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# Single-trial multisensory memories affect later auditory and visual object discrimination

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ABSTRACT

Multisensory memory traces established via single-trial exposures can impact subsequent visual object recognition. This impact appears to depend on the meaningfulness of the initial multisensory pairing, implying that multisensory exposures establish distinct object representations that are accessible during later unisensory processing. Multisensory contexts may be particularly effective in influencing auditory discrimination, given the purportedly inferior recognition memory in this sensory modality. The possibility of this generalization and the equivalence of effects when memory discrimination was being performed in the visual vs. auditory modality were at the focus of this study. First, we demonstrate that visual object discrimination is affected by the context of prior multisensory encounters, replicating and extending previous findings by controlling for the probability of multisensory contexts during initial as well as repeated object presentations. Second, we provide the first evidence that single-trial multisensory memories impact subsequent auditory object discrimination. Auditory object discrimination was enhanced when initial presentations entailed semantically congruent multisensory pairs and was impaired after semantically incongruent multisensory encounters, compared to sounds that had been encountered only in a unisensory manner. Third, the impact of single-trial multisensory memories upon unisensory object discrimination was greater when the task was performed in the auditory vs. visual modality. Fourth, there was no evidence for correlation between effects of past multisensory experiences on visual and auditory processing, suggestive of largely independent object processing mechanisms between modalities. We discuss these findings in terms of the conceptual short term memory (CSTM) model and predictive coding. Our results suggest differential recruitment and modulation of conceptual memory networks according to the sensory task at hand.

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## 1. Introduction

A substantial body of work suggests that multisensory interactions can already occur at early latencies and within primary or near-primary cortices (reviewed in Murray,

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Cappe, Romei, Martuzzi, & Thut, 2012; Van Atteveldt, Murray, Thut, & Schroeder, 2014). Moreover, these interactions have been correlated with behavior (Cappe, Thelen, Romei, Thut, & Murray, 2012; Romei, Murray, Merabet, & Thut, 2007; Thelen, Matusz, & Murray, 2014; Van den Brink et al., 2013; Van der Burg, Talsma, Olivers, Hickey, & Theeuwes, 2011). Cappe et al. (2012) found that increases in neuronal response strength at early latencies were positively correlated with multisensory gains in a motion discrimination task. Similarly, Romei et al. (2007) found correlations between multisensory events and the impact of a TMS pulse delivered over the occipital pole on auditory detection response speed. In another study, Van der Burg et al. (2011) showed auditory facilitation effects in a visual search task modulating activity within parieto-occipital cortices. Following up on the latter results, Van den Brink et al. (2013) found that this facilitation was predicted by the strength of anatomical connections between sub-cortical and cortical auditory structures.

While these and similar data reveal much about the instantaneous interactions between the senses, other studies have focused on how multisensory interactions taking place at one point in time have an impact on subsequent unisensory processing. For example, a large number of studies have investigated how unisensory stimulus discrimination and perceptual learning are affected by prior multisensory experiences (Gottfried, Smith, Rugg, & Dolan, 2004; Nyberg, Habib, McIntosh, & Tulving, 2000; Shams & Seitz, 2008; Shams, Wozny, Kim, & Seitz, 2011; von Kriegstein & Giraud, 2006; Wheeler, Petersen, & Buckner, 2000). Likewise, Meylan and Murray (2007) showed that occipital cortical activation, due to the processing of visual stimuli was significantly attenuated when these stimuli were preceded by a multisensory stimulus. Our group has therefore specifically focused on how multisensory contexts may exert their influences in a more implicit manner and via single-trial exposures (Lehmann & Murray, 2005; Murray, Foxe, & Wylie, 2005; Murray & Sperdin, 2010; Murray et al., 2004; Thelen, Cappe, & Murray, 2012; Thelen & Murray, 2013; Thelen et al., 2014). These studies show that visual object recognition is improved when the initial multisensory context had been semantically congruent and can be impaired if this context was either semantically incongruent or meaningless, when compared to recognition of visual stimuli only encountered in a unisensory visual context. More generally, these "single-trial" memories (i.e. memories that form after a single, initial pairing of a semantically congruent image and sound) of multisensory object associations are formed incidentally (i.e. parenthetically) and despite many intervening stimuli, are distinguishable from encoding processes, and promote distinct object representations that manifest as differentiable brain networks whose activity is correlated with recognition performance (