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Representations of temporal information in short-term memory: Are they modality-specific?☆

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ABSTRACT

Rattat and Picard (2012) reported that the coding of temporal information in short-term memory is modality-specific, that is, temporal information received via the visual (auditory) modality is stored as a visual (auditory) code. This conclusion was supported by modality-specific interference effects on visual and auditory duration discrimination, which were induced by secondary tasks (visual tracking or articulatory suppression), presented during a retention interval. The present study assessed the stability of these modality-specific interference effects. Our study did not replicate the selective interference pattern but rather indicated that articulatory suppression not only impairs short-term memory for auditory but also for visual durations. This result pattern supports a crossmodal or an abstract view of temporal encoding.

1. Introduction

Processing of temporal information is an important function of the cognitive system. Temporal information is required in many processes such as anticipating and estimating the duration of events, and initializing coordinative behavior. Even basic learning processes like classical conditioning would be impossible without temporal processing. In order to utilize temporal information, this information needs to be maintained within the organism at least for short periods of time. Therefore it is important to understand how temporal information is encoded and maintained in short-term memory. There are at least three different views regarding this matter.

First, it has often been suggested that the memory representation of temporal information is based on accumulation of internal signals like neural pulses or ticks elicited by an internal pacemaker (Creelman, 1962; Gibbon, Church, & Meck, 1984; Treisman, 1963). Within the framework of such pacemaker-accumulator models, the number of accumulated pulses represents the duration of an interval as an abstract amodal code (Rammsayer & Ulrich, 2005; Wearden, Todd, & Jones, 2006). Second and more recently, it has been suggested that temporal information is primarily encoded in the auditory system (crossmodal encoding; Bratzke, Seifried, & Ulrich, 2012; Guttman, Gilroy, & Blake, 2005; Kanai, Lloyd, Bueti, & Walsh, 2011). This view assumes that irrespective of input modality, temporal information is stored as an auditory representation because the auditory system is especially suited for temporal processing (Welch & Warren, 1980). Third, another recent view holds that the representation of temporal information is specific to the sensory input modality. This view is implied by intrinsic timing models which assume that temporal processing is an inherent feature of early sensory processing (Buonomano & Karmarkar, 2002; Ivry & Schlerf, 2008).

There is evidence for each of these views. First, an *amodal view* appears plausible because it is possible to compare short durations not only within the same modality but also across modalities. Moreover, differences in discrimination of visual and auditory durations are consistent with the amodal view if one assumes that the pacemaker runs faster for auditory than for visual input (Ulrich, Nitschke, & Rammsayer, 2006; Wearden, Edwards, Fakhri, & Percival, 1998). Second, the *crossmodal view* receives support from transcranial magnetic stimulation (TMS) studies showing that disruption of the primary auditory cortex not only impairs discrimination of auditory but also of visual (Kanai et al., 2011) and tactile durations (Bolognini, Papagno, Moroni, & Maravita, 2010). In addition, incongruent information impairs visual rhythm discrimination more strongly if it is presented in the auditory rather than in the visual modality (Guttman et al., 2005). Similarly, duration perception of visual intervals is much more strongly impaired by irrelevant auditory information than vice versa (Bausenhart, de la Rosa, & Ulrich, 2014). Moreover, Bratzke et al. (2012) found that perceptual learning of temporal discrimination transfers from the auditory to the visual modality but not vice versa. Third, one piece of evidence supporting the *modality-specific view* is the

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finding of modality-specific subjective shortening effects. That is, Takahashi and Watanabe (2012) reported subjective shortening of perceived duration with increasing delay between a standard and a comparison duration, when the comparison was visual but not when it was auditory (but see Wearden, Goodson, & Foran, 2007, for subjective shortening also in the auditory modality). Even more direct evidence for the modality-specific view is provided by a recent study by Rattat and Picard (2012), which forms the basis for the present research.

In their study, Rattat and Picard (2012) used an interference paradigm to investigate short-term memory for visual, auditory and visual-auditory durations ranging from 400 to 600 ms. Participants were asked to discriminate between two durations separated by a retention interval of 8 s. During the retention interval they performed either an articulatory suppression task, a visuo-spatial tracking task, or no task at all. The results revealed a selective interference pattern: articulatory suppression impaired discrimination of auditory but not of visual and bimodal durations, and visual tracking impaired discrimination of visual but not of auditory and bimodal durations. This pattern of results strongly supports the modality-specific view. A similar interference effect of articulatory suppression on auditory temporal short-term memory has been reported by Franssen, Vandierendonck, and Van Hiel (2006). Additionally, Rammsayer and Ulrich (2005) also found no interference effect of a visuo-spatial secondary task (pattern recognition) on temporal discrimination of auditory stimuli. However, regarded in isolation, these types of interference would also be consistent with both the amodal and the crossmodal view of temporal short-term memory as described above. Thus, Rattat and Picard's finding of an interference effect induced by visuo-spatial tracking on the memory representation of visual but not of auditory temporal information is especially important for their conclusion in favor of the modality-specific view. Yet, this particular finding appears to be isolated in the literature so far.

