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A Role for Memory in Prospective Timing informs Timing in Prospective Memory

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Abstract

Time-based prospective memory (TBPM) tasks require the estimation of time in passing – known as prospective timing. Prospective timing is said to depend on an attentionally-driven internal clock mechanism, and is thought to be unaffected by memory for interval information (for reviews see, Block, Hancock, & Zakay, 2010; Block & Zakay, 1997). A prospective timing task that required a verbal estimate following the entire interval (Experiment 1) and a TBPM task that required production of a target response during the interval (Experiment 2) were used to test an alternative view that episodic memory does influence prospective timing. In both experiments, participants performed an ongoing lexical decision task of fixed duration while a varying number of songs were played in the background.

Experiment 1 results revealed that verbal time estimates became longer the more songs participants remembered from the interval, suggesting that memory for interval information influences prospective time estimates. In Experiment 2, participants who were asked to perform the TBPM task without the aid of an external clock made their target responses earlier as the number of songs increased, indicating that prospective estimates of elapsed time increased as more songs were experienced. For participants who had access to a clock, changes in clock-checking coincided with the occurrence of song boundaries, indicating that participants used both song information and clock information to estimate time. Finally, ongoing task performance and verbal reports in both experiments further substantiate a role for episodic memory in prospective timing.

Keywords

prospective memory; time estimation; time perception; duration

Attending a meeting at 2:00 pm, removing hair dye after 10 minutes, stopping by the grocery store to pick up milk – what do all these tasks have in common? They are tasks that need to be performed at an appropriate point in the future, otherwise known as prospective memory tasks. Such tasks are ubiquitous in everyday life, and failure to successfully perform them can cause not only minor annoyance or stress, but it can also have potentially damaging consequences for one's physical health (e.g., forgetting to take medication).

Two types of prospective memory scenarios are typically distinguished in the literature – *event-based prospective memory* (EBPM), which involves remembering to perform a task in response to a specific external cue, and *time-based prospective memory* (TBPM), which

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involves remembering to perform a task either at a specific future time or after a certain amount of time has passed. Although great strides have been made toward understanding the mechanisms of EBPM (e.g., Einstein & McDaniel, 1996; McDaniel & Einstein, 2000; Smith, 2003), there is still a paucity of studies examining the mechanisms of TBPM, of which time estimation is thought to be a central component (e.g., Block & Zakay, 2006, Cockburn, 2006; Graf & Grondin, 2006; Harris & Wilkins, 1982; Jager & Kliegel, 2008; Kvavilashvili & Fisher, 2007; Labelle, Graf, Grondin, & Gagne'-Roy, 2009; Mantyla & Grazia-Carelli, 2006; Park, Herzog, Kidder, Morrell, & Mayhorn, 1997). Despite wide agreement that time estimation plays a critical role in TBPM, there is a clear lack of integration between research in the TBPM and the time estimation domains. Therefore, the goal of the current research was to utilize experimental paradigms from both fields to investigate how time estimation processes contribute to TBPM performance.

Retrospective and Prospective Time Estimation

Block and Zakay (2006) proposed the only TBPM model to date that draws upon time estimation research. This model distinguishes between two types of timing -- retrospective timing and prospective timing. For instance, to answer the question: “How long was your drive?” one must make a *retrospective time estimate* –that is, an unexpected time estimate of a past interval. Conversely, *prospective time estimates* are those that people expect to make and are used in situations where it is important to keep track of time in passing, such as in TBPM tasks.

Retrospective and prospective timing are studied in the lab using similar methods. For instance, the verbal estimation method requires that an estimate described in minutes and seconds be made following the completion of a target interval. While verbal estimates are made unexpectedly in the retrospective paradigm, participants in the prospective paradigm are warned of the upcoming estimation requirement. Time estimation can also be studied using methods other than verbal responses. For instance, the production method is often used to study prospective timing and requires participants to make a target response once they estimate that a specific target duration has elapsed.

Early experiments conducted using different methods of estimation revealed double dissociations between retrospective and prospective estimates. Specifically, researchers found that manipulations varying memory for interval information (e.g., the number of context changes or segments experienced during the task) affected retrospective but not prospective estimates, whereas manipulations varying the amount of attention required by the task (e.g., processing difficulty) affected prospective but not retrospective estimates (e.g., Block, 1992; Hicks, Miller, & Kinsbourne, 1976). These double-dissociations have convinced many researchers that prospective estimates are determined by attentional processes, and that retrospective estimates are driven by memory processes (for reviews, see Block, Hancock, & Zakay, 2010; Block & Zakay, 1997).

Block and Zakay (2006) state that because people are aware that accurate timing is essential to successful TBPM performance, TBPM tasks require prospective time estimation. Therefore, they conclude that the same timing mechanisms outlined in their attentional-gate model of prospective timing also likely contribute to TBPM performance. The attentional-gate model of prospective timing (Zakay & Block, 1996) is an internal-clock model wherein a pacemaker mechanism produces temporal “pulses” which pass through an attentional-gate and into an accumulator. Prospective estimates arise from a cognitive comparison between the contents of the accumulator and pulse count information stored in long-term duration reference memories. For instance, a verbal prospective estimate of two minutes may be given following an interval because the number of pulses collected in the accumulator best matches the pulse count associated with the two minute reference memory. If a response is to be produced after two minutes, the number of pulses collected in the accumulator is continuously transferred to working memory where it is then compared with the pulse count of the two minute reference memory. In this case, a production response is made only once the pulse count held in working memory matches that of the reference memory. The attentional-gate is a vital component of this model, because it determines the rate at which pulses reach the accumulator. This gate opens only when the passage of time is actively monitored, and remains closed when attention is devoted to other tasks. Therefore, temporal pulses will accumulate more quickly and a match between the pulse counts of working memory and the duration reference memory will occur earlier as time is monitored to a greater extent. As a result, production responses are made *earlier* when more attention is devoted to monitoring time than when time is monitored to a lesser extent. Additionally, verbal estimates, which are made based on the total number of pulses accrued during an entire interval, will *lengthen* as time is monitored to a greater extent.

Many prospective timing studies support Zakay and Block’s (1996) attentional-gate model. For instance, when attention is divided between prospective timing and an ongoing task, not only does ongoing task performance suffer compared to single task conditions, but prospective estimates also decrease resulting in shorter verbal estimates and later productions (e.g., Brown & Stubbs, 1992; Brown, 1997; Brown, 2006; Brown & Merchant, 2007). Prospective estimates also decline when an ongoing task is complex compared to when it is simple (e.g., Brown & Boltz, 2002; Block, 1992; Hicks et al., 1976; Zakay & Block, 2004, Zakay, Nitzan, & Glicksohn, 1983). Finally, when participants are informed that the timing task is more important than an additional ongoing task, performance on the ongoing task decreases and prospective estimates increase compared to when the ongoing task is emphasized over the timing task (e.g., Kladopoulos, Hemmes, & Brown, 2004; Labelle et al, 2009; Macar, Coull, & Vidall, 2006; Macar, Grondin, & Casini, 1994; Zakay, 1998). Together, these findings suggest that prospective timing is attentionally demanding, and that as more attentional resources are devoted to monitoring time, fewer resources are available for ongoing task performance.

Block and Zakay (2006) extended their attentional gate model of prospective timing to TBPM via addition of an intention retrieval component. They explain that just as in a time production task, temporal pulses are collected in the accumulator when one attends to the passage of time during a TBPM task. Once the number of pulses collected matches that of the TBPM target response time, the internal clock signals that it is time to make a TBPM response. At this point, the intention must be successfully retrieved from long term memory to be performed. Therefore, according to Block and Zakay’s model, TBPM failure can occur either if the intention is forgotten, or if the intention is remembered but prospective timing is inaccurate. Unlike Block and Zakay’s (2006) TBPM model, their original prospective timing model does not include an explicit intention retrieval component (Zakay and Block, 1997). This is likely the case because prospective timing tasks are designed so that intention memory plays little, if any, role in participants’ ability to make a time estimate. For instance, in the verbal estimation method, the experimenter elicits a time estimate, thus negating the need for intention memory all together. Like TBPM tasks, the production method does require that participants produce a target response on their own. However, this method has most often been used with durations in the seconds range (Block & Zakay, 2006), and participants routinely make over 100 productions in a single experiment (e.g. Gil & Droit-Volet, 2011). Overall, the short duration and repetitiveness of these production tasks makes it very unlikely that the production response will be forgotten. As a result, the role of intention memory is negligible in these tasks. Production has also been used with longer durations, and in these cases, additional measures, such as displaying visual reminders of the target time, are used to minimize intention memory requirements (e.g. Craik & Hay, 1999).

While the need for intention memory is often eliminated entirely in prospective timing tasks, self-initiated retrieval of intention memory is always required in TBPM tasks. McDaniel and Einstein (2007b) explain that while the intention must be retrieved for successful PM performance, they also note that the memorability of PM intentions can fall anywhere along a continuum. Therefore, like production tasks, some TBPM intentions may be very easy to remember (e.g. go back to work after a 30 min lunch), while others may be very difficult to remember (e.g. go to doctor appointment next Tuesday at 3pm). Traditionally, TBPM experiments have replicated scenarios in which the intention is difficult to remember by using durations that span minutes rather than seconds as in prospective timing tasks (Block & Zakay, 2006). Additionally, compared to the hundreds of production responses required in a single prospective timing experiment, participants typically complete only one (e.g. Cook et al., 2005) to five (e.g. Jager & Kleigel, 2008) TBPM responses during a single session to ensure that the intention does not become too routine and thus very easy to remember. Experimenters have also increased the likelihood that the TBPM intention will be forgotten by using measures such as explicitly labeling the ongoing task as the primary task (e.g. Park et al. 1997), by allowing participants to practice the ongoing task but not the TBPM task (e.g. Jager & Kleigel, 2008), and by including delays between TBPM instructions and task performance (e.g. Cook et al. 2005).

