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Shared and distinct factors driving attention and temporal processing across modalities

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Abstract

In addition to the classic finding that "sounds are judged longer than lights," the timing of auditory stimuli is often more precise and accurate than is the timing of visual stimuli. In cognitive models of temporal processing, these modality differences are explained by positing that auditory stimuli more automatically capture and hold attention, more efficiently closing an attentional switch that allows the accumulation of pulses marking the passage of time (Block & Zakay, 1997; Meck, 1991; Penney, 2003). However, attention is a multifaceted construct, and there has been little attempt to determine which aspects of attention may be related to modality effects. We used visual and auditory versions of the Continuous Temporal Expectancy Task (CTET; O'Connell et al., 2009) a timing task previously linked to behavioral and electrophysiological measures of mind-wandering and attention lapses, and tested participants with or without the presence of a video distractor. Performance in the auditory condition was generally superior to that in the visual condition, replicating standard results in the timing literature. The auditory modality was also less affected by declines in sustained attention indexed by declines in performance over time. In contrast, distraction had an equivalent impact on performance in the two modalities. Analysis of individual differences in performance revealed further differences between the two modalities: Poor performance in the auditory condition was primarily related to boredom whereas poor performance in the visual condition was primarily related to distractibility. These results suggest that: 1) challenges to different aspects of attention reveal both modality-specific and nonspecific effects on temporal processing, and 2) different factors drive individual differences when testing across modalities.

Keywords

interval timing; attention; modality; distraction; sustained attention; individual differences

1. Introduction

Thunder during a storm grabs our attention more readily than lightning. The idea that auditory stimuli capture and hold attention automatically, whereas attention to visual stimuli requires cognitive control, finds behavioral (Posner, 1976; Liu, 2001; Spence & Driver, 1997; Schmitt, Postma, & De Haan, 2000) and emerging neural (Chen, Huang, Luo, Peng, & Liu, 2010) support. The relative automaticity of attention to auditory stimuli is often used to

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explain modality effects in interval timing, including the common finding that “sounds are judged longer than lights” for durations in the hundreds of milliseconds to minutes range (e.g., Penney, Gibbon, & Meck, 2000), and that the perception of intervals in this range is more precise for auditory than visual stimuli (e.g.,Ulrich, Nitschke, & Rammsayer, 2006). However, attention is a multi-faceted construct and there has been little attempt to determine which of its aspects may be subject to these modality effects. The present study begins to address that gap by examining modality effects in an interval timing paradigm that assesses multiple aspects of attention, and by connecting modality-specific timing performance with trait and state self-report measures of attention.

Evidence for modality effects in interval timing dates back at least to Vierordt's 1868 book *Der Zeitsinn* (as described by Lejeune & Wearden, 2009). Auditory stimuli are judged to have longer durations than visual stimuli of the same physical duration (Behar & Bevan, 1961; Goldstone & Goldfarb, 1964a & b; Ortega, Lopez, & Church, 2009; Penney, 2003; Penney et al., 2000; Stevens & Greenbaum, 1966; Ulrich et al., 2006; Walker & Scott, 1981; Wearden, Edwards, Fakhri, & Percival, 1998). There is also substantial evidence for greater temporal precision and sensitivity for auditory than visual stimuli. For example, the discrimination threshold for differences in interval duration is smaller for auditory than visual stimuli (Grondin, 1993; Grondin, Meilleur-Wells, Ouellette, & Macar, 1998; Ulrich et al., 2006). Finally, auditory rhythm perception is more sensitive than visual (Collier & Logan, 2000).

These modality differences may be explained via attentional mechanisms within the framework of pacemaker-accumulator information processing models of timing such as Scalar Expectancy Theory (SET, Gibbon, Church, & Meck, 1984). In SET and related models, during a to-be-timed interval, a pacemaker emits pulses that are sent through an attention-controlled switch before being collected by the accumulator (Gibbon et al., 1984; Meck, 1991; Penney, 2003; see Zakay & Block, 1997; Zakay, 2000 for a slightly different formulation). The accumulator pulse count is compared to values stored in reference memory to make judgments about current time intervals relative to past. The influence of attention on the switch provides a mechanism for modality effects.

When the attention-controlled switch “flickers” due to a lapse or interruption of attention, the number of pulses collected by the accumulator is reduced (Lejeune 1998; Penney et al., 2000). Because the visual modality captures and holds attention less automatically, it will be associated with more lapses of attention and thus more flickering of the mode switch. If the smaller accumulator values accrued during visual stimuli are compared to a reference-memory distribution that includes larger values from auditory stimuli, the visual stimuli will be perceived as shorter.

As Penney and colleagues noted (Penney et al., 2000), this explains why the “sounds are judged longer than lights” finding is usually confined to experiments that use multiple modalities for the same durations within the same subjects. That is, reference–memory mixing of accumulator values from both modalities representing the same physical duration is required to obtain the effect of perceived longer durations for auditory stimuli (see Gu & Meck, 2011 for further implications of the memory-mixing hypothesis). The flickering-switch idea also explains other modality effects that do not require a common, mixed-modality memory representation (Penney, 2003). For example, it can explain the lower precision of visual durations (regardless of whether auditory stimuli are presented to the same subjects within the same durations): Assuming that the flicker is random, the number of pulses associated with a particular physical duration will be more variable for visual than auditory stimuli, and the reference-memory distribution for visual stimuli will be noisier.

Support for an attentional-switch account of modality differences comes not only from experimental manipulations, but also from examination of group and individual differences. Children and older adults, both of whom have reduced attentional control compared to healthy young adults, show exaggerated modality effects (Lustig & Meck, 2001; Droit-Volet, Tourret, & Wearden, 2004; Droit-Volet, Meck, & Penney, 2007), although in the case of children these may be more strongly related to working or reference memory (Lustig & Meck, 2011; Zelanti & Droit-Volet, 2012). Attentional difficulties are a hallmark of schizophrenia present during both psychosis and remission (Asarnow & MacCrimmon, 1978; Wohlberg & Kornetsky, 1973; Nuechterlein, Luck, Lustig, & Sarter, 2009; Demeter, Taylor, Guthrie, Sarter, & Lustig, 2013), and both patients and individuals at high genetic risk have particular difficulty timing stimuli presented in the visual modality (Carroll, Boggs, O'Donnell, Shekhar, & Hetrick, 2008; Penney, Meck, Roberts, Gibbon, & Erlenmeyer-Kimling, 2005). Importantly, not all psychiatric populations that show timing deficits show differential modality effects, and this specificity may provide clues as to their neural underpinnings (see discussion by Allman & Meck, 2012). In healthy young adults, visual timing correlates more highly with measures of psychometric intelligence (Haldemann, Stauffer, Troche, & Rammsayer, 2012), which have been linked to executive attention (see discussion by Kane & Engle, 2002).

