiment 2 in a session lasting approximately 60 min. Measured WMC was statistically different between groups, $t(42) = -11.63$, $p < .001$ (high-WMC $M = .895$, $SD = .394$; low-WMC $M = -1.064$, $SD = .707$).

7.2. Ravens matrices

We had scores from two related measures of *gF* for two different sub-sets of participants in Experiment 2. For one sub-set (high-WMC $n=11$; low-WMC $n=12$), we had scores from a 12-item set of Raven's matrices (Raven, Raven, & Court, 1998). Participants had 5 min to complete twelve problems administered by computer. Participants selected (by mouse click) from an array of choices shown at the bottom of the screen the figure that would best complete an abstract matrix. One point was assigned for each correct response, making the possible range (0, 12). In previous large-sample correlational work this *gF* test correlated strongly with the same measures of WMC used in the present work, (Operation Span $r = .49$, Symmetry Span $r = .51$; Unsworth et al., 2009). For a different sub-set (high-WMC $n=11$; low-WMC $n=10$), we had scores from an 18-item set of Raven's matrices. Participants had 10 min to complete 18 problems, but otherwise procedures were the same as in the 12-item test. One point was assigned for each correct response, making the possible range (0, 18). In previous correlational work (involving two large samples) this *gF* test correlated strongly with the same measures of WMC used in the present work (Operation Span $r_s = .42$ and $.50$, Symmetry Span $r_s = .56$ and $.62$; Broadway & Engle, 2010). To facilitate combining data across test-versions, raw scores were converted to proportion-correct.

7.3. Procedure

7.3.1. Temporal reproduction task

Participants performed the temporal reproduction task after first performing a temporal discrimination task (not reported) in a session lasting approximately 60 min. In the demonstration phase the word “INTERVAL” appeared to define the target duration. Target durations were the same as in Experiment 1 (500 ms, 1500 ms, or 2500 ms). Participants pressed the ‘Enter’ key to proceed to the reproduction phase. Participants pressed and released the ‘space’ bar to initiate reproductions. Participants terminated reproductions with a second key-press as part of a concurrent non-temporal task, described below. There were 10 trials per block and 5 blocks per duration in Experiment 2. Feedback concerning temporal reproductions was provided as in Experiment 1.

7.3.2. Concurrent non-temporal task

An arrow pointing left or right appeared centrally on the screen when participants initiated their reproductions. Participants were

prompted on each trial to terminate their reproductions by pressing (at the appropriate time) the 'n' key if the arrow pointed right or the 'b' key if the arrow pointed left. Left- or right-pointing arrows were equally likely on each trial. Feedback was not provided concerning the non-temporal task.

8. Experiment 2: Results

8.1. Concurrent non-temporal task

High-WMC were slightly more accurate than low-WMC at performing the concurrent non-temporal task across the range of target durations (see Table 2). ANOVA revealed no statistically significant effects of target duration, WMC, or the interaction.

8.2. Temporal reproduction accuracy (bias)

Only trials in which the concurrent non-temporal task was performed correctly were included in the following analyses. No outliers were identified. Means and standard deviations for median absolute errors across are presented in Table 1. Reproduction ratios were analyzed statistically as in Experiment 1. See Fig. 2 (A; three left-most, not starred). A 3 (Target Duration: 500 ms, 1500 ms and 2500 ms) × 2 (WMC: High and Low) mixed model ANOVA revealed a significant main effect of target duration, $F(2, 41) = 13.26, p < .001, \eta_p^2 = .240$. The main effect of WMC was not significant, $F < 1$, but the interaction of WMC with target duration was significant, $F(2, 41) = 7.87, p = .004, \eta_p^2 = .158$. These results are much the same as in Experiment 1. Pair-wise comparisons for the effect of target duration indicated that reproduction ratios for the shortest duration were greater than those for the longest, $p = .001$, and greater than those for the intermediate, $p = .007$; also ratios for the intermediate duration were greater than those for the longest, $p = .014$. Reproduction ratios were overall monotonically decreasing with increasing target duration.