While previous TBPM studies were largely designed to investigate the role of intention memory rather than time estimation, there is indirect evidence from these studies to support Block and Zakay's (2006) view that the same attentionally demanding time estimation processes involved in prospective timing tasks are involved in TBPM situations. Particularly, decreases in ongoing task performance have been observed with the addition of a TBPM task – known as 'costs' (e.g., Hicks, Marsh, Cook, 2005; Marsh, Hicks, & Cook, 2006; Smith, 2003). While the observation of costs is often attributed to monitoring for the target event in EBPM studies (e.g., McDaniel & Einstein, 2007a; McDaniel & Einstein, 2007b; Smith, 2003), there is no target event embedded within TBPM tasks for which to monitor. Therefore, it is likely that TBPM costs arise, at least in part, because attentional resources are allocated to monitoring time.

There is only one previous study, of which we are aware, that was specifically designed to investigate the timing component of TBPM (Labelle et al., 2009). In this study, participants were asked to produce a target response after either 30, 60, or 90 seconds of a category decision task had elapsed. In one condition, participants were allowed to use a clock to make these responses, while in another condition, no clock was provided. Unsurprisingly, time-based responses were more accurate when participants could check a clock than when no clock was available. More interesting perhaps was that reaction times to the lexical decision task were slower in the no-clock condition than in the clock condition, suggesting that time estimation may become more attentionally-demanding as clock-availability declines. In other words, an attentionally-driven internal clock may be used to a greater extent, and thus affect ongoing task performance to a greater degree when participants are less able to rely on an external clock. While Labelle et al.'s (2009) study suggests that costs to the ongoing task may increase when clock access is limited, unfortunately, they did not include a baseline condition in which the ongoing task was performed in the absence of a timing task. Therefore, it remains unclear whether costs to the ongoing task increase significantly as clock availability decreases.

In sum, evidence for involvement of an attention-dependent internal clock is available in the prospective timing literature and, to a lesser extent, in the TBPM literature. However, there are also a number of reasons to doubt that the prospective timing involved in many real-world situations, such as TBPM, relies solely on an attentionally driven mechanism.

Limitations of the attentional-view

While there is growing evidence to suggest that prospective timing is attentionally demanding under classic laboratory conditions, some researchers have also argued that people may employ other less costly strategies in real-world situations that require prospective timing. (e.g., Kvavilashvili & Fisher, 2007; Mantyla & Grazia-Carelli, 2006). For instance, it is unlikely that people continuously monitor time in numerous real-world TBPM situations that include delays of days, weeks, or even months (e.g., Graf & Grondin, 2006; Kvavilashvili & Fisher, 2007). Indeed, Kvavilashvili and Fisher (2007) found that people reported thinking about a TBPM intention only 8–12 times over an entire 7 day period. Despite this infrequent rehearsal, the majority of participants successfully performed the TBPM intention within 10 minutes of the target time. According to Block and Zakay’s (2006) model, accurate TBPM performance requires attention be actively devoted to monitoring time from intention formation. However, given that people do not often attend to the TBPM over long delays, it can be inferred that active monitoring for the target time also occurs infrequently. Therefore, it is unclear how this model can accommodate successful performance of long-delay TBPM intentions. Indeed, Block and Zakay (2006) acknowledge that because the attentional-gate model of prospective timing applies primarily to short durations in the seconds to minutes range, that their TBPM model also may not sufficiently capture processes that are involved when a TBPM target time is hours, days, or weeks in the future.

An additional finding that is not adequately explained by the attentional-view of prospective timing is that older adults commonly outperform younger adults in naturalistic TBPM tasks (for a review, see Henry, McCloud, Phillips, & Crawford, 2004). Block and Zakay (2006) depict TBPM as a dual task situation that requires division of attention between monitoring time and performing the ongoing task. Older adults are more likely to be impaired in dual task situations than younger adults (e.g., Anderson, Craik, Naveh-Benjamin, 1998; McDowd, & Craik, 1988), and therefore should be more impaired than younger adults in all TBPM situations. However, this is not the case.

It is possible that older adults are able to avoid TBPM performance decrements in naturalistic settings by using the known duration of common events/tasks to help estimate the passage of time (e.g., TV programs are typically 30 minutes long). Indeed, Roy and Christenfeld (2007) found a direct relationship between peoples’ estimates of how long it took to perform a task in the past and how long they believed it would take to perform the same task in the future (also see Boltz, Kupperman, & Dunne, 1998). Overall, if people use duration memory to make future time estimates, it is also reasonable to assume that these same duration memories can be used to make prospective time estimates.

Given that there is strong evidence for a role of episodic memory processes in both retrospective (e.g. Block & Zakay, 1997) and future time estimation (e.g. Roy, Christenfeld & McKenzie, 2005; Roy & Christenfeld, 2007), we propose that similar memory processes also likely play a role in prospective timing. While previous prospective timing studies have often failed to observe episodic memory effects, this may largely be a consequence of the ongoing tasks used in these studies - rating lists of words (e.g., Block, 1992), identifying tones (e.g., Zakay, 1998), sorting cards (e.g., Hicks et al., 1976) and generating random numbers (e.g., Brown, 2006). While these tasks vary in many ways, they all have one thing in common – they do not provide duration relevant information. In other words, the novelty and variable nature of these tasks likely prohibits participants from associating specific durations with events experienced during the interval. Thus, participants have had no choice but to rely on the internal clock mechanism described by Zakay and Block’s (1996) attentional-gate model in previous prospective timing studies. Overall then, the conditions of previous experiments have not been ideal for investigating the role of episodic memory in prospective timing.

While most time estimation studies have not provided any relevant duration information, one notable exception comes from a Bailey and Areni (2006a), who manipulated the number of background songs participants experienced during an interval. They found that retrospective time estimates increased significantly as the number of background songs increased. However, they chose not to include a prospective timing condition because previous research has indicated a lack of episodic memory effects in prospective timing. We challenge this established notion, and predict that if participants experience events for which they already possess duration knowledge, such as background songs, they can use their memory for these events to estimate time prospectively. While we are particularly interested in examining the role of prospective timing in TBPM, it is clear that we must first obtain a better understanding of the mechanisms involved in prospective timing itself. Therefore, in Experiment 1, we used a classic prospective timing paradigm to directly test the hypothesis that memory for events experienced during an interval influences prospective time estimation.

Experiment 1

In Experiment 1, all participants first performed a lexical decision task without any timing requirement, and then performed a second lexical decision task under prospective timing conditions. Some participants performed both sessions in silence while others heard popular songs play in the background. The number of background songs was varied between participants, while the objective duration of the interval was held constant across conditions.

If people use episodic memory and duration knowledge to make prospective time estimates, participants who hear background songs should be able to use their knowledge of how long pop songs typically last along with their memory of the number of songs played to make their prospective estimate. Such a strategy would be evidenced by participants who heard more songs judging the interval as having been longer than those who heard fewer songs. For instance, if people apply knowledge that pop songs generally last 3–4 minutes, those who hear four songs should estimate the duration to have been about 12–16 minutes, whereas those who hear only two songs should make an estimate of 6–8 minutes. In other words, although the objective duration of the interval is kept constant, the number of songs played during the interval can introduce time estimation biases if people rely on memory for the number of songs to make their estimates.

In addition to time estimates, we also examined a number of other dependent measures, including lexical decision performance. According to the attentional view of prospective timing, as attention to time increases, more temporal pulses are accumulated in the internal clock and verbal estimates become longer. At the same time, increased attention to time detracts from the resources available for ongoing task performance, and it suffers (e.g., Brown, 1997; Brown & Merchant, 2007; Kladopoulos et al., 2004; Labelle et al., 2009; Macar et al., 1994; Macar et al., 2006; Zakay, 1998;). Therefore, if an attentionally-dependent internal clock is driving prospective estimates, increases in verbal prospective estimates should be associated with decreases in ongoing task performance.

We also analyzed verbal reports of time estimation strategy to establish whether self-reports converge with strategies suggested by the time estimation findings. Finally, because previous studies have reported that background song liking (e.g., Cameron, Baker, Peterson, & Braunsberger, 2003; Lopez & Malhorta, 1991) and song familiarity (e.g., Bailey & Areni, 2006b; Yalch & Spangenberg, 2000) can affect time estimates we also investigated whether either of these factors influenced time estimates in the current study.

Method

Participants

Participants were 160 UNCG undergraduates who participated for course credit. Thirty-two participants were randomly assigned to one of five between-subjects background conditions (silence vs. metronome vs. 2-songs vs. 3-songs vs. 4-songs). Each participant completed two lexical decision task *sessions* (baseline vs. prospective timing). Therefore, this study employed a 2 × 5 mixed-factorial design.

Materials

Lexical decision task—Stimuli were 266 words (mean frequency, 146 per million; Kucera & Francis, 1967) and 266 pronounceable nonwords drawn from the ARC nonword database (Rastle, Harrington, & Coltheart, 2002). The pool of 532 items was randomly divided into three lists; one practice list of eight items and two experimental lists of 262 items (List A and List B). One half of the items on each list were words, and the remaining items were nonwords. List A was presented during the baseline session and List B was presented during the prospective timing session, or vice versa. The presentation order of the items within each list was randomized.