Despite the overwhelming evidence for modality effects in interval timing and their connection to attentional function, there has been little consideration of how specific aspects of attention may relate to specific aspects of modality effects. Examination of reported results suggests that attention effects are not universal: For example, dividing attention by asking participants to simultaneously time variable-onset and variable-duration auditory and visual stimuli in a bisection task does not exaggerate modality effects for young adults (Lustig & Meck, 2001; Penney et al., 2000), although it does reduce overall temporal sensitivity for older adults (Lustig & Meck, 2001). To examine this issue in greater depth, we tested young adult participants in auditory and visual versions of an interval timing task that assesses multiple aspects of attention.

The Continuous Temporal Expectancy Test (CTET; O'Connell et al., 2009) requires participants to monitor a stream of stimuli with a fixed duration (800 ms filled interval) and respond to infrequent target stimuli with a longer duration (1070 ms). The original, visual version has been linked to neural correlates of lapses of attention (O'Connell et al., 2009). In addition, the frequency of lapses increases as a function of time-on-task, indexing declines in sustained attention. We created an auditory version of the task to allow the examination of modality effects, and added an external distractor (videos playing on an adjacent laptop) to test how distraction might influence both overall performance and the rate of performance decline for both modalities. Because we were primarily interested in attention effects rather than memory mixing, the modality manipulation was implemented across subjects. To gain further insight into how different aspects of attention might affect performance in the two modalities, we also examined correlations with self-report measures of mind-wandering, distractibility, and boredom.

We were therefore able to test several hypotheses on the nature of attentional influences on modality effects, some with previous support from the literature and others relatively novel. First, the common finding that temporal judgments are more precise for auditory than visual stimuli predicts that performance in the auditory version should be overall better than in the visual version. The finding that dividing attention in the mixed-modality temporal bisection task does not exaggerate modality effects (Lustig & Meck, 2001; Penney et al., 2000) suggests that the distractor manipulation used here should have equivalent effects for the auditory and visual tasks, although differences from those previous studies may occur given the large differences in procedure.

There is less precedent for predictions on how modality might interact with time-on-task effects related to sustained attention. A few studies using visual stimuli alone show that lapses of attention increase with time-on-task if feedback is not provided (Lustig & Meck, 2005; Wearden, Philpott, & Win, 1999). We are aware of only one investigation of modality differences in time-on-task effects. Wearden, Pilkington, and Carter (1999) used a temporal generalization paradigm and found that over repeated blocks of testing, participants were increasingly likely to inaccurately judge longer test durations (450–700 ms) as equivalent to the standard (400 ms). The effect was significant for visual but not auditory stimuli, although the modality by time-on-task interaction did not reach statistical significance. Power in that experiment was relatively low (n = 14 per modality group), which may have made it difficult to detect both the time-on-task effects in the auditory condition and the potential interaction between time-on-task and modality. As acknowledged by those authors, other procedural factors including stopping after each block to conduct an assessment of subjective arousal and the need to maintain a reference-memory representation of the standard complicated the interpretation of time-on-task effects and the relative contributions of attention and memory.

The present study greatly reduces the demands on reference memory (since the standard is presented repeatedly) and trades the finer-grained assessment of subjective arousal by Wearden, Pilkington and Carter (1999) for longer uninterrupted periods of task performance that may make time-on-task effects easier to detect. If the gradual increase in lapses of attention observed for visual stimuli results from failures in high-level executive control of attention, then modality effects might be expected to increase over time as fatigue and boredom place increasing demands on those processes. The additional demands on controlled attention required to ignore the distractor might further exacerbate these effects. However, there is significant controversy as to whether and how mind-wandering and attention lapses are related to executive control (Levinson, Smallwood, & Davidson, 2012; McVay & Kane, 2009), and it may be that modality, time-on-task, and distraction effects are independent.

Finally, correlations between performance and the self-report measures may provide additional insight into the processes underlying different aspects of performance on the visual and auditory tasks. In another study using a relatively large (n = 64) community-based sample tested only on the visual version of our task, overall performance was related to self-rated difficulty keeping attention focused during the task, whereas vulnerability to distraction during the task correlated with both task-specific and trait self-report measures of distractibility (Berry et al., 2013). We expected to replicate these patterns, and also examined whether they might differ for the auditory version. In particular, if performance in the auditory version is governed by more automatic processes, it might be more strongly related to subjective measures of task engagement than difficulty. In other words, performance in the auditory version may be more a matter of motivation than ability.

2. Methods

2.1 Participants

Final analyses included data from 32 participants who performed the visual CTET (16 female, mean age = 18.63 years, range 18–21) and 32 participants who performed the auditory CTET (19 female, mean age = 18.84 years, range 18–22). Participants were recruited from the Introductory Psychology subject pool at the University of Michigan and received academic credit for participation. Participants did not have history of anxiety, depression, ADHD, or head injury, take medications that affect cognition, or have Extended Range Vocabulary Test Version 3 (ERVT; Educational Testing Service, 1976) scores below 9 out of a possible 48. Although the CTET does not have an obvious verbal component, the

ERVT score is commonly used in our lab to screen out participants who may be unable or unwilling to follow task instructions (e.g., Lustig & Meck, 2001; Bissig & Lustig, 2007; Craig et al., 2013). Two individuals who completed the tasks were excluded for poor performance: One failed to perform the task (hit rate below 40% even in the first minute of the No Distractor condition); the other had an excessive number of false alarms (> 3 standard deviations above the mean).