Independent sample t-tests at the shortest (500 ms), longest (2500 ms), and intermediate (1500 ms) durations indicated that the difference between low-WMC and high-WMC reproduction ratios did not reach statistical significance for the shortest, $t(42) = 2.40, p = .075$, the longest, $t(42) = -1.82, p = .249$, or the intermediate, $t(42) = -.886, p = 1$. Pair-wise comparisons indicated that low-WMC reproduction ratios for the shortest were significantly greater than those for the intermediate, $p = .016$, and greater than those for the longest, $p = .005$. Ratios for the intermediate were not greater than those for the longest, $p = .085$. In contrast, high-WMC reproduction ratios for the shortest duration were not significantly different from those for the intermediate, $p = 1$, nor were they different from those for the longest, $p = .237$; ratios for the intermediate duration were greater than those for the longest, $p = .046$.

Thus low-WMC reproduction ratios were monotonically decreasing with increasing duration. In contrast, high-WMC reproduction ratios

Table 2

Means (standard deviations) of proportions of correct responses in the concurrent non-temporal task in Experiments 2 and 3.

Experiment 2					
	500 ms	1500 ms	2500 ms		
High	.968 (.077)	.974 (.115)	.972 (.111)		
Low	.886 (.166)	.906 (.189)	.906 (.186)		
Experiment 3					
	1500 ms	2500 ms	3500 ms	4500 ms	5500 ms
High	.978 (.085)	.981 (.083)	.979 (.084)	.980 (.083)	.979 (.083)
Low	.971 (.072)	.977 (.081)	.973 (.086)	.974 (.084)	.969 (.085)

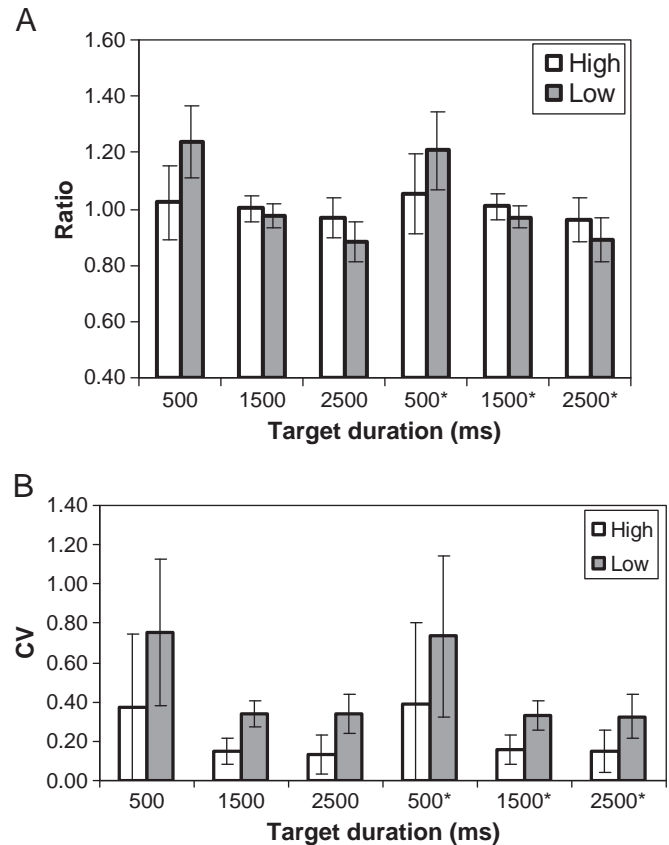


Fig. 2. Experiment 2: (A) Means of median reproduction ratios (not starred) and with gF as covariate (starred). (B) Means of reproduction coefficients of variation (not starred) and with gF as covariate (starred). Error bars represent 95% confidence intervals. Legends refer to WMC groups.

were about the same between shortest and intermediate; but like low-WMC, high-WMC reproductions were too short for the longest. Overall, low-WMC showed the migration effect/Vierordt's Law to a greater extent than high-WMC, as in Experiment 1. 13 (out of 22) low-WMC and 10 (out of 22) high-WMC individually over-estimated the shortest and under-estimated the longest durations. Unlike in Experiment 1, this association was not statistically significant, $\chi^2(1) = 1.45, p = .175$.