Background tracks—Seven different background tracks were created for use during the baseline and prospective timing sessions. Six of these background tracks were comprised of popular songs by top 40 artists (e.g. “Ray of Light” by Madonna, “Boom, Boom, Pow” by the Black Eyed Peas), and the final track was a recording of a metronome. Eighteen popular songs were chosen to create the six different song tracks, and each song was placed onto only one of the 6 song tracks. Two of the song tracks were comprised of two songs each (tracks 2a & 2b), two tracks consisted of three songs (tracks 3a & 3b), and two tracks were comprised of four songs each (tracks 4a & 4b). The ‘a’ and ‘b’ tracks of each song condition were assigned equally often to play during the baseline and prospective timing sessions.

The baseline and prospective timing sessions were each 11.02 minutes in duration, therefore, the songs included on the 2-song tracks were longer in duration ($M = 5.53$, $SD = 0.34$) than the songs included on the 3-song ($M = 3.80$, $SD = 0.44$), and 4-song tracks ($M = 2.78$, $SD = 0.40$). In addition to controlling for the total duration of each track, the average tempo of each song was also controlled. Previous studies have shown that participants exposed to repetitive click presentations make longer prospective estimates than do participants not exposed to clicks (e.g., Penton-Voak, Edwards, Percival, & Wearden, 1996; Treisman, Faulkner, Naish, & Brogan, 1990; Wearden, Edwards, Fakhri, & Percival, 1998; Wearden, Philpott, & Win, 1999; Zakay et al., 1983). The clicks are thought to increase prospective estimates by increasing arousal and subsequently the rate at which the internal clock emits pulses. Because songs have an inherent beat, a variety of resources including an online DJ database (http://www.djbpmstudio.com) and tempo calculation software (Mixmeister, LLC., 2010) were used to ensure that each song deviated no more than five bpm from any other song. Finally, a metronome set to the mean song bpm (129) was recorded for the final background track.

Post-experiment verbal report materials

Time-estimation form—This form contained the sentence: “I think that the time estimation segment of the experiment lasted for ______minutes and _______seconds.” Participants were asked to fill in both blanks to indicate their estimate. (‘time estimation segment’ was the informal term used to describe the prospective timing session)

Time-estimation strategy report form—This sheet contained the sentence "In the blank space below please describe, in as much detail as you can, the thinking that led you to decide on the time estimate you wrote on the sheet of paper I just collected from you."

Song questionnaire—This form contained three questions that inquired about the songs played during the prospective timing segment. The first question asked participants to report the number of songs they remembered hearing during the time estimation segment of the experiment. The second question assessed participants' familiarity with the songs by asking them to report how many of the songs they had heard prior to the experiment. The third question asked participants to rate how much they liked or disliked the song track by using a scale from 1–7, where a rating of 1 represented "like very much" and 7 represented "dislike very much."

Procedure

Participants were informed that they would be participating in an experiment designed to determine how quickly they could process visually presented items, and were given the lexical decision task instructions. They were told to indicate as quickly as possible if each letter string presented on the screen was or was not an English word by pressing the "P" key on the keyboard for words and the "Q" key for nonwords.

Each lexical decision trial was fixed at 2524 milliseconds (ms) so that both the number of trials and the total duration of each lexical decision task totaled 11.02 minutes for each participant. Each stimulus item was presented on the computer screen either for a maximum of 2500 ms or until a word/nonword response was recorded. If a response occurred prior to the 2500 ms time limit, the stimulus item disappeared and an 'xxx' display replaced the item on the screen for some variable amount of time until the total 2500 ms duration elapsed. Finally, a blank screen was displayed for 24 ms prior to each new stimulus item.

Following completion of an 8-item practice session, all participants performed the baseline lexical decision task session either in silence, or while a metronome, two, three, or four songs played in the background. Next, all participants engaged in the second session of lexical decision under prospective timing conditions. They were told that they were about to perform the "time estimation segment" of the experiment during which they would again be asked to make word/nonword decisions. Participants were also informed that that they would later be asked to estimate, in minutes and seconds, the entire duration of the time estimation segment. All participants were then asked to put watches and cell phones out of sight. The background conditions present during the prospective timing session were the same as those experienced during the baseline session. That is, if participants heard two songs during the baseline session, they heard two different songs during the prospective timing session, etc.

Following the prospective timing session, participants were asked to first complete the time estimation form, then the strategy report form, and finally those in the song conditions were also asked to complete the song questionnaire.

Results

The primary question of interest is whether participants used their memory for events experienced during the interval (i.e., the number of songs played) to make prospective time estimates. A one-way ANOVA conducted on the number of songs participants reported remembering on the song questionnaire indicated a significant main effect of number of songs played, $F(2,93) = 176.82$, $MSe = .149$, $p < .001$, $\eta_p^2 = .792$. Pairwise comparisons confirmed that song memory was greater in the 4-song condition ($M=3.81$, $SD = 0.54$) than in the 3-song condition (M= 2.97, SD = 0.31), which in turn was greater than in the 2-song condition (M=2.00, SD = 0.25) (all *ps* < .001). However, it is clear that song memory was not perfect (see Table 1). Because our hypothesis concerns participants' use of remembered events to make prospective time estimates, we investigated time estimates based on participants' reported memory for the number of songs played, rather than the objective number of songs played[1].

Analyses of Prospective Time Estimates

Duration estimates were converted to proportional time estimation error scores (e.g. Block & Zakay, 1997; Roy & Christenfeld, 2007) by first dividing each participant's subjective time estimate by the objective duration of the interval (11.02 minutes) and then subtracting a value of 1 from each quotient so that negative error scores represent underestimation of the interval while positive error scores represent overestimation. A score of zero represents perfect accuracy. The results are shown in Figure 1.

An initial analysis indicated that estimates in the silence and metronome conditions did not differ, $t < 1$ suggesting that the tempo used in the current experiment likely did not affect the rate of an internal-clock mechanism in a way that would alter time estimates. [2] Therefore, we collapsed across these two conditions in the subsequent analysis and refer to them as the no-song condition.

A one-way ANOVA was conducted on proportional error scores using participants' *remembered background* (no-song vs. 2 songs vs. 3 songs vs. 4 songs). One participant in the 2-song condition reported remembering one song, and one participant in the 4-song condition reported hearing five songs; these two participants were not included in this analysis. [3] There was a significant effect of remembered background, $F(3, 154) = 7.15$, $MSe = 10.679$, $p < .001$, $\eta_p^2=.122$. Pairwise comparisons revealed that estimates made by those who remembered three songs did not differ from those made in the no-song condition ($p =.37$). More importantly, the magnitude of time estimates increased as song memory increased. Particularly, participants who remembered either three or four songs made significantly longer estimates than did those who remembered two songs (both *ps* < .0.02). Additionally, estimates were numerically, though not significantly, longer for those who remembered four songs compared to those who remembered three songs (p=.37). Thus, the more songs participants remembered having played during the task, the longer their estimates tended to be.

Next, proportional error scores in each background condition were compared to zero to determine if significant under- or overestimation was present. Results revealed that in neither the silence nor metronome conditions did estimates deviate significantly from zero (both *t's* < 1). However, in the song conditions, participants who remembered hearing two songs significantly underestimated the duration of the interval, $t(32) = 2.83$, $p < .01$, $d = 0.49$, and participants who remembered four songs significantly overestimated the interval duration, $t(25) = 6.69$, $p < .001$, $d = 1.31$. Those who remembered three songs also showed a numerical, though non-significant trend toward overestimation, $t(34) = 1.74$, $p = .09$, $d = 0.29$.

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[1] The pattern of estimation findings is unaffected if the objective number of songs played is used as a variable, although the number of songs remembered leads to stronger differences in estimates between the three song conditions.

[2] Estimates in the 3-song condition did not differ from those made in either the silence or metronome conditions (both *t's* <1). Therefore, it appears that the presence of songs did not influence arousal beyond that of a metronome and thus also did not affect arousal to a degree that altered time estimates.

[3] The participants who remembered one and five songs made estimates of 10.05 minutes and 15.5 minute respectively. These estimates are in-line with the use of a song-memory estimation strategy and removal of these participants did not strengthen our findings.

Analyses of Ongoing Task Performance—Because lexical decision accuracy was near ceiling in both the prospective timing (*M*=.95, *SD*= .04) and baseline sessions (*M*=.95, *SD* = .06), we limited performance analysis to reaction times of accurate word responses (2.3% of total word responses removed) (e.g. Hicks et al. 2005; Marsh et al, 2003; Smith, Hunt, McVay & McConnell., 2007; Smith, 2010). Additionally, reaction times were trimmed so that any responses more than three standard deviations from a participant's grand mean response time were eliminated (additional 1.9%) (e.g., Einstein, et al. 2005; Ratcliff, 1978).

A mixed-factorial ANOVA on reaction times using *session* (baseline vs. prospective timing) and *remembered background* (silence vs. metronome vs. two songs vs. three songs vs. four songs), produced a significant main effect of session, $F(1, 153) = 12.89$, $MSe = 1820.82$, $p = .001$, $\eta_p^2 = .078$. The results are summarized in Figure 2. Overall, participants responded significantly slower during the prospective timing session ($M = 628.25$, $SD = 106.96$) than during the baseline session ($M = 610.37$, $SD = 80.07$), indicating prospective timing costs. However, neither the main effect of remembered background nor the interaction were significant (both *F*'s <1), suggesting that not only were reaction times unaffected by background, but also that prospective timing costs were equivalent across all background conditions.

Analyses of Time Estimation Strategies

At the conclusion of the experiment, participants were asked to write an explanation describing how they had made their time estimate. Experimenters identified ten general strategies that encompassed all participants' strategy reports (see Table 2). Two independent raters classified each reported strategy into one of the ten bins. Inter-rater reliability was 95%, and discrepancies were resolved through discussion.