2.2 Continuous Temporal Expectancy Task

The CTET was originally described by O'Connell et al. (2009) and linked to neural measures of mind-wandering. The original version was presented in the visual modality and without distraction. For the current study, we added a distraction condition and created an auditory version. In addition, we modified some procedural aspects (e.g., target and standard durations, response window) based on pilot testing and to allow the task to be used with a wider range of populations including older adults and patients with psychiatric or neurological disorders. Results from those populations will be reported elsewhere. The present paper focuses on modality, time-on-task, and distraction effects in healthy young adults.

Participants were randomly assigned to the visual or auditory condition. The overall structure of the task was the same for both modalities: Participants monitored a stream of stimuli with a standard filled-interval duration of 800 ms for an infrequent target duration of 1070 ms, and were instructed to press the spacebar as soon as they detected the target. A 20 ms empty interval separated stimuli (Figure 1). Responses were recorded as correct (hits) for up to 2.46 seconds following a target. Responses outside this window were coded as false alarms (FAs). Participants received performance feedback at the end of each run. If hits were below 75%, participants were presented with the message: “Please try harder next time!”

Before beginning the experiment, participants were given 6 practice runs that contained 3 targets each. For the first practice run, the duration difference between target and standard trials was exaggerated to ensure participants understood the task rules (target: 1600 ms, standard: 800 ms). Participants were informed that the timing parameters of the subsequent 5 practice runs would be more challenging and would be identical to the test runs (target: 1070 ms, standard: 800 ms). To ensure participants were able to discriminate between standard and target durations, they were required to continue practice until they achieved 100% (3/3 targets detected) if they had not already reached this criterion in the mandated 5 practice runs. (In the present study, only one participant needed an additional practice run.) Participants then performed 10 task runs (4 minutes each) with 24 targets per run. Stimuli were pseudo-randomly intermixed such that there were between 7 and 17 (average of 10) standard trials (thus, 5.76–10.68 s (average 8.22 s) between each target presentation. Participants took a 1 minute break between each experimental run.

For each participant, half of the runs were presented in the No Distractor condition and half were presented in the Distractor condition. No Distractor and Distractor runs alternated and their order was counterbalanced across participants. Both were implemented using a laptop computer oriented 32° to the left of the CTET task and 65 cm from the participant. During No Distractor runs (5 runs), the laptop displayed a blank grey screen and was silent. During Distractor runs the laptop played a series of 30-second video clips featuring game shows, cartoons, movies, and sports, spliced together to create 4 minute runs. Distracting videos did not contain music or other obviously rhythmic content or content that was overtly violent or sexual. (All materials and procedures were approved by the University of Michigan Institutional Review Board.)

The only difference between the visual and auditory conditions was the modality in which the to-be-timed durations were presented. In the visual condition, the stimulus was similar to that used by O'Connell et al. (2009): a 13.2 cm^2 square divided into a 10 × 10 grid of identical square tiles (13.2 mm^2 each), each divided diagonally into black and white triangular halves. (Fig 1.) A change in grid orientation (90, 180, or 270 degrees, chosen randomly) indicated the start of a new trial, and the grid's orientation remained constant throughout a trial's duration. Trials were separated by 20 ms empty intervals during which the screen was gray. In the auditory condition the to-be-timed stimulus was a 500 Hz square tone played through external computer speakers, with a 20 ms empty (silent) interval between each trial. During the auditory condition, the monitor of the computer used to present the CTET displayed a black screen with a white fixation cross.

2.2.1 Continuous Temporal Expectancy Task Analysis—As noted earlier, responses (spacebar presses) recorded within 2.46 seconds after termination of a target interval were coded as hits; responses occurring outside of this window were coded as false alarms (FAs). To examine changes in timing performance as a function of time-on-task, we calculated the percent hits and FAs for each minute of the four-minute runs. Because target stimuli occurred randomly throughout the four-minute run, the number of targets and nontargets (standard-duration stimuli) presented in each minute varied (range = 4–8 for targets; 32–50 for standards). To account for this variability, the averages for the percent hits and FAs for each minute were weighted by the number of possibilities (target and standard stimuli) for that type of response in that minute.

Previous studies using the CTET have focused on hits, and our own earlier study suggests that this may be the dependent variable most sensitive to group differences (O'Connell et al., 2009; Berry et al., 2013; Li, Lin, Berry, & Lustig, 2013). However, for completeness we also assessed standard signal-detection measures of sensitivity (d') and bias (Swets, Tanner, & Birdsall, 1961). d' was calculated from the proportions of hits (P_H) and of false alarms (P_{FA}) using the standard formula: $d' = z(P_H) - z(P_{FA})$ (Green & Swets, 1966). The following substitution was made for hit rates of 100%: 1 – 1/(2N), where N is the number of targets. For FA rates of 0, we used 0.002 as a substitution value approximating a percentage equivalent to half a FA (1/(2N) where N is the number of standard-duration stimuli). Bias measures were calculated using the formula $B''_D = [(1-P_H)(1-P_{FA}) - P_H P_{FA}]/[(1-P_H)(1-P_{FA}) + P_H P_{FA}]$ (Donaldson, 1992). Bias scores range from −1 to + 1, with −1 indicating a liberal response bias, and +1 indicating a conservative response bias. These analyses are reported in the Appendix.

2.3 Questionnaires

2.3.1 Poor Attentional Control (PAC) scale—Participants completed 36 items from the Imaginal Processes Inventory (IPI) (Singer & Antrobus, 1970). Each item consisted of a statement (ex. “I find it difficult to concentrate when the TV or radio is on”), and participants rated the degree to which they identified with each statement on a scale from 1 to 5. Our analyses focus on the 15 items that make up the Poor Attentional Control (PAC) subscale identified in a later factor analysis (Huba, Singer, Aneshensel, & Antrobus, 1982). The PAC has good internal consistency (coefficient alpha = .83) and test-retest reliability (r = .73; see also Tanaka & Huba, 1985–1986).

The PAC is further subdivided into measures of distractibility, mind-wandering, and boredom, with 5 questions each. Although Huba et al. (1982) do not provide psychometric data on these subscales, analyses of a large dataset from our lab (N = 510) indicate good internal consistency within subscales (mind-wandering coefficient alpha = .84, distraction coefficient alpha = .79, boredom coefficient alpha = .77). Additionally, these scales showed

reasonable discriminant validity (average correlation between subscale total and items not in that subscale all $r < .49$ compared to items in that subscale all $r > .72$).