8.2.1. Fluid intelligence as covariate

Including gF as covariate accounted for substantial variance in reproduction accuracy (bias). See Fig. 2 (A; three right-most, starred). Compared to ANOVA, the main effect of target duration was attenuated (but still statistically significant) in ANCOVA, $F(2, 40) = 5.327, p = .017, \eta_p^2 = .086$; the main effect of WMC was not significant (like in the ANOVA), $F < 1$, and compared to ANOVA, the interaction of target duration with WMC was attenuated (although not completely removed), $F(2, 40) = 3.25, p = .069, \eta_p^2 = .073$. Results indicate that variance in temporal reproductions was related to gF as well as to WMC. The main effect of gF was not statistically significant, $F(1, 41) = .638, p = .429, \eta_p^2 = .015$; neither was the interaction of target duration with gF , $F(2, 40) = 1.63, p = .209, \eta_p^2 = .038$. However, like WMC, lower gF was related to greater tendency to show the migration effect/Vierordt's Law. Spearman's rank-order correlation⁶ between gF and the migration effect/Vierordt's Law (estimated for each individual

⁶ Spearman's rank-order correlations were used because we had formed the WMC variable by pre-selecting the sample (the extreme-groups' technique), although in principle the factors for gF and the migration effect/Vierordt's Law were still free to vary. Pearson's product-moment correlations did not lead to different conclusions.

as the average difference between reproduction ratios for shortest and longest durations) was statistically significant, $\rho = -.309$, $p = .041$.

8.3. Temporal reproduction variability

See Fig. 2 (B; three left-most, not starred). A 3 (Target Duration: 500 ms and 1500 ms, 2500 ms) \times 2 (WMC: High and Low) mixed-model ANOVA revealed statistically significant main effects of target duration, $F(2, 41) = 5.96$, $p = .017$, $\eta_p^2 = .124$, and WMC, $F(1, 42) = 6.97$, $p = .012$, $\eta_p^2 = .142$. The interaction of target duration with WMC was not statistically significant, $F < 1$. These results are consistent with Experiment 1. Pair-wise comparisons for the effect of target duration indicated reproduction variability for the shortest was not greater than for the longest, $p = .056$, or greater than for the intermediate, $p = .052$ (although these differences fell just short of statistical significance). Reproduction variability for the intermediate duration was not different from that for the longest, $p = 1$.

8.4. Fluid intelligence as covariate

Including gF as covariate accounted for substantial variance in reproduction variability. See Fig. 2 (B; three right-most, starred). The main effect of target duration was not statistically significant in ANCOVA, $F < 1$ (unlike the previous ANOVA), and compared to ANOVA, the main effect of WMC was attenuated (although not completely removed), $F(1, 41) = 3.95$, $p = .054$, $\eta_p^2 = .088$. The interaction of target duration with WMC group was not statistically significant, $F < 1$ (like ANOVA). The main effect of gF was not statistically significant; neither was the interaction of target duration with gF , $F < 1$. However, like WMC, lower gF was related to greater reproduction variability. Spearman's rank-order correlation between gF and reproduction CV for the shortest duration was not significant, $\rho = -.256$ (although in the expected direction), $p = .094$; but was significant for the intermediate, $\rho = -.345$, $p = .022$; and the longest, $\rho = -.354$, $p = .018$.