Participants who heard songs play in the background more often reported using the songs to make their time estimates (94%) than all other strategies combined, $\chi^2(1, N = 96) = 73.50$, $p < .001$. This finding indicates that when songs are present, participants strongly prefer to use a song-based estimation strategy over other non-song strategies.

We also evaluated whether liking of the songs or familiarity with the songs influenced time estimates. The extent to which participants liked the songs was assessed using a scale of 1–7, where lower numbers represent greater liking. Overall, the reported mean liking score was 2.72 ($SD = 1.21$). Familiarity scores for each participant were calculated by dividing the number of songs they reported being familiar with on the song questionnaire by the number of songs they remembered hearing. The mean familiarity score was 0.63 ($SD = .33$), indicating that participants were familiar with more than half of the songs they remembered hearing.

The number of remembered songs, song liking, and song familiarity were simultaneously regressed on the proportional time estimation error scores in the song conditions. The results are summarized in Table 3. Although the three predictors explained a significant proportion of variance in estimation error, $R^2 = .26$, $F(3, 91) = 10.87$, $p < .001$, the number of remembered songs was the only significant predictor ($\beta = .49$, $t(93) = 5.39$ $p < .001$).

Discussion

The results of Experiment 1 demonstrate that, contrary to the attentional view of prospective timing, prospective estimates are strongly influenced by episodic memory for interval information. Participants' memory of the number of songs played during a lexical decision task was directly related to the magnitude of prospective time estimates, with increasing number of remembered songs leading to longer time estimates. Additionally, despite significant differences in time estimates across background conditions, lexical decision reaction times slowed to an equal extent from the baseline session to the prospective timing session in all the background conditions. In other words, while prospective time estimates varied across background conditions, lexical decision performance did not. Therefore, it is unclear how the attentional view of prospective timing, which predicts a negative relationship between prospective time estimates and lexical decision performance, could account for the current pattern of results. Overall, the findings suggest that memory for interval events rather than attention to temporal information better accounts for the different prospective estimates across the song conditions. This conclusion is further supported by the verbal reports analyses in which the majority of participants who heard songs reported that they used the songs to make their prospective estimates. Neither familiarity with the songs, nor the liking of the songs influenced the time estimates.

Experiment 2

The results of Experiment 1 demonstrate that memory for interval events influences prospective time estimates. These findings suggest that people could deploy similar memory-based strategies in many everyday situations that require prospective time estimation, such as TBPM tasks. Therefore, the aim of Experiment 2 was to determine if the time estimation findings of Experiment 1 can be extended to TBPM.

In this experiment, participants in the TBPM condition were told to make a target response after 10 minutes of a lexical decision task had elapsed. Participants in the baseline condition performed the lexical decision task in the absence of any time-based intention. As in Experiment 1, background condition was varied between participants, with some participants performing the lexical decision task in silence, while others heard two or four songs play in the background. We aimed to minimize the possibility that participants would forget the time-based intention because we were primarily interested in examining how time estimation, rather than intention memory, affects TBPM task performance. Therefore, similar to Labelle et al. (2009) who also studied time estimation processes in TBPM, we allowed participants to practice both the ongoing task and the TBPM task immediately prior to the TBPM session. We also avoided manipulations that are commonly used in TBPM studies to induce forgetting of the time-based intention, such as deemphasizing the timing task and/or including a delay between TBPM instructions and performance.

The results of Experiment 1 showed that the more songs participants remembered, the more time they thought had elapsed during the lexical decision task. If participants use a similar memory-based estimation strategy in the current experiment, we should see similar timing biases emerge in the target responses of a TBPM task. Namely, relative to participants in the 4-song condition, participants in the 2-song condition should judge that less time has elapsed during the interval and thus wait longer to make their target response. Because use of such a strategy may vary according to how much participants can rely on an external clock to monitor time, we also varied how accessible a clock was during the TBPM task.

In addition to examining target responses, we will also consider a variety of additional dependent measures to elucidate the timing mechanisms of TBPM. For instance, the pattern of clock-checking behavior across the course of the experiment can indicate whether the presence of songs affects when participants select to check the clock. Additionally, as in Experiment 1, ongoing task performance can be used to determine whether an attentionally-driven internal clock influences time-based responses. The attentional view assumes that when production of a time-based response is required during an interval, increased attention to time will result in both ongoing task performance declines and the faster accumulation of pulses in the internal clock, which in turn, leads to earlier production of the target response. Therefore, if an internal clock drives target response production in the current experiment, earlier target responses should be associated with poorer ongoing task performance. However, if this relationship is absent, it would suggest that a mechanism beyond an attentionally-driven internal clock is at work.

Method

Participants

Participants were 384 UNCG undergraduates who participated for course credit. None of them had participated in Experiment 1. Thirty-two participants were randomly assigned to each of the 12 between-subjects conditions. *Session* (baseline vs. no-clock vs. low-consequence clock vs. high-consequence clock) and *background* (silence vs. 2-songs vs. 4-songs) were both varied between subjects.

Materials

The materials were identical to those used in Experiment 1, with a few minor exceptions. First, the metronome condition was not included in the current experiment because it was not notably different from the silence condition in Experiment 1. Also, because the strongest estimation biases appeared when participants reported remembering two or four songs, the three song condition was also omitted. For the TBPM clock conditions, a “clock key” was created by covering the “T” key on the keyboard with a picture of a clock. Pressing this designated “clock key” displayed the exact elapsed duration of the lexical decision task at the bottom of the computer screen for two seconds. Finally, an additional 8-item practice session was created for use in the clock conditions.

Procedure

The initial lexical decision instructions and practice session were identical to those used in Experiment 1. All participants then performed an experimental session of the lexical decision task while zero, two, or four songs played in the background. As in the previous experiment, the length of the experimental session was 11.02 minutes across all conditions.

Prior to the start of the experimental session, participants in the baseline condition were informed that they should perform the lexical decision task as quickly and accurately as possible. Participants in the baseline condition were not given a TBPM task. Participants in the TBPM conditions were asked to remove watches and/or place cell phones out of sight and were informed that in addition to performing the lexical decision task they should also remember to press the ‘Z’ key on the keyboard after exactly 10 minutes had elapsed. Two thirds of the participants in the TBPM condition had access to a clock, whereas the remaining one third did not. Participants in the *no-clock* condition were simply told that they should press the ‘Z’ key on the keyboard when they estimated that 10 minutes had elapsed. Participants in the *clock* conditions were informed that they could view the exact amount of elapsed time by pressing the “clock key” at any point during the task. All participants in the clock conditions then performed an additional eight item lexical decision practice session during which they were asked to press the ‘Z’ key after 15 seconds had elapsed. Participants were encouraged to practice using the clock key to help them perform this task on time. Following this practice session, participants were informed that the same clock would be available during the rest of the experiment and while participants in the *low-consequence* clock condition were told that frequent clock-checking may interfere with performance on the lexical decision task, they were not given specific ramifications for checking the clock. Conversely, participants in the *high-consequence* clock condition were told that each clock check would result in an additional two minutes of the lexical decision task being added onto the end of the task. The purpose of this instruction was to reduce reliance on the clock and encourage the use of other time estimation strategies. The clock-checking consequence was not actually enforced.

Following completion of the experimental session, participants in the clock conditions were given a strategy sheet which asked them to describe, in a much detail as possible, how they decided when to check the clock and when to make their target response. Participants in the no-clock condition were simply asked to indicate how they decided when to make their target response. The experimenter also told participants that if they did not make a “Z” response, they should use the strategy report form to explain why they did not respond. Finally, participants who heard background songs filled out the same song questionnaire used in Experiment 1.

Results

The objective number of songs played rather than the number of remembered songs was used to conduct analyses in the current experiment. Whereas in Experiment 1 participants made a verbal estimate for the entire duration of the lexical decision task, in the current experiment, participants needed to estimate when 10 minutes had elapsed *during* the lexical decision task. Therefore, song information was likely only important to participants until a response was made, making retrospective memory for total number of songs irrelevant for this experiment.

Analyses of Target Response Times

Preliminary analyses indicated that while 90% of participants in the clock conditions made a target response, only 66% of participants in the no-clock condition made a target response during the lexical decision task. One way to interpret the low response rate in the no-clock condition is to assume that participants who did not have clock access may have been more likely to forget the TBPM intention compared to those in the clock conditions. However, additional analyses suggested that this is unlikely to be the case. Specifically, while in the 2-song condition, target response production declined significantly when no clock was available (50% response rate) compared to when participants had clock access (91% response rate) $\chi^2(1, N = 96) = 19.93$, $p < .001$, no such decline was observed in the 4-song condition. In fact, participants who heard four songs were just as likely to make a target response when they did not have access to a clock as when they had access to a clock (91% response rate in both conditions). Given that there is no a priori reason to think that changes in clock access would affect intention memory in the 2-song condition but not in the 4-song condition, it is more likely that prospective timing biases influenced target response production in the no-clock condition. Specifically, just as in Experiment 1, participants who heard two songs often underestimated the passage of time. While those who had clock access could realize and correct for this estimation error, those in the no-clock condition had no opportunity to determine if their time estimate was accurate. Consequently, those who heard two songs in no-clock condition often failed to make a target response because they perceived that 10 minutes had not yet elapsed when the lexical decision task came to an end. Participants who heard four songs were more likely to make a target response because they estimated that more time was elapsing than did those who heard two songs. Therefore, they were also more likely to think that the 10 minute target time occurred during the lexical decision task.

Strategy reports further substantiate that target response failure in the 2-song condition was due primarily to time underestimation rather than to forgetting of the TBPM intention. Specifically, during strategy reporting, we instructed participants to indicate why they never pushed the “Z” key if they failed to do so. Of all 52 participants who did not make a target response, only one participant specifically reported that their failure was due to forgetting of the TBPM intention. The remaining participants overwhelmingly reported that they did not make a target response simply because they thought that 10 minutes had not yet elapsed when the lexical decision task ended.

