Acta Psychologica 147 (2014) 42–50

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

Shared and distinct factors driving attention and temporal processing across modalities

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ARTICLE INFO

Article history:
Received 20 January 2013
Received in revised form 22 July 2013
Accepted 28 July 2013
Available online 24 August 2013

PsycINFO classification:
2320
2340
2346

Keywords:
Interval timing
Attention
Modality
Distraction
Sustained attention
Individual differences

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 (Penney, Gibbon, & Meck, 2000). 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.

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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 (Liu, 2001; Posner, 1976; Schmitt, Postma, & De Haan, 2000; Spence & Driver, 1997) and emerging neural (Chen, Huang, Luo, Peng, & Liu, 2010) support. The relative automaticity of attention to auditory stimuli is often used to 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, 1964b; 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

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http://dx.doi.org/10.1016/j.actpsy.2013.07.020

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 et al. (2000) noted, 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 (Droit-Volet, Meck, & Penney, 2007; Droit-Volet, Tourret, & Wearden, 2004; Lustig & Meck, 2001), 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; Demeter, Guthrie, Taylor, Sarter, & Lustig, 2013; Nuechterlein, Luck, Lustig, & Sarter, 2009; Wohlberg & Kornetsky, 1973), 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. Second, 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, et al. (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

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