9. Experiments 2: Discussion

As in the much simpler reproduction task in Experiment 1, the migration effect/Vierordt's Law was more pronounced for low-WMC observers compared to high-WMC. In the present experiment, response complexity and a concurrent non-temporal task were not sufficient to make reproductions by WMC groups more similar, i.e., to make high-WMC behave more like low-WMC. However, performance overall appeared somewhat worse compared to Experiment 1 (Table 1), perhaps suggesting that the concurrent non-temporal task and greater response complexity were effective in distracting attention away from time.

As in the much simpler task in Experiment 1, low-WMC reproductions were more variable than high-WMC, and both groups showed greater variability for the shortest target duration compared to longer ones. These findings had suggested a possible contribution from motor skills/RT to temporal reproduction. Specifically, it seemed plausible that the migration effect/Vierordt's Law shown by low-WMC could be accounted for by motor variability when reproducing the shortest (sub-second) target duration. However, results of Experiments 1 and 2 suggest that the migration effect/Vierordt's Law shown predominantly by low-WMC observers was somewhat independent of WMC-related differences in reproduction variability.

The migration effect/Vierordt's Law was related to variance common to both WMC and gF . Including gF as covariate attenuated but did not completely remove the interaction of WMC and duration, whereby low-WMC showed the migration effect/Vierordt's Law to a greater extent. Like WMC, gF was related to reproduction variability. Including gF as covariate attenuated but did not completely remove the main effect of WMC on reproduction variability. In contrast, the

effect of greater reproduction variability for the shortest target duration was completely removed by accounting for gF . To summarize, results imply a fairly reliable and general relationship between WMC and temporal processing, over and above contributions from motor skills/RT and gF , and consistent with the few previous studies to address these questions (e.g., Troche & Rammsayer, 2009).

10. Experiment 3

The memory mixing account of the migration effect/Vierordt's Law implies that the direction of temporal reproduction errors should not depend much on the absolute durations tested. Instead, temporal reproductions should tend to be too long for the shortest, and too short for the longest durations, in a manner that is *context-dependent*. Experiment 3 was designed specifically to test this idea, and to further dissociate contributions from motor skills/RT. High- and low-WMC observers in Experiment 3 performed temporal reproductions for a larger set of longer target durations (1500 ms, 2500 ms, 3500 ms, 4500 ms, and 5500 ms). This also allowed us to extend upward the range of time scales at which WMC might predict temporal judgment.

Note that the shortest duration here (1500 ms) was the same length as intermediate durations in the previous experiments. Likewise, the intermediate duration here (3500 ms) was longer than the longest durations in the previous experiments. Finally, the longest duration here (5500 ms) was much longer than durations in previous experiments. These correspondences across experiments suggested the following *temporal context* and *absolute duration* hypotheses.

If the direction of temporal reproduction errors depends mainly on *temporal context* instead of absolute duration, low-WMC observers should selectively over-estimate the shortest target duration in Experiment 3 (1500 ms), even though the same absolute duration had been accurately estimated when it was intermediate in previous experiments. Additionally, low-WMC observers should accurately estimate the intermediate target duration in Experiment 3 (3500 ms) even though this is longer than the absolute durations in previous experiments.

In contrast, if the direction of temporal reproduction errors depends primarily on *absolute duration*, the shortest target duration (1500 ms) in Experiment 3 should be accurately estimated by low-WMC, because the same absolute duration had been accurately estimated in previous experiments. Furthermore, we expected to clarify contributions from motor skills/RT in Experiment 3, because the shortest target duration was supra-second (1500 ms); therefore the confounding in previous experiments of "shortest/sub-second" target durations was absent.

11. Experiment 3: Method

11.1. Participants

A total of 71 individuals (36 high-WMC, 17 women; 35 low-WMC, 17 women) participated in Experiment 3. None had participated in Experiments 1 or 2. WMC measurement and recruitment for Experiment 3 were the same as in the previous experiments. Participants returned to the lab to perform the temporal reproduction task in a session lasting approximately 60 min. Measured WMC was statistically different between groups, $t(69) = -13.53$, $p < .001$ (high-WMC $M = .835$, $SD = .461$; low-WMC $M = -1.06$, $SD = .713$).