Because the data suggest that target response failure was due to time underestimation rather than to forgetting of the intention, we chose to replace the missing values in all conditions with a response time of 11.03 minutes (1 second later than the end of the experimental session). We reasoned that the participants who never made a target response underestimated the duration of the task by at least 1.02 minutes because the target response time was 10 minutes, and the entire session lasted for 11.02 minutes. It is important to note that the estimated target response times produced by this analysis will provide a very conservative approximation and may not capture the true degree of underestimation that was present. The actual response times may have been much later than the replacement value of 11.03 had the task continued until a response was recorded.

Target response times were associated with significant negative skew (skewness = −2.20, SE = .14). This was confirmed by both the Kolmogorov-Smirnov and Shapiro-Wilk tests of normality (both ps <.001). Therefore, proportional error scores (participant response time divided by the target response time) were log transformed. Note that because log transformation centers values around zero, it was unnecessary to subtract a value of one from each quotient as we did in Experiment 1. Negative error scores represent responses made too early while positive scores represent responses made too late; zero scores represents perfect target response accuracy.

A factorial ANOVA conducted on target response error scores using *TBPM condition* (high-consequence clock vs. low-consequence clock vs. no-clock) and *background* (silence vs. 2-songs vs. 4-songs) revealed significant main effects of both TBPM condition, $F(2, 279) = 32.72$, $MSe = 0.004$, $p < .001$, $\eta_p^2 = .190$, and background, $F(2, 279) = 8.62$, $p < .001$, $\eta_p^2 = .058$. However, these two main effects were qualified by a significant interaction, $F(4,279) = 7.76$, $p < .001$, $\eta_p^2 = .100$ (see Figure 3). Analysis of simple main effects indicated that while there was no effect of background in either the high consequence or low consequence conditions (both F's <1), background did have a significant effect in the no-clock condition, $F(2, 279) = 24.11$, $p < .001$. Pairwise comparisons revealed that participants in the 2-song condition responded significantly later than those who performed the task in silence. Those in the silence condition, in turn, waited longer to respond than those in the 4-song condition (all $ps < .01$).

Overall, background did not affect final target response times when participants could rely on an external clock during the task. However, when no clock was available, response times mirrored the estimation biases observed in Experiment 1. Specifically, participants estimated that more time was passing when they heard four songs than when they heard two songs, which led to significantly earlier response times in the 4-song than in the 2-song condition.

Importantly, the pattern of target response time results is unaffected if the analysis is limited only to the participants who actually made a target response (i.e., forgetting of the intention can be ruled out entirely for these participants). Those in the no-clock condition waited significantly longer to respond when they heard 2-songs ($M= -.04$, $SD= .08$) than when they performed the task either in silence ($M= -.16$, $SD= .14$), $t(32) = 2.85$, $p < .01$ or while 4-songs played ($M= -.13$, $SD= .10$), $t(43) = 3.07$, $p < .01$. Therefore, it seems clear that in the no-clock condition, the number of background songs influenced time perception, which in turn influenced target response production both for those who made a target response and for those who did not.

Analyses of Clock Checking Behavior Across Temporal Intervals

Given that background songs influenced target response production in the no-clock condition, we evaluated whether songs may have also influenced clock-checking behavior. If participants utilized prior knowledge of song duration to track time, then we would expect clock-checking to increase at song boundaries in the song conditions compared to the same time points in the silence condition. Because clock-checking was much more frequent in the low-consequence (M = 13.70, SD = 12.00) than in the high-consequence condition (M = 3.91, SD = 5.03), $t(190) = 7.37$, $p < .001$, instead of analyzing the overall number of clock checks, we examined whether at least one clock check was made during any minute of the experiment. The results are displayed in Figure 4 (top panel).

After visual inspection of Figure 4 and preliminary analyses, we divided the experiment into five temporal intervals. Minutes 1–4 were grouped into the *Early Segment*, minutes 6–7 were designated as the *Middle Segment*, and finally minutes 9–11 were designated as *Final Segment*. In addition, minute 5 was designated as *Critical Boundary 1* (CB-1) because both the end of the second song in the 4-song condition and the end of the first song in the 2-song condition occurred during minute 5. Minute 8 was designated as *Critical Boundary 2* (CB-2) because in the 4-song condition, the end of the third song occurred during this minute. Although in the 4-song condition, the first song ended during the *Early Segment* (e.g., minute 2), we did not designate this time point as a critical boundary because initial examination of clock-checking probability across each minute of the experiment using McNemar’s within subjects chi square analysis did not indicate significant increases in clock-checking at that particular junction in any of the background conditions (all $ps > .05$). We defer further discussion of this point until the General Discussion section.

A mixed factorial ANOVA was then conducted on the average probability of clock-checking using *temporal interval* (Early Segment vs. CB-1 vs. Middle Segment vs. CB-2 vs. Final Segment) as the within-subjects factor, and *background* (silence vs. 2-songs vs. 4-songs), and *consequence condition* (high vs. low) as the between-subjects factors. If knowledge of song duration influenced clock-checking, then we would expect to obtain a temporal interval x background interaction. Indeed, while there was no 3-way interaction, $F<1$, the temporal interval x background interaction, $F(8,744)=2.15$, $p < .05$, $\eta^2=.023$ was significant (see Figure 4, middle panel)[4]. Post-hoc analyses indicated that this interaction was driven by changes in clock-checking that occurred at song boundaries. For instance, participants in both the 2- and 4-song conditions experienced a song boundary during CB-1, whereas participants in the silence condition obviously did not. Pairwise comparisons confirmed that clock-checking increased significantly from the Early Segment to CB-1 in both the 2-song, and 4-song conditions (both $ps < .02$), but not in the silence condition, p = 1.0. Additionally, only participants in the 4-song condition experienced a song boundary during CB-2, and indeed, a significant increase in clock-checking was observed from the Middle Segment to CB-2 in the 4-song condition ($p<.03$), but not in the 2-song or silence groups (both ps = 1.0). None of the remaining contrasts between adjacent temporal intervals were significant.

To summarize, consistent with our predictions, clock-checking increased with the occurrence of critical song boundaries in both the 2-song and 4-song conditions. However, such increases were not evident at matched time-points in the silence condition. Overall,

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[4] There were also significant main effects of consequence condition, $F(1,186)=128.22$, $MSe=.279$, $p<.001$, $\eta^2=.408$, and temporal interval, $F(4,744)=28.02$, $MSe=.092$, $p<.001$, $\eta^2=.131$, and a significant interaction between these two factors, $F(4,744)=6.80$, $p<.001$, $\eta^2=.035$. Clock-checking increases are commonly observed as the target response time approaches (e.g., Ceci & Bronfenbrenner, 1985) and post-hoc analyses suggest that the temporal interval x consequence condition interaction (see Figure 4, bottom panel) was driven by an earlier increase in clock-checking in the low consequence compared to the high consequence group.

these findings suggest that even when a clock is available, people use duration knowledge associated with interval events to help them estimate the passage of time and determine *when* to perform clock checks.

Analyses of ongoing task performance

As in Experiment 1, we examined ongoing task performance to determine whether the TBPM conditions were associated with slower lexical decision responses than the baseline condition. Furthermore, we examined whether any reaction time costs may have varied according to clock availability or background condition. As in Experiment 1, we included only accurate word responses in this analysis (2.2% of total word responses removed for inaccuracy) and all reaction times at least three standard deviations from a participant's grand mean response time were also eliminated (additional 2.1%). An ANOVA conducted on reaction times using *session* (baseline vs. no-clock vs. low-consequence vs. high-consequence) and *background* (silence vs. 2-songs vs. 4-songs) revealed a significant main effect of session, $F(3, 383) = 12.64$, $MSe = 9852.76$, $p < .001$, $\eta_p^2 = .093$ (see Figure 5). Pairwise comparisons revealed that the reaction times in the baseline condition ($M = 600.96$, $SD = 85.12$) were significantly faster than those in the low-consequence group ($M = 641.26$, $SD = 90.20$), which in turn were significantly faster than reaction times in both the high-consequence group ($M = 680.96$, $SD = 112.90$), and the no-clock group ($M = 671.43$, $SD = 105.40$), (all *p*s <.04). The high-consequence and the no-clock groups did not differ from each other, ($p=.51$). Neither the main effect of background, nor the session x background interaction was significant (both *F*'s < 1). [5]

These results reveal that there were reaction time costs to the ongoing task with the addition of a TBPM task, because reaction times were comparatively slower in the TBPM condition than in the baseline condition. Furthermore, the requirements of the TBPM task led to differential costs. Specifically, TBPM conditions that required more self-reliant timing (i.e. the no-clock and high-consequence clock conditions) led to greater reaction time costs than the same task performed with a readily available clock (i.e. the low-consequence clock condition). We observed neither a main effect of background, nor any higher order interactions involving background.

Analyses of Time Estimation Strategies

Strategy classification was performed in the same manner as in Experiment 1. Inter-rater reliability was 94%, and discrepancies were resolved through discussion. The results of chi-square analyses confirmed that of participants who heard songs, a significantly higher proportion reported using the songs to track time (80%) than all other strategies combined, $\chi^2(1, N = 192) = 70.08$, $p < .001$. However, reported song use seemed to vary according to clock availability. Specifically, the proportion of participants reporting song-use in the no-clock condition (94%) was greater than in the high-consequence clock condition (81%), $\chi^2(1, N = 128) = 4.57$, $p = .05$, which in turn was significantly greater than in the low-consequence condition (66%), $\chi^2(1, N = 128) = 4.01$, $p < .05$. Overall, the strategy reports indicate that participants utilized songs to estimate the passage of time during the TBPM task. However it is also apparent that reliance on song information decreased as clock information became more accessible in the high consequence and low-consequence clock conditions respectively.