Therefore, the present study aimed to provide a further evaluation of the three encoding views. To this end, we employed Rattat and Picard's (2012) interference design but excluded the bimodal condition because this condition is not diagnostic for the distinction between the different memory views. In order to increase statistical power, we used a within-subject instead of a between-subject design with the same overall number of participants as in their study. According to the modality-specific view, we would expect a selective interference pattern as observed in Rattat and Picard's study. That is, articulatory suppression should impair discrimination of auditory but not of visual durations whereas visual tracking should impair discrimination of visual but not of auditory durations. Under the crossmodal view, articulatory suppression should impair discrimination of both auditory and visual durations whereas visual tracking should not impair discrimination in either modality. For the amodal view, at least two outcomes are conceivable. First, it is possible that the abstract time information is stored at an amodal memory level, as for example in the episodic buffer (Baddeley, 2012). According to this possibility, neither visual nor auditory discrimination performance should be affected by any of the interference tasks. Second, the abstract time information might be retained in the phonological loop and thus the predictions would resemble those of the crossmodal view.

2. Method

2.1. Participants

36 participants (31 women) with a mean age of 22.94 ($SD = 6.81$) years volunteered to take part in two separate sessions of the experiment. They received either course credit or payment for their participation.

2.2. Apparatus and stimuli

The experiment was implemented in Matlab using the Psychophysics Toolbox extension (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007). Participants sat in front of a computer screen with a viewing distance of approximately 70 cm. All auditory stimuli were presented binaurally via headphones. A 500 Hz sinewave tone with a peak amplitude of 65 dB(A) SPL and rise and fall times of 5 ms served as the auditory duration stimulus. There were six different durations of this stimulus: 400, 440, 480, 520, 560, and 600 ms. Also, recordings of ten German syllables ('ar', 'en', 'ip', 'ot', 'uk', 'be', 'to', 'su', 'li', and 'ke'), spoken by a female voice, were each presented with a peak amplitude of 72 dB SPL and served as stimuli for the articulatory suppression task.

All visual stimuli were presented on a white background (81 cd/m^2) on a 17-in. CRT monitor (1024 × 768 pixels) running at 100 Hz. Visual stimuli consisted of a black fixation dot (<1 cd/m^2, 1 mm diameter), a black question mark (3 × 5 mm) which served as response prompt, and a blue square (7.7 cd/m^2, 44 × 44 mm) which served as the visual duration stimulus. All these visual stimuli were presented at the center of the screen. There were six different durations of the visual duration stimulus: 320, 380, 440, 560, 620, and 680 ms. These visual durations span a wider range than the auditory durations (400–600 ms) employed in the present study, and also than the visual durations employed in Rattat and Picard's (2012) original study. We chose these duration ranges in order to compensate for the typically observed larger discrimination thresholds for visual than auditory durations (e.g., Grondin, 1993; Ulrich et al., 2006), such that comparable performance levels would be obtained for the two modalities. In addition, 9 different black shapes (circle, triangle, diamond, cross, pentagon, trapezoid, kite, parallelogram, hexagon, and quadrilobe, all with a diameter of approximately 17 mm) served as stimuli for the visual tracking task. Responses were collected using the 'x' and 'm' keys on a standard German keyboard.

2.3. Procedure

Each participant took part in two experimental sessions, an auditory discrimination session and a visual discrimination session (with a maximum separation of 8 days between the two sessions).

The time course of each trial was as follows: Each trial started with the presentation of the fixation point at the center of the screen. After 750 ms, the first duration stimulus was presented, chosen randomly with equal probability from the six possible durations. In auditory trials, the fixation point remained on the screen during this duration. At the end of the first duration, the 8 s retention interval started with a blank screen. 1000 ms before the end of the retention interval the fixation point reappeared and remained at the center of the screen during presentation of the second duration (only in auditory trials) and for another 1000 ms thereafter (in all trials). The second duration was presented immediately after the end of the retention interval. It was either equal to the first duration (50% "same" trials) or it differed from the first duration (50% "different" trials). In "different" trials, when the first duration was shorter than 500 ms, the second duration was 120 (240) ms longer in auditory (visual) trials. By contrast, when the first duration was longer than 500 ms, the second one was 120 (240) ms shorter in auditory (visual) trials. 1000 ms after the end of the second duration, the fixation point was replaced by a question mark, which prompted participants to indicate whether they perceived the two durations as being equal or different. As soon as a key press was registered, the response prompt disappeared, and the next trial started after another 750 ms.

Within each modality session, participants completed three blocks of trials, each differing in the nature of the interference task presented during the retention interval. In "no interference" blocks, the screen remained empty during the first 7 s of the retention interval. In "visual