2.3.2 Cognitive Failures Questionnaire—Participants completed the Cognitive Failures Questionnaire (CFQ) (Broadbent, Cooper, FitzGerald, & Parkes, 1982) which asked participants to rate how frequently they find themselves making minor mistakes (ex. "Do you fail to listen to people's names when you are meeting them?"). The questionnaire is composed of 25 questions, and possible answers ranged from 0–4 (never-very often). A single CFQ score was determined by summing all responses. We included the CFQ to keep the experimental session the same as in our previous studies using the CTET; however it does not typically show correlations with CTET performance and will not be discussed further here.

2.3.3 Video content quiz and post-experiment questionnaire—Upon completion of the CTET, participants answered a questionnaire containing 15 multiple-choice questions that assessed their memory of the distracting video clip content. Afterwards, participants were asked to rate the level of mind-wandering, distractibility, and boredom they experienced during the task. These questions were intended to be similar in form and content to items from the PAC. Participants were given five statements and asked to rate the degree to which they identified with each statement on a scale from 1 to 5. (See Table 2.) Questions 1, 2, and 4 measured mind-wandering, question 3 measured boredom, and question 5 measured distractibility. When we first constructed the ratings we emphasized mind-wandering (3 questions) as that had been the focus of the original O'Connell et al (2009) paper. However, subsequent analyses pooling across experiments in our lab using the CTET with distraction, PAC, and these questions show that question 4 consistently shows the highest correlations with the PAC mind-wandering score and with CTET performance. For that reason, and so that an equal number of items are used for the mind-wandering, distractibility, and boredom scores, we focus on question 4 as the "state" measure of mind-wandering.

In that pooled dataset ($n = 128$), correlations between these "state" items and PAC "trait" measures were in the expected direction (mind-wandering: $r = .34$, $p < .001$; distractibility: $r = .46$, $p < .001$; boredom: $r = .30$, $p < .001$). If only the current dataset ($n = 64$) is examined, the patterns are similar, though in some cases with slightly smaller effect sizes (mind-wandering: $r = .29$, $p = .02$; distractibility: $r = .27$, $p = .03$; boredom: $r = .32$, $p = .01$).

3. Results

3.1 Summary and analysis plan

Figure 2 shows the average accuracy (percent of correctly-detected targets) for each modality and distraction condition for each of the four minutes of the run. (Secondary analyses showed that all time-on-task effects occurred within runs; there were no significant cross-run main effects or interactions that would indicate systematic changes in performance across the experimental session.) As expected, we replicated the standard finding of better performance in judgments of the duration of auditory stimuli than of visual stimuli. Both modalities were affected by distraction and time-on-task. While the impact of distraction was equivalent across modality, declines in performance over time were greater for the visual modality.

Section 3.2 provides the formal statistical analyses of these patterns for hits (correct detections of the target duration). Analyses of false alarms and signal detection measures are presented in the Appendix. Each dependent measure was analyzed using a mixed-design ANOVA with the between-subjects factor modality (visual, auditory), and within-subjects

factors distraction (No Distractor, Distractor), and time (minute 1, 2, 3, 4). The Greenhouse-Geisser sphericity correction was applied as needed. In the text, degrees of freedom are rounded to the nearest integer for ease of reading. For repeated-measures ANOVAs, effect sizes for significant effects and interactions were computed using generalized eta squared (η^2_G) (Bakeman, 2005), which gives smaller values than the frequently-used η^2_P but is preferable as it reduces error when comparing across studies (Fritz, Morris, & Richler, 2012).

Section 3.3 provides the results from the questionnaire measures and their correlations with CTET performance. Given the large number of possible correlations, unless otherwise noted we restricted our analyses to those questions of theoretical interest and comparisons consistent with patterns we see in our other datasets using the (visual) CTET with distraction and these questionnaires. Deviations from those expected patterns are noted in the text. For correlations spanning the full dataset (n = 64), power is at .80 for r values of .31 in a one-tailed test, r values of .34 in a two-tailed test. For correlations within each modality condition (n = 32), power is at .80 for r values of .42 in a one-tailed test, .47 in a two-tailed test. Power analyses were conducted using G*Power 3.1.7 (Faul, Erdfelder, Buchner, & Lang, 2009). Full correlation tables are available from the authors on request.

3.2 Continuous Temporal Expectancy Task: Effects of modality, distraction, and time on task

Results from the statistical analyses for percent hits generally followed what would be expected from visual inspection of Figure 2: better overall performance in the auditory condition than in the visual condition, $F(1,62) = 10.27$, $p = .002$, $\eta^2_G = .12$; significantly worse performance under distraction, $F(1,62) = 51.36$, $p < .001$, $\eta^2_G = .05$, and declining performance as a function of time-on-task, $F(2,152) = 36.87$, $p < .001$, $\eta^2_G = .04$.

The only interaction to reach statistical significance was that between modality and time, $F(3,186) = 7.11$, $p < .001$, $\eta^2_G = .01$, suggesting a steeper time-on-task performance decline in the visual condition. Follow-up analyses indicated that the visual condition's greater sensitivity to time-on-task declines was significant for both No Distractor and Distractor conditions (No Distractor: $F(3,186) = 3.99$, $p = .009$, $\eta^2_G = .01$; Distractor: $F(3,186) = 3.57$, $p = .02$, $\eta^2_G = .01$). Distraction did not interact with modality or time-on-task effects, nor did the 3-way interaction approach significance, both $F < 1$.

3.3 Questionnaires

3.3.1 Average results and group comparisons—Overall the groups were quite similar in both their trait (PAC) and state (post-test questionnaire) ratings, and in their performance on the surprise quiz for memory for the distractors. (Table 2). The only difference to approach significance was a trend for participants in the visual condition to report more difficulty ignoring distraction during the task (Question 5), $t(62) = 1.89$, $p = .06$, $d = 0.47$. This trend is consistent with the idea that visual stimuli may capture and hold attention less automatically than do auditory stimuli, but should be interpreted with caution given the large number of comparisons.