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[5] These results are nearly identical if trials on which a clock check is made are removed. Furthermore, limiting reaction time analyses to trials completed prior to the target response also does not alter the pattern of results. This indicates that even if analyses are limited to trials during which time estimation is important (i.e. before a target response is produced), there is no indication that target response times are associated with lexical decision performance.

Finally, we examined whether song liking and song familiarity influenced target response times. One participant did not report song familiarity, and therefore was excluded from the subsequent analyses. Across all participants, the mean liking rating was 2.63 (SD = 1.28), and participants reported being familiar with about one half of the songs they remembered hearing ($M = .55$, $SD = .32$). We conducted separate multiple regressions on log proportional target response error scores in each of the three TBPM conditions (e.g., no clock, high-consequence, and low-consequence groups). We simultaneously entered background condition (2 songs vs. 4 songs), song liking, and song familiarity as predictors. Together, they explained a significant proportion of variance in the no-clock condition, $R^2 = .30$, $F(3, 60) = 8.45$, $p < .001$. However, the same three predictors did not explain a significant amount of variance in either the low-consequence condition ($R^2 = .05$, $F < 1$) or the high-consequence conditions ($R^2 = .01$, $F < 1$). Furthermore, in the no-clock condition, where the model captured significant variance, only background was a significant predictor of target response error score ($\beta = -.55$, $t(62) = 5.00$ $p < .001$, see Table 5).

Discussion

Experiment 2 was conducted to determine if memory for interval events would influence behavior during a TBPM task. When participants were required to press a target key at a pre-specified point during the experiment without the aid of a clock, their target responses revealed systematic time estimation biases. Namely, participants made target responses significantly earlier when they heard four songs compared to when they heard two songs indicating that an increase in the number of songs resulted in increased estimates of elapsed time. Because those who heard four songs perceived that more time had elapsed during the lexical decision task, they were not only more likely to make earlier target responses than those who heard two songs, but also more likely to respond in general. Given that it is unlikely that intention memory would differ across these background conditions, it is more likely that participants in the 2-song condition often failed to respond due to time underestimation. Indeed, participants who did not make a target response often reported that they simply thought that 10 minutes had not yet elapsed when the task ended. Overall, the pattern of results in the no-clock condition suggests that the number of background songs that played during the lexical decision task influenced time estimation, and as a result affected both if and when target responses were produced.

While background had a large effect on target responses when no clock was available, this factor did not produce any effects on target responses when participants had access to a clock. The lack of a background effect in the clock groups could indicate that rather than relying fully on the memory-based strategy that led to response biases in the no-clock condition, participants used available clock information to avoid such biases. Indeed, while 74% of participants in the two clock conditions reported using songs to help them estimate time, only 5% of these participants never made a clock-check. Therefore, it is clear that when participants use environmental duration information to estimate time, they also prefer to utilize an available external clock to supplement this information.

Participants' decisions to check the clock also point to use of a song based time estimation strategy. Particularly, clock-checking increased at critical song boundaries in the song conditions, but did not increase at matched time-points in the silence condition. This pattern suggests that participants used the occurrence of song boundaries to determine if the objective duration provided by the clock aligned with the subjective duration inferred from the background songs. In other words, a clock-check following a song allowed participants to determine if an estimate based on prior song knowledge was accurate.

We also analyzed the ongoing task performance to determine if any differences in target response times could be explained by the attentional-view of prospective timing. While the attentional view predicts poorer ongoing task performance in conditions associated with earlier target responses, no such association was observed. Therefore, it is unclear how an attentional-clock explanation alone could account for the current results. Finally, verbal strategy reports provided converging evidence that participants used songs to help them estimate time both in the clock and in the no-clock conditions.

General Discussion

Contrary to the popular conclusion that prospective time estimates are derived from attentional rather than memory-based mechanisms (e.g. Block, Hancock, and Zakay, 2010; Block & Zakay 1997), the current results demonstrate a powerful role for episodic memory not only in a traditional prospective timing task that requires a verbal estimate following an interval (Experiment 1), but also in a TBPM task that involves production of a target response at a pre-specified time during an interval (Experiment 2). In both experiments, participants performed a lexical decision task while a varying number of songs were played in the background. Participants' prospective time estimates increased as the number of background songs increased. In Experiment 1, this was evidenced by a direct relationship between memory for interval information and verbal time estimates -- namely, participants' estimates became longer the more songs they remembered from the interval. Similarly, in Experiment 2, participants who had no access to a clock made their TBPM target responses earlier as the number of songs increased, indicating that estimates of elapsed time increased as more songs were experienced.

Not only did songs influence the behavior of participants who had no access to a clock, but they also affected participants who actually had clock access in Experiment 2. Particularly, changes in clock-checking coincided with the occurrence of song boundaries, indicating that these participants used song information in addition to clock information to help them estimate the passage of time. Further evidence that participants used songs to estimate time came from the verbal reports of time estimation strategy collected in both experiments. Participants who heard songs overwhelmingly reported using these songs to make their verbal estimates in Experiment 1, and to determine when to check the clock and when to perform the target response in Experiment 2.

The attentional-view of prospective timing assumes that the magnitude of prospective estimates depends on the amount of attention that is allocated to monitoring time during an interval. Therefore, the attentional-view predicts a negative relationship between ongoing task performance and prospective estimates. Contrary to this prediction, there was no evidence of such a relationship in either experiment, further suggesting that processes beyond those of an attentionally-dependent internal clock influenced time estimates in the current study.

Why did these two experiments produce strong episodic memory effects while a number of previous prospective timing studies have failed to do so? The answer to this question lies in the experimental conditions used in the current studies, which were unlike those previously used in prospective timing. Particularly, while previous prospective timing studies have employed unfamiliar ongoing tasks from which participants likely cannot glean useful duration information, in our experiment participants were provided with duration-relevant information in the form of pop songs. Relative to the ongoing lexical decision task, participants came into the experiment with knowledge about how long pop songs typically last. Unsurprisingly then, it was this established duration knowledge that participants utilized to estimate time. The results of the current study suggest that memory for events that occur during an interval, along with the duration knowledge associated with such events, plays an important role in prospective timing.

While the results of Experiment 1 indicate that people use memory for duration relevant information to make prospective time estimates, the results of Experiment 2 suggest that reliance on such information in a TBPM task is mediated by the availability of external clock information. Therefore, the results of Experiment 2 have important implications for two distinct types of TBPM situations –Namely, (1) when no meaningful clock information is available, and (2) when clock information is available and meaningful. We first consider the former TBPM situation which has been overlooked in the literature. In the current experiment, this situation was represented by the no-clock condition, in which participants were required to make a 10 minute target response without the aid of an external clock. In this condition, we found that participants' target responses were significantly affected by the number of background songs. Participants who heard two songs estimated that less time had elapsed and thus made their target responses significantly later than participants who heard four songs. Not only were those in the two-song condition more likely to respond later than those in the four-song condition, but they were also more likely to miss making a target response all together, which demonstrates just how harmful underestimating the passage of time can be in terms of TBPM performance. Together, the pattern of results suggests that when no clock information is available, biases observed in traditional prospective timing paradigms (Experiment 1) also greatly affect TBPM performance.

Despite the fact that nearly all previous TBPM experiments have provided unlimited clock access, there are many TBPM situations in real-life that are akin to the no-clock condition. These situations include all of those during which a clock is simply not available (you forgot your watch), the clock information obtained in not meaningful (you do not know what time you put the cookies in the oven, so a clock reading 2:53 is irrelevant), or a clock is available but not monitored (you are so sure you can grade five more papers before walking to class, you do not monitor the clock while grading). The present results suggest that in any of these situations, people can likely use duration knowledge and memory to help them estimate the passage of time, and that the time estimation biases associated with such a strategy can affect when or if a target response is successfully performed.

The results of Experiment 2 also provide new insight into TBPM situations where clock information is available and meaningful. First, while background had a large effect on target responses in the no clock condition, this factor did not produce any effects on target responses in either of the clock conditions. This may be surprising given that like participants in the no-clock condition, a majority of participants in the two clock conditions also reported using the songs to help them estimate time. The lack of a background effect in the clock groups, therefore, suggests that participants in these conditions were able to avoid estimation biases and make accurate target responses by supplementing their song-use with clock information. In contrast, those who did not have an external timer had no choice but to rely on their own prospective estimate and consequently produced target responses that reflected biased time estimation. While it is clear that those in the clock conditions did not rely as heavily on prospective estimates to make their target response as did those in the no-clock condition, the clock-checking pattern suggests that participants used a song-based prospective timing strategy to help them determine *when* to check the clock. Overall then, it seems that while prospective timing influences behavior in both groups, it primarily determines when participants check the clock when one is available, and determines target response time when no clock is available.

While the increased likelihood of clock-checking at song boundaries clearly suggests that the presence of songs influences when participants decided to check the clock, some could argue that these checks may have occurred primarily from bottom-up processes rather than from top-down strategic processes as we have suggested. For instance, it is possible that the occurrence of a perceptually salient event (e.g. the end of one song and beginning of another) simply cues the time-based intention and the need to check the clock. If such a bottom-up process were involved, we would have expected to see an increased probability of clock-checking at all song boundaries. However, participants in the 4-song condition did not demonstrate an increased likelihood of clock-checking at minute 2 despite experiencing the first song boundary at this time-point. This finding seems to suggest that clock-checks made at song boundaries are not simply cued by a salient change, but instead are related to the top-down use of duration knowledge. Indeed, many participants (38%) in the 4-song clock condition specifically reported waiting until at least two or three songs played prior to checking the clock. The overall pattern of clock-checking and verbal strategy reports, therefore, suggests that when an external clock and duration relevant events are available, people can use these two sources of information in a strategic, top-down fashion to estimate time.