11.2. Procedure

11.2.1. Temporal reproduction task

Procedures were as in Experiment 2, except for a larger set of longer target durations (1500 ms, 2500 ms, 3500 ms, 4500 ms, and 5500 ms). There were 10 trials per block and 5 blocks per target duration in Experiment 3. As in Experiment 2, temporal reproductions

were terminated by a choice response as part of a concurrent non-temporal judgment task. This procedure was retained from Experiment 2 but effects were not expected.

12. Experiment 3: Results

12.1. Concurrent non-temporal task

High-WMC participants were slightly more accurate at judging whether arrows pointed left or right during temporal reproductions. See Table 2. ANOVA revealed no statistically significant effects of target duration, WMC, or the interaction (as in Experiment 2).

12.2. Temporal reproduction accuracy (bias)

Trials in which the concurrent non-temporal task was performed correctly were included in analyses of temporal reproduction accuracy (bias) and variability. No outliers were identified. Means and standard deviations for median reproduction errors across target durations are presented in Table 1. Reproduction ratios were analyzed as in Experiments 1 and 2. See Fig. 3 (A). A 5 (Target Duration: 1500 ms, 2500 ms, 3500 ms, 4500 ms, and 5500 ms) \times 2 (WMC: High and Low) mixed model ANOVA revealed a significant main effect of target duration, $F(4, 66) = 14.80, p < .001, \eta_p^2 = .177$; the main effect of WMC was not significant, $F < 1$; the interaction of target duration with WMC significant, $F(4, 66) = 3.51, p = .020, \eta_p^2 = .048$. Results are all consistent with the previous experiments.

Pair-wise comparisons for the effect of target duration indicated that reproduction ratios for the shortest duration were greater than those for the longest, $p < .001$, and greater than those for the intermediate, $p = .035$; also reproduction ratios for the intermediate

duration were greater than those for the longest, $p < .001$. Independent sample *t*-tests at the shortest (1500 ms), longest (5500 ms), and intermediate (3500 ms) durations indicated that the difference between low-WMC and high-WMC reproduction ratios was not significant for the shortest, $t(69) = 1.89, p = .189$; nor for the longest, $t(69) = -.975, p = 1$; nor for the intermediate, $t(69) = -.635, p = 1$. Pair-wise comparisons indicated that low-WMC reproduction ratios for the shortest duration were significantly greater than those for the intermediate, $p = .037$, and greater than those for the longest, $p = .002$; reproduction ratios for the intermediate duration were not significantly greater than those for the longest, $p = .090$. In contrast, high-WMC reproduction ratios for the shortest duration were not different from those for the intermediate, $p = 1$, but were significantly greater than for the longest, $p = .014$; also high-WMC ratios for the intermediate duration were greater than for the longest, $p = .002$.

Thus low-WMC reproduction ratios were monotonically decreasing with increasing durations (like in the previous experiments). High-WMC reproduction ratios were again about the same for the shortest and intermediate durations (like in the previous experiments) but were too short for the longest (unlike in the previous experiments). 20 out of 36 low-WMC and 15 out of 35 high-WMC individually over-estimated the shortest and under-estimated the longest durations. This association was not statistically significant, $\chi^2(1) = .693, p = .625$.

12.3. Temporal reproduction variability

CVs were calculated and analyzed as in Experiments 1 and 2. See Fig. 3 (B). A 5 (Target Duration: 1500 ms, 2500 ms, 3500 ms, 4500 ms and 5500 ms) \times 2 (WMC: High and Low) mixed model ANOVA indicated that the main effect of target duration was not significant (unlike in the previous experiments), $F(4, 66) = 2.06, p = .106, \eta_p^2 = .029$. The main effect of WMC was significant (like in the previous experiments), $F(1, 69) = 10.58, p = .002, \eta_p^2 = .133$. The interaction of target duration with WMC was not significant (like in the previous experiments), $F(4, 66) = 1.05, p = .371, \eta_p^2 = .015$. Low-WMC reproductions were more variable than high-WMC (like in the previous experiments).