3.3.2 Correlations—In previous community-based datasets using a wide range of participants including those with conditions expected to affect attentional function, the PAC distractibility score has correlated with the size of the distractor effect (r = .26 – .43; Berry et al., 2013; Kim et al., 2013). The present data showed a trend in this direction but it did not approach significance either when collapsing across modalities or within each modality, all $r < .24$, $p > .13$). In this dataset, performance in the visual condition correlated with PAC mind-wandering ($r = -.50$, $p = .004$) and distractibility ($r = -.37$, $p = .04$). However, these

correlations are not present in the auditory condition (both $r < .01$) and appear only sporadically in our other datasets (r values ranging from −.06 to −.39) and therefore we report them here for completeness but do not interpret them strongly. As we will discuss further in Section 4, it is currently unclear whether these differences from our previous study are the result of differences in sample composition (community vs university-based) or sample size.

Correlations between performance and task-specific measures of subjective attention measured in the post-test questionnaire were more consistent and compelling. (Figures 3 and 4; similar patterns are found when d' rather than percent hits is used as the criterion measure). We tested the relationship between timing performance and these state measures of attention (mind-wandering, distractibility, and boredom) separately for each modality (visual, auditory), resulting in a total of six comparisons. Significant correlations reported below survive a Bonferroni correction ($p < .008$).

For both the visual and auditory conditions, consistent with our other datasets, target detection was negatively correlated with self-rated difficulty in keeping attention focused on the task (visual: $r = -.49$, $p = .004$; auditory: $r = -.51$, $p = .003$) (Figure 3). However, there were also some important differences between the modalities: In the visual condition, target detection was negatively related to self-reported distractibility ($r = -.55$, $p = .001$) but not to boredom ($r = -.27$, $p = .13$), whereas the opposite pattern was observed in the auditory condition (distractibility: $r = -.29$, $p = .11$; boredom: $r = -.51$, $p = .003$) (Figure 4). Taken together, these patterns suggest that while poor performance in both the visual and auditory conditions may be related to mind-wandering, the underlying reasons may be somewhat different.

Specifically, poor performance in the visual condition may be more strongly related to ability ("No matter how hard I tried to concentrate…") whereas performance in the auditory condition may be more influenced by boredom and willingness to engage in the task. As an exploratory test of this possibility, we used partial correlation analyses to examine how the relation between the attention focus question and detection of the target duration might be affected by controlling for distractibility and boredom for the two modalities. For the visual modality, controlling for self-rated distractibility reduced the relation between self-rated difficulty in keeping attention focus and detection of the target duration (from $r = -.49$, $p = .004$ to $r = -.37$, $p = .04$); controlling for self-rated boredom also reduced this relationship, but only by half as much (to $r = -.43$, $p = .02$). The opposite pattern occurred for the auditory modality: Controlling for self-rated distractibility had little effect on the relation between ratings of attention focus and target detection (small change from $r = -.51$, $p = .003$ to $r = -.45$, $p = .01$), whereas controlling for boredom eliminated this relationship ($r = -.27$, $p = .14$). Thus, although difficulties maintaining attention focus are related to poor performance in both the visual and auditory modalities, that relationship is driven by different factors for the two modalities.

Finally, the magnitude of the distractor effect (reduction in percent hits between the No Distractor and Distractor conditions) was positively related to memory for the content of the distractors as assessed by the surprise multiple-choice quiz at the end of the session. This pattern has been observed in some but not all of our previous datasets; in the present dataset it only reached traditional significance levels for the visual condition ($r = .39$, $p = .03$; for the auditory condition $r = .28$, $p = .12$; when the results for the two modalities are combined $r = .32$, $p = .01$). Power issues due to moderate sample sizes may play a role in the failure to detect a significant correlation in the auditory condition. (For a 2-tailed test, $p < .05$; power is estimated at .35 for $r = .28$, .61 for $r = .39$). However, given the somewhat sporadic nature

of this correlation across different datasets, it should be interpreted with some caution pending further replication.

4. Discussion

Our results replicate classic findings regarding modality effects in interval timing, and revealed new patterns that may shed light on the role played by different aspects of attention. First, we found the typical result that performance was better for duration judgments on auditory stimuli than on visual ones. Second, we found that although performance declined as a function of time-on-task for both modalities, this decline was more pronounced in the visual condition, replicating and clarifying patterns earlier found by Wearden, Pilkington and Carter (1999) using a temporal generalization task. Third, we found that although distraction reduced performance, it did not exacerbate modality effects. This finding has some precedent in bisection experiments with healthy young adults, where both modality and divided attention manipulations affect performance but do not interact (Lustig & Meck, 2001; Penney et al., 2000). However, those previous experiments divided attention by introducing multiple to-be-timed stimuli; the present study extends those results by testing the effects of an external, to-be-ignored distractor. Finally, our individual-difference analyses suggest that difficulties maintaining attentional focus are related to poor performance for both modalities, but may be more driven by distractibility in the visual condition and more by boredom and a failure to stay engaged in the task in the auditory condition.

Together, our results indicate that multiple aspects of attention influence duration judgments. In particular, those aspects leading to modality differences appear to be related to those related to sustaining attention and performance over time, but independent of those related to avoiding distraction. In addition, different factors may be driving attention lapses and poor performance in the different modalities. These findings raise several questions, including whether they are unique to temporal processing and how current models of interval timing might explain them.

As described in the Introduction (Section 1), evidence that auditory stimuli capture attention more automatically than visual ones comes from a wide variety of cognitive tasks, not just interval timing. However, there may be a special role for the auditory system in temporal processing: Several neuroimaging studies have found that regions involved in auditory processing (particularly along the superior temporal and angular gyri) are active during both auditory and visual timing, while the reverse is not true, leading to the suggestion that visual stimuli may be transformed to auditory representations for temporal processing (Grahn, Henry, & McAuley, 2011; Jantzen, Steinberg, & Kelso, 2005; Karabanov, Blom, Forsman, & Ullen, 2009; Konoike et al., 2012). If so, this extra transformation would provide another opportunity for noise and variability to be introduced when processing the duration of visual stimuli, reducing the precision of their representations.