To this point, we have enumerated a variety of evidence to suggest that clock availability influences behavior in TBPM. The lexical decision reaction time findings provide yet further evidence that clock availability is an important factor that has been too often overlooked in previous research. Particularly, reaction time costs were greater in the no-clock and high-consequence clock conditions than in the low consequence clock condition indicating that ongoing task performance declines as an external clock becomes less available. Similar reaction time results were observed by Labelle et al. (2009), who found that participants performed an ongoing category decision task more slowly when asked to make target responses without the aid of a clock compared to those who performed the same task with a clock readily available. Labelle et al. (2009) explained that faster reaction times occurred in the clock condition because participants who have access to an external clock can largely avoid using an attention-demanding internal clock. Indeed, it may have been the case that in the current study, greater reaction times emerged in the no-clock and high consequence clock conditions because participants with limited or no clock access had to rely on more self-reliant and thus more attentionally demanding timing strategies than did those in clock conditions. However, what remains to be seen is why equivalent reaction times emerged across background in both the clock and no-clock conditions given that time estimation strategy likely differed across participants in the silence and song conditions. For instance, participants in the silent background condition were not provided with a clear memory-based time estimation strategy, and therefore may very well have relied on an internal-clock mechanism to make their estimates. In contrast, the current findings clearly indicate that time estimates in the song conditions were driven by song memory. So, why would reaction times be equivalent for those who likely relied on an internal clock in the silence condition and for those who used a memory-based strategy in the song conditions? There are a number of potential answers to that question. First, it is possible that an attentionally-dependent internal clock was employed to the same extent in each background condition, leading to equivalent reaction time results, but that participants provided with song information chose to rely more heavily on memory rather than available internal clock information to make their time estimates. Indirect support for contribution of both memory and an internal-clock mechanism emerged in Experiment 2. Specifically, the probability of clock-checking increased significantly following the first song in the 2-song condition, but did not in the 4-song condition. Participants in the 2-song condition may have been more likely to check the clock following the end of the first song because an internal clock signaled that the song was relatively long and that a check was warranted. Indeed, a number of participants in both experiments reported that the songs in the 2-song condition simply “seemed longer” than typical songs. Such reports may imply that participants were accessing and using both internal clock information and song duration knowledge to make their estimates.

While an internal clock may have contributed to the reaction time costs observed in the song conditions, it is also possible that the use of elaborate memory-based strategies was a factor in the appearance of costs. For instance, while some participants simply reported that the songs in the 2-song condition seemed longer than typical songs, others reported specific memory-based information to explain this feeling, such as repetitive elements of the songs, instrumental solos, etc. Therefore, it may have been the case that in addition to the total number of songs, participants may have also tracked other musical elements such as the number of choruses, verses, instrumental breaks, etc. According to Boltz (1998, 1999, 2005), when people experience predictable, regular events, such as Western music, they encode both temporal and nontemporal event information because these two types of information are naturally linked in such events. Furthermore, Boltz (1999) found that on initial learning trials, attending to different structural characteristics of songs such as rhythm or pitch has deleterious effects on memory for unattended characteristics. In other words, initial attempts at tracking song characteristics are resource demanding. Given that participants experienced each song only once in the current study, the presence of reaction time costs in the song conditions may have emerged, at least in part, because participants were actively attending to the structural characteristics of each song to further inform their time estimates.

In summary, because the current experiments were designed expressly to test the role of memory factors in prospective timing, they do not address the extent to which an attentionally-driven internal clock mechanism may also have been involved. Prior research documents many cases where attentional manipulations influence prospective time estimates. However, prior research has also largely dismissed the role of episodic memory in prospective timing, whereas the current research re-establishes episodic memory as an important determinant of prospective timing. Future research is needed to directly manipulate both memory for the events of the interval (using manipulations that enable the use of duration knowledge) and attentional factors to determine the relative contributions of these mechanisms in prospective timing situations.

In conclusion, contrary to the attentional view of prospective timing, the results of the current studies clearly demonstrate that memory for interval information plays a vital role in prospective timing. A marked role for episodic memory likely emerged in this study because it is the first, of which we are aware, to examine prospective timing under conditions that allowed for and even encouraged participants to rely on memory-based time estimation. The background songs provided the same type of duration-relevant information that is normally available in everyday situations. The similar influence of songs on prospective time estimates across two distinct tasks (i.e. a traditional prospective timing task that required a verbal estimate and a TBPM task that required participants to produce a time-based response) is especially impressive given that experimental manipulations sometimes affect verbal estimation and production differently (Block, Hancock, & Zakay, 2010). Given the parallel findings observed across different timing situations in the current study, it seems clear that when duration-relevant information is available, people use memory for such information to estimate time prospectively.

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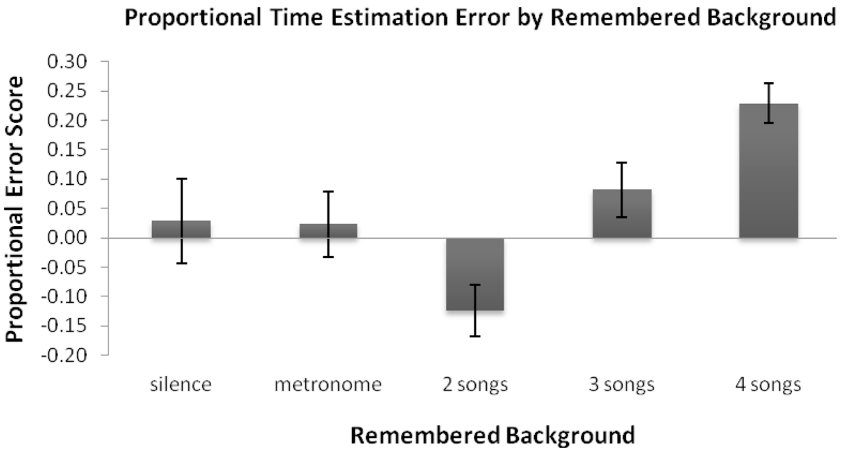

Figure 1.

Proportional time estimation error by Remembered Background in Experiment 1. Negative scores represent underestimation and positive scores represent overestimation. Scores of zero represents an accurate estimate of 11.02 minutes. Error bars represent ±*SE* of the mean

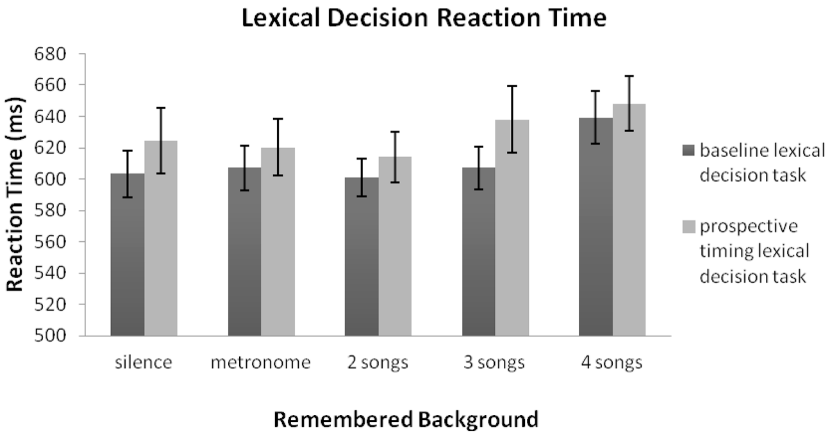

Figure 2.
Lexical decision reaction time by Remembered Background in Experiment 1. Error bars represent ±*SE* of the mean

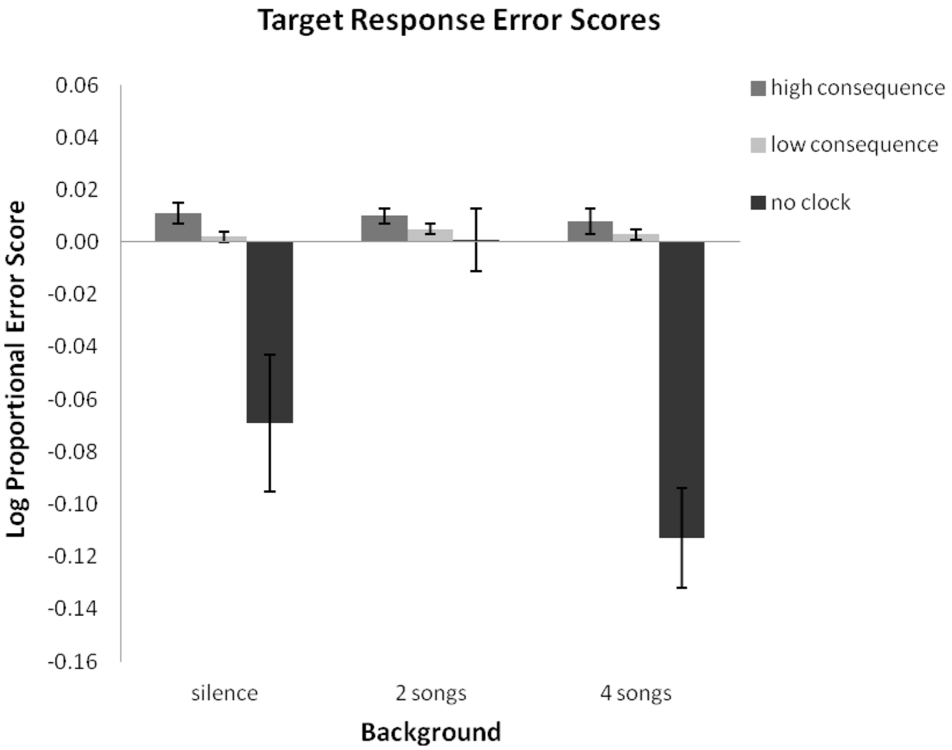

Figure 3.