13. Experiment 3: Discussion

The pattern of temporal reproduction errors in Experiment 3 was similar to Experiments 1 and 2, but with longer absolute durations corresponding to “shortest,” “longest,” and “intermediate” target durations. Results across experiments suggest that the direction of temporal reproduction errors is largely *context-dependent* and sensitive to individual differences in WMC. Low-WMC reproductions were more variable than high-WMC, as in the previous experiments. Results across experiments suggest that the tendency for low-WMC reproductions to show the migration effect/Vierordt's Law is not entirely attributable to motor skills/RT. Among the mechanisms considered in this article, this tendency could be due to lapsed attention (combined with confused memories) for elapsed time. At a deeper level these functional deficits could depend on poor neural efficiency and/or coordination.

14. General discussion

We examined individual differences in WMC in relation to temporal processing in three experiments. We assumed that WMC would be necessary for performing temporal reproduction tasks because a person would need to encode and maintain access to two distinct representations of elapsed time in an ongoing dynamic manner, for comparison and temporal judgment. Furthermore we assumed that the quality of these representations would depend on how consistently attention was allocated to judging time. High-WMC

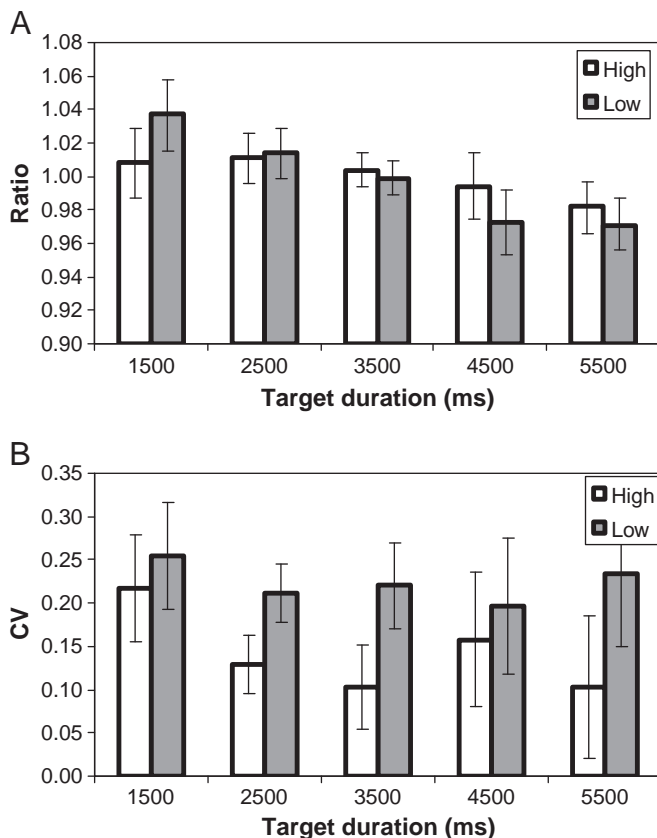


Fig. 3. Experiment 3: (A) Means of median reproduction ratios. (B) Means of reproduction coefficients of variation. Error bars represent 95% confidence intervals. Legends refer to WMC groups.

reproductions were generally more accurate (unbiased) and less variable than low-WMC. Thus our basic predictions were confirmed.

In Experiment 1, reproduction accuracy (lack of bias) showed a basic pattern (and a template for subsequent experiments). Low-WMC reproductions were consistently too long for the shortest duration (but high-WMC were more accurate), and were too short for the longest duration (but high-WMC were more accurate); while both WMC groups were equally accurate (unbiased) for the intermediate duration. Thus low-WMC showed the classic migration effect/Vierordt's Law more than high-WMC did. Reproduction variability also showed a basic pattern: Decreasing variability with increasing durations (for both WMC groups), and greater variability for low-WMC compared to high-WMC.