This perspective conceptualizes attention's role in modality effects at a relatively low level of perceptual attention influencing the precision of representations. Noisier representations of visually-presented durations could explain the more pronounced time-on-task declines for the visual condition: Degraded or less distinctive stimuli place larger demands on sustained attention and lead to steeper time-on-task performance declines (Nuechterlein, Parasuraman, & Jiang, 1983). In contrast, requirements to divide attention or ignore distraction may place demands on executive functions involved in allocating attention across tasks and keeping attention directed away from the distractor, rather than on the processing of the target stimulus representation per se. This would in turn explain why, in this study and others,

modality effects are relatively independent of those higher-order executive functions, at least in healthy young adults.

As noted earlier, older adults often show a different pattern of interactions between modality effects and higher attention functions, especially divided attention (e.g., Lustig & Meck, 2001; see also McAuley, Miller, Wang, & Pang, 2010 for evidence from the peak procedure). Age-related declines in the dopaminergic system contribute to declines in the fidelity of low-level sensory representations as well as higher-order executive functions (Li, Lindenberger, & Sikstrom, 2001), and this system is critical for timing (Coull, Cheng, & Meck, 2011; Meck, 1996). Furthermore, older adults compensate for age-related declines in lower-level functions by increasing executive attention at earlier levels of task difficulty, with the cost of reduced performance as executive demands increase (Reuter-Lorenz & Cappell, 2008). This view predicts that if stimuli were sufficiently degraded, young adults might also begin to show interactions between perceptual and divided-attention demands.

The question of age differences points out a limitation of the present study: the relatively small range of age and ability. For the visual condition, we replicated some but not all of the correlation patterns seen in our other datasets using this task. It is possible that those patterns are not robust, or that they were not detectable here due to sample size or power issues. However, a more likely explanation is restriction of range effects related to the homogeneity of the current sample (students in an introductory psychology course) compared to our other work using community-based samples that have a wider range of age and socioeconomic status. The limitations of undergraduate samples is a topic of increasing interest in psychology and related disciplines (Henrich, Heine, & Norenzayan, 2010), although a verdict on the present findings can only be reached by replication.

In contrast, the correlations between task performance and the post-test questionnaire measures of subjective attention are quite striking, particularly the different patterns found for the auditory and visual conditions (Figure 4). However, these too should be treated with some caution until further replication, especially since they are based on single items. We are continuing to investigate these issues using varied populations and direct manipulations of factors such as motivation (Kim et al., 2013; Li et al., 2013).

Finally, there is the question of how the present results fit with current models of interval timing. We are not aware of a detailed treatment of how different aspects of attention may function in SET and other pacemaker-accumulator models. One possibility is that low-level perceptual attention and representational distinctiveness operate primarily at the “switch”, whereas those aspects of attention more strongly related to executive control act at the memory and/or decision stages. Applying this model to the current findings, modality differences may primarily arise when aspects of attention act at the level of the switch rather than when attention acts at the memory and/or decision stages.

Another intriguing perspective is offered by more recent, neurobiologically-realistic models such as the striatal beat frequency (SBF) model, in which temporal information is derived from oscillations in the activity of the cortical neurons representing the to-be-timed stimulus (Buhusi & Meck, 2005; Coull et al., 2011; Matell & Meck, 2004). This perspective offers an immediate mechanism for modality effects: Oscillations in visual neurons may be inherently noisier, or as suggested above, noise may be introduced if visual representations are translated to an auditory code for temporal processing. Early versions of the SBF model did not specifically address questions of attention, especially at the executive control level. However, recent efforts to integrate SBF with more comprehensive models of cognition such as ACT-R could provide a framework for their operation (Van Rijn, Gu, & Meck, in prep.).

5. Summary

Our findings replicate classic modality effects in interval timing, and provide new data that may help elucidate how different aspects of attention do – or do not – play a role in such effects. Specifically, they suggest time-on-task challenges to sustained attention differentially impact temporal processing in the visual modality, while distractor challenges that divide attention cause equivalent disruption across modalities. The individual-differences analyses suggest that visual and auditory temporal processing both require an attentional focus on time. However, for visual stimuli lapses in this focus may be more related to distractibility, whereas for auditory stimuli they may be more related to boredom. These findings are intriguing but require replication and direct manipulation of factors influencing attentional performance, such as motivation.

William James's quote "Everybody knows what attention is" has wide renown, but few people are familiar with his discussion of the different varieties of attention and their roles in cognitive function (James, 1890/1983). Likewise, the critical role of attention in the perception of time is recognized both in popular culture ("A watched pot never boils") and formal models of temporal processing, but the role of different components of attention (e.g., sustained attention, divided attention, selective attention) remains underspecified. By incorporating a multifaceted view of attention and how those facets interact with factors such as motivation and arousal, interval timing models may be better able to account for individual and group differences in temporal processing, as well as differences within the same individual that occur with changes in variables such as emotion and circadian phase.

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Appendix

Table 1A

ANOVA results for each performance measure (hits, false alarms, d', and bias). Each of these measures was analyzed using mixed-design ANOVA with the between-subjects factor modality (visual, auditory), and within-subjects factors distraction (No Distractor, Distractor), and time (minute 1, 2, 3, 4). The Greenhouse-Geisser sphericity correction was applied as needed.

	Modality	**Distraction**	**Time**	**Modality * Distraction**	**Modality * Time**	**Distraction * Time**	**Distraction * Time * Modality**
	df (1,62)	df (1,62)	df (3,186)	df (1,62)	df (3,186)	df (3,186)	df (3,186)
Hits	F = 10.27	F = 51.36	F = 36.87	F = 0.05	F = 7.11	F = 1.07	F = 0.17
	p = 0.002	p < 0.001	p < 0.001	p = 0.83	p < 0.001	p = 0.36	p = 0.92
FA	F = 1.26	F = 0.82	F = 0.70	F = 3.80	F = 0.42	F = 1.43	F = 0.64
	p = 0.27	p = 0.37	p = 0.53	p = 0.06	p = 0.74	p = 0.24	p = 0.59
d'	F = 9.25	F = 50.68	F = 22.37	F = 0.67	F = 5.66	F = 1.68	F = 0.35

	Modality	Distraction	Time	Modality * Distraction	Modality * Time	Distraction * Time	Distraction * Time * Modality
	p = 0.003	p < 0.001	p < 0.001	p = 0.42	p = 0.001	p = 0.17	p = 0.79
D''_D	F = 2.48	F = 1.10	F = 7.70	F = 2.35	F = 0.48	F = 0.55	F = 1.13
	p = 0.12	p = 0.30	p = 0.001	p = 0.13	p = 0.70	p = 0.59	p = 0.34

Exact p values are provided for p = .005 and greater; smaller p values are noted as p < .001.