Log proportional target response error by TBPM Condition and Background in Experiment 2. Negative scores represent target responses made too early (prior to the 10 minute critical time) and positive scores represent target responses that were made too late (after the 10 minute critical time). Scores of zero represent accurate 10-minute target responses. Error bars represent ±*SE* of the mean.

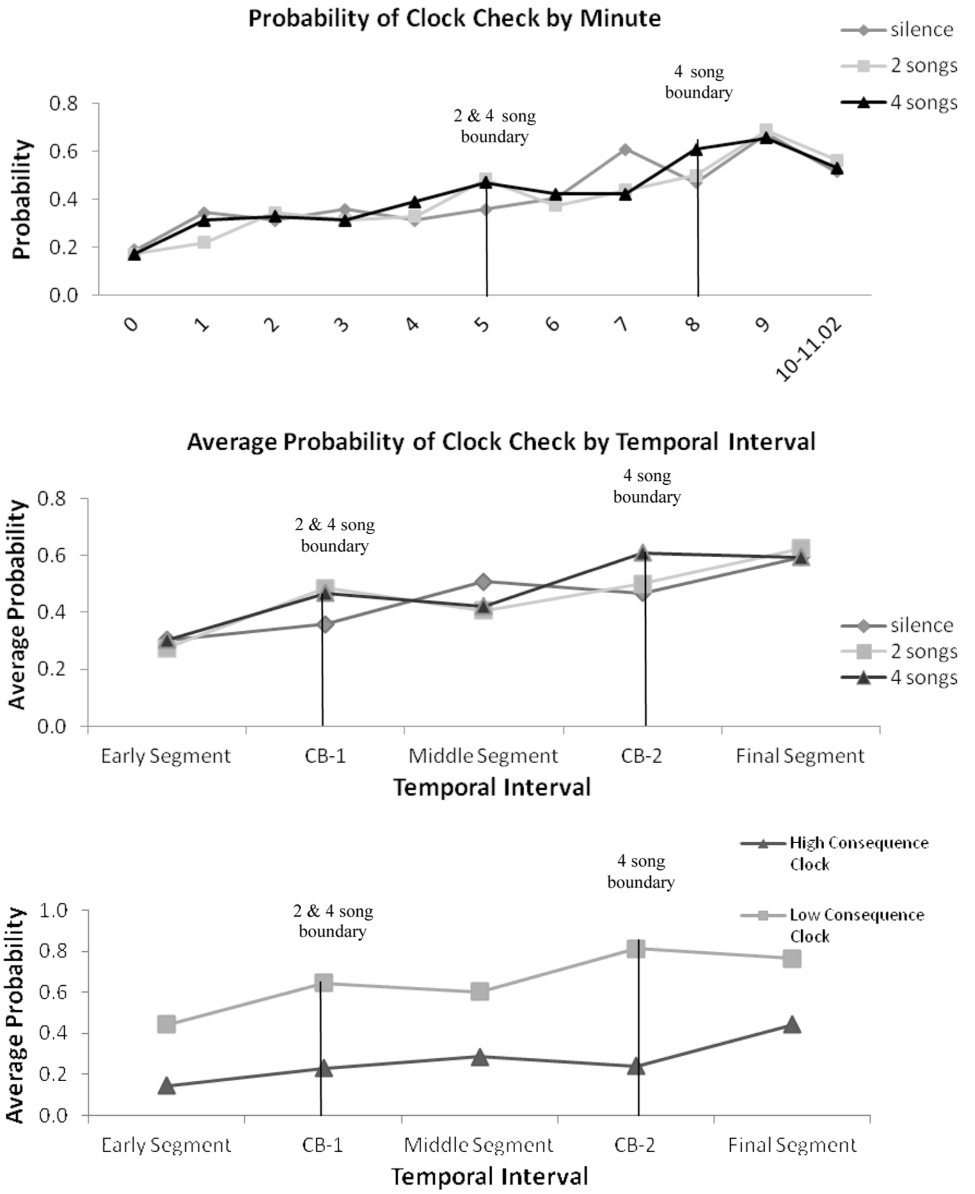

Figure 4.

Probability of a clock check in Experiment 2 by Minute and Background Condition (top panel). Average Probability by Temporal Interval and Background Condition (middle panel) and by Temporal Interval and Consequence Condition (bottom panel). Minutes 0–4 = *Early Segment*, Minute 5 = *Critical Boundary 1*, Minutes 6–7 = *Middle Segment*, Minute 8 = *Critical Boundary 2*, Minutes 9–11 = *Final Segment*.

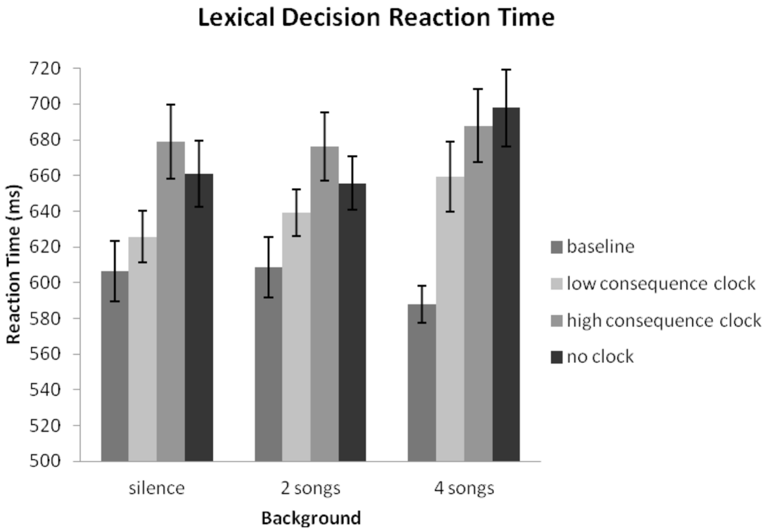

Figure 5.

Lexical decision reaction time by Session and Background in Experiment 2. Error bars represent ±*SE* of the mean

Table 1

Proportion of participants reporting each number of remembered songs by Background Condition in Experiment 1.

Background Condition	Remembered 1	Remembered 2	Remembered 3	Remembered 4	Remembered 5
2 songs played	3%	94%	3%	0	0
3 songs played	0	6%	91%	3%	0
4 songs played	0	3%	16%	78%	3%

Table 2

Proportion of participants reporting each time estimation strategy in Experiment 1.

Song Strategies	**Song Conditions N=96**	**No-Song Condition N=64**
Used Songs	84%	-
Used Songs plus an additional strategy	10%	-
Sang song of known duration in head	-	3%
Total	**94%**	**3%**
Non-song Strategies		
Made estimate based on a “feeling”	1%	31%
Counted seconds or stimuli	3%	23%
Used knowledge of experiment duration	1%	3%
Compared feeling to that of task with known duration	-	8%
Made estimate based on physical symptoms (e.g., fatigue, eye strain)	-	5%
Kept track of every time is felt like certain amount of time (e.g., 1 min.) had elapsed	-	11%
Combination of non-song strategies	1%	16%
Total	**6%**	**97%**

Table 3

Summary of multiple linear regression analysis predicting relative time estimation error in Experiment 1.

	All Song conditions		
Variable	***B***	***SE B***	**β**
# Remembered Songs	.163	.030	.491**
Liking	−.010	.023	−.043
Familiarity	.056	.084	.066

Note: All factor entered simultaneously

** $p < .001$

Table 4

Proportion of participants reporting each time estimation strategy in Experiment 2. Totals for the silence condition are collapsed across clock-condition.

	Song Conditions				Silence Condition
Song Strategies	**High Consequence N=64**	**Low Consequence N=64**	**No-clock N=64**	**Total N=192**	**Total N=96**
Use song info only	52%	23%	91%	**55%**	-
Use songs & simultaneous counting	2%	6%	3%	**4%**	-
Use songs for initial clock checks, then counted when close to 10 minutes	15%	9%	-	**8%**	-
Use songs for initial checks and then “feeling” of elapsed time when close to 10 minutes	12%	27%	-	**13%**	-
Sang song of known duration in head	-	-	-	-	1%
Total	**81%**	**66%**	**94%**	**80%**	**1%**
Non-song Strategies					
Use “feeling” of elapsed time	11%	23%	5%	**13%**	50%
Counted seconds or stimuli	5%	-	2%	**2%**	17%
Use “feeling” for initial clock checks, then count when close to 10 minutes	3%	11%	-	**5%**	25%
Compared to feeling of a 10 minute everyday task	-	-	-	-	7%
Total	**19%**	**34%**	**6%**	**20%**	**99%**

Table 5

Summary of multiple linear regression analyses predicting relative target response time in Experiment 2.

	High-Consequence Clock			Low-Consequence Clock			No Clock		
Variable	***B***	***SE B***	**β**	***B***	***SB***	**β**	***B***	***SB***	**β**
Song Condition	−.056	.006	−.051	−.042	.003	−.043	−0.115	.023	−.545[**]
Liking	.055	.012	.066	−.105	.001	−.106	.000	.009	−.002
Familiarity	.011	.277	.010	−.216	.005	−.213	.023	.035	.073

Note: Song Condition dummy coded with 2-songs serving as the reference group all factors entered simultaneously

[**] p<.001