To facilitate interpretation we generated four relatively distinct hypotheses by combining assumptions from separate WMC and timing literatures. Results were not very consistent with the so-called *arousal*, *strong lapsed attention*, and *strong temporal resolution power* hypotheses: These predicted low-WMC reproductions to be 1) *consistently too short and/or shorter* than high-WMC. Results were more consistent with the so-called *memory mixing*, *weak lapsed attention*, and *weak temporal resolution power* hypotheses: These predicted low-WMC reproductions to be 2) *more variable* than high-WMC. Among these, the memory mixing hypothesis was most direct in predicting low-WMC to show 3) the *migration effect/Vierordt's Law*. Results were not very consistent with the so-called *cognitively controlled timing* hypothesis, which uniquely predicted WMC to distinguish temporal reproductions for 4) *supra-second but not sub-second* time scales.

14.1. Lapsed attention to elapsed time?

Variability and precision are clearly inter-related measurement concepts. The present article documents the close association of temporal reproduction variability with a consistent bias to over-estimate shorter durations and under-estimate longer ones, i.e., to show the migration effect/Vierordt's Law. As noted, any of the hypotheses considered that predicted low-WMC reproductions to be more variable than high-WMC can also explain the tendency for low-WMC to show a greater migration effect/Vierordt's Law. This is because in the long run a more variable system will have more opportunities to "over-shoot" relatively short durations and "under-shoot" relatively long ones, whether this is due to lapsed attention, memory mixing, or poor neural efficiency and/or coordination. Additional work is needed to separate these influences on temporal judgment.

14.2. Alternatives to WMC

Experiment 2 addressed contributions from motor skills/RT and *gF*. Observers reproduced the same set of target durations as in Experiment 1, but with increased response complexity and a concurrent non-temporal task; *gF* was included as a covariate. Task changes did not lead to a greatly altered set of findings. High-WMC observers were not induced to behave more like low-WMC, and low-WMC behaved much like their counterparts in Experiment 1. Including *gF* as covariate attenuated but did not completely remove the tendency for low-WMC to show the migration effect/Vierordt's Law, even though lower *gF* was also associated with this tendency. Lower *gF* was also related to greater reproduction variability. Notably, including *gF* as covariate completely removed the effect in which reproductions (by both WMC groups) were more variable for the shortest duration versus longer ones. However the overall difference between WMC groups for reproduction variability was attenuated but not completely removed by including *gF* as covariate. Overall, Experiment 2 provided a novel "micro-analytic" treatment of the interplay of WMC, temporal processing and *gF*, converging with the limited amount of previous "macro-analytic" work in this area (i.e., Troche & Rammsayer, 2009).

Experiment 3 further isolated contributions from motor skills/RT. With a set of (mostly) longer absolute durations, low-WMC reproductions again showed the migration effect/Vierordt's Law to a greater extent than high-WMC. Here the shortest target duration was supra-second, and the same absolute duration as the intermediate target duration in the previous experiments (which had been accurately reproduced by both WMC groups). Furthermore the effect of duration on reproduction variability observed in the previous experiments (in which reproductions by both WMC groups had been more variable for the shortest duration versus longer ones) was absent in Experiment 3. Together these results imply differences in reproduction accuracy (bias) due to differences in WMC, over and above contributions from motor skills/RT. Experiment 3 also showed that the migration effect/Vierordt's Law is largely *context-dependent* (as well as sensitive to WMC and *gF*).

15. Summary and conclusions

The present work adds to the few existing studies examining individual differences in WMC in relation to temporal judgment in the population of healthy younger adults. Using the method of reproduction, low-WMC showed a classic "migration effect" (Vierordt's Law) more than high-WMC, and were more variable. Low-WMC showed evidence of lapsed attention and/or confused memories for elapsed time. Such deficits could depend on poor neural efficiency and/or coordination.

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