Hit and d' results were in strong agreement as both measures showed main effects of modality, distraction, time, and significant modality by time interactions. Effect sizes were also similar: $\eta_G^2=0.11$ for the effect of modality, $\eta_G^2=0.05$ for distraction, $\eta_G^2=0.03$ for time, and $\eta_G^2=0.01$ for the time by modality interaction.

For FAs, there were no significant main effects or interactions. Overall, the rate of FAs was very low (less than 1.2% in any cell) and was stable across modality, time and distraction. The only interaction to come close to statistical significance was between distraction and modality. This trend was driven by a significant increase in FAs for the auditory condition when tested under distraction, $F(1,31) = 5.63$, $p = 0.02$, $\eta_G^2<0.001$, whereas the visual condition did not show a change in FAs under distraction, $F(1,31) = 0.43$, $p = 0.52$. The reasons for this are not entirely clear but may be due to enhanced interference of the auditory distraction on the auditory CTET stimulus processing.

The analysis of B''_D revealed participants were overall quite conservative and became moreso as a function of time-on-task. Only the main effect of time-on-task reached statistical significance.

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Highlights

- We examined how modality, distraction, and time-on-task affect duration judgments
- Findings reproduced classic modality effects. These appeared independent of distraction but not time-on-task.
- Individual differences analyses suggest different factors driving performance across modalities.
- Attention's role in timing and modality effects may be more complex than originally conceived.

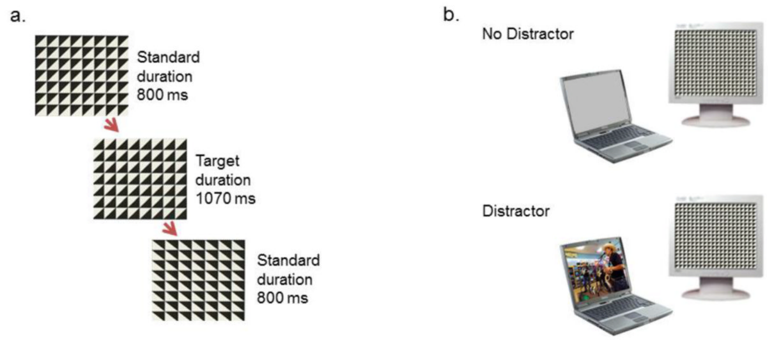

Figure 1. Continuous temporal expectancy task (CTET) with distraction

a. As described in the text (Section 2.2) durations were presented either in the form of a grid that rotated to indicate a new to-be-timed duration, or a square tone. The participant's task was to press the spacebar in response to the longer target duration. b. The distractor manipulation was implemented using a laptop computer oriented 32° to the left of the CTET task computer, and 65 cm from the participant. In the No Distractor condition, the laptop was silent and displayed a solid grey screen. In the Distractor condition, the laptop played 30 second video clips, including the audio component. The illustration here uses the visual CTET; in the auditory version the screen of the main (CTET) computer was grey and the tone played over the computer speakers.

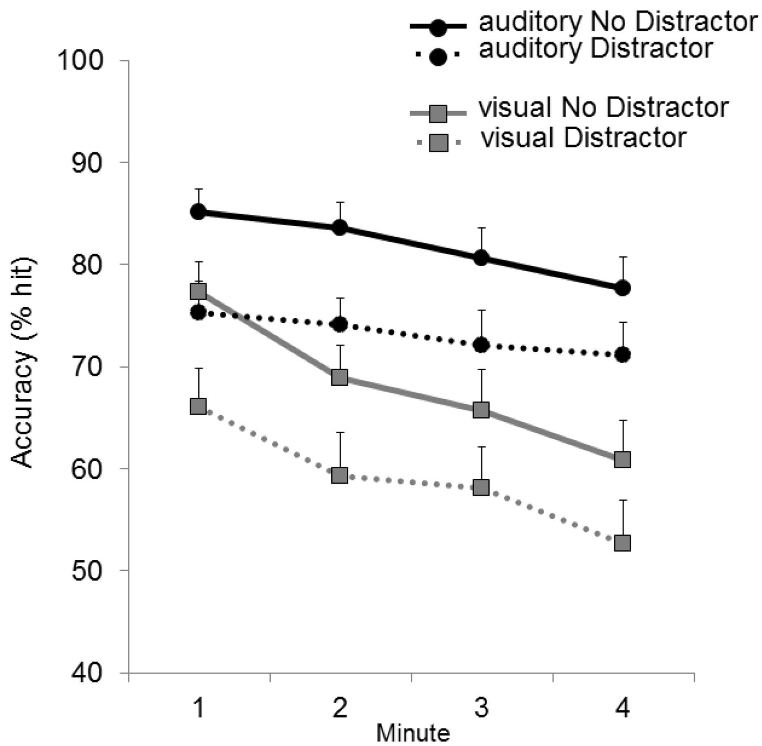

Figure 2. Detection of the target duration is affected by modality, distraction, and time on task
See section 3.2 for statistical analyses; Table 1 for other performance measures (false alarms, d', bias). As expected, the rate of correct target detection is higher in the auditory condition than the visual one. Distraction and time-on-task also lead to performance decrements, but only time-on-task interacts with modality.

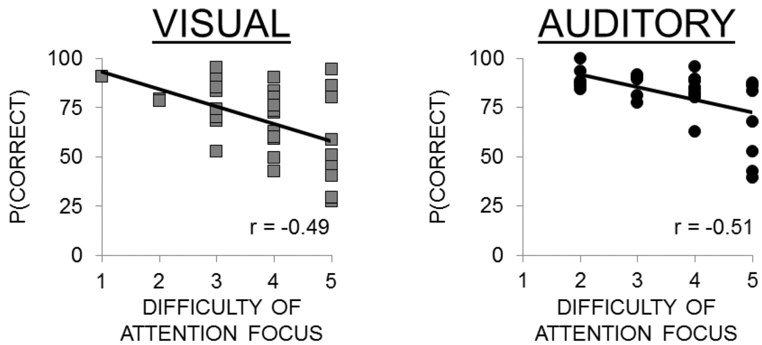

Figure 3. For both modalities, performance was negatively correlated with self-rated difficulty of attention focus

(“I had difficulty in keeping my attention focused on this long, tedious task.”).

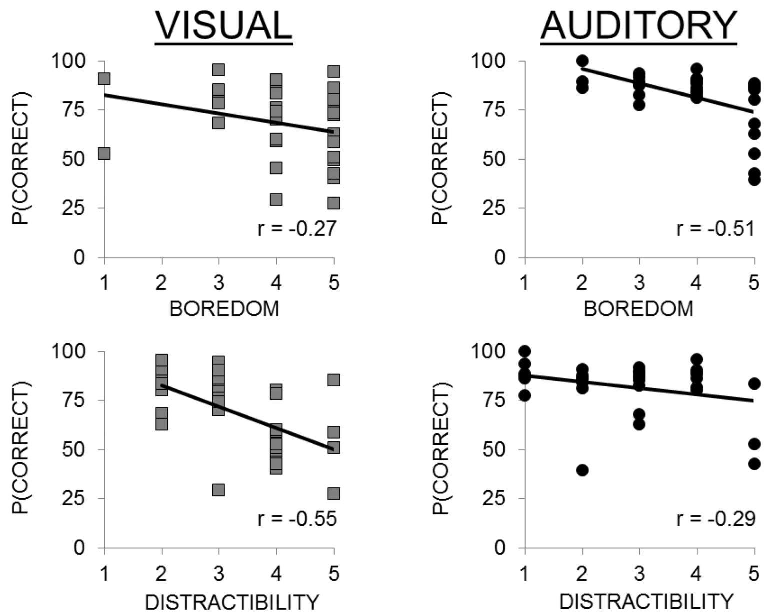

Figure 4. Performance was negatively related to self-rated distractibility in the visual condition, self-rated boredom in the auditory condition

After the CTET, participants completed a questionnaire including ratings of self-reported distractibility and boredom (1 = strong disagreement, 5 = strong agreement; see Table 2). As seen above, failures to detect the target were associated with distractibility in the visual CTET, boredom in the auditory CTET. As described in the main text (Section 3.3.2), these factors (distractibility for visual; boredom for auditory) appear to mediate the correlation between performance and attention focus seen in Figure 3.

Table 1

Means and standard deviations for each performance measure (hits, false alarms, d', and bias).

	Minute 1	Minute 2	Minute 3	Minute 4
Vis No Distractor Hits (%)	77.25 *(16.91)*	68.84 *(18.10)*	65.73 *(22.62)*	60.82 *(22.22)*
Vis Distractor Hits (%)	66.07 *(21.41)*	59.27 *(24.14)*	58.11 *(22.71)*	52.66 *(23.66)*
Aud No Distractor Hits (%)	85.18 *(12.68)*	83.54 *(14.17)*	80.62 *(16.60)*	77.70 *(17.52)*
Aud Distractor Hits (%)	75.29 *(17.75)*	74.07 *(15.12)*	72.11 *(19.52)*	71.14 *(18.30)*
Vis No Distractor FA (%)	1.08 *(2.02)*	1.13 *(2.18)*	1.01 *(1.87)*	1.11 *(1.75)*
Vis Distractor FA (%)	1.03 *(2.18)*	1.10 *(1.75)*	0.87 *(1.33)*	1.01 *(1.27)*
Aud No Distractor FA (%)	0.56 *(1.44)*	0.46 *(1.24)*	0.68 *(1.22)*	0.42 *(0.93)*
Aud Distractor FA (%)	0.81 *(1.15)*	0.93 *(1.94)*	0.59 *(0.97)*	0.67 *(1.35)*
Vis No Distractor d'	3.46 *(0.94)*	3.12 *(0.89)*	3.06 *(1.03)*	2.81 *(0.90)*
Vis Distractor d'	3.08 *(0.95)*	2.78 *(1.00)*	2.77 *(0.86)*	2.54 *(0.85)*
Aud No Distractor d'	3.88 *(0.74)*	3.83 *(0.72)*	3.62 *(0.79)*	3.58 *(0.81)*
Aud Distractor d'	3.37 *(0.74)*	3.31 *(0.72)*	3.32 *(0.72)*	3.27 *(0.76)*
Vis No Distractor B''_D	0.90 *(0.16)*	0.94 *(0.11)*	0.95 *(0.06)*	0.96 *(0.05)*
Vis Distractor B''_D	0.95 *(0.07)*	0.97 *(0.04)*	0.97 *(0.03)*	0.97 *(0.04)*
Aud No Distractor B''_D	0.90 *(0.14)*	0.91 *(0.11)*	0.91 *(0.13)*	0.95 *(0.06)*
Aud Distractor B''_D	0.87 *(0.26)*	0.92 *(0.16)*	0.92 *(0.17)*	0.93 *(0.16)*

Table 2

Self-report ratings of trait (PAC) and state (exit questionnaire) subjective attention, and performance on the post-CTET quiz on content of video distractors.

		VISUAL	AUDITORY
PAC Mind-Wandering			
	mean	14.78	14.41
	SD	*3.84*	*3.31*
PAC Boredom			
	mean	13.00	13.41
	SD	*3.87*	*3.50*
PAC Distractibility			
	mean	15.53	14.34
	SD	*3.48*	*3.14*
Exit questionnaire			
1.At times of this task, it was hard for me to keep my mind from wandering			
	mean	4.03	3.38
	SD	*0.86*	*1.16*
2.(*reverse scored*) During the task, my thoughts seldom drifted from the subject before me.			
	mean	3.75	3.75
	SD	*0.88*	*0.92*
3.I was easily bored during this task.			
	mean	4.09	3.94
	SD	*1.09*	*0.98*
4. I had difficulty in keeping my attention focused on this long, tedious task.			
	mean	3.84	3.56
	SD	*1.05*	*1.13*
5.No matter how hard I tried to concentrate, I felt easily distracted by the videos playing			
	mean	3.34	2.81
	SD	*0.97*	*1.26*
Surprise quiz			
% correct recognition of distractor content			
	mean	74.57	72.08
	SD	*18.42*	*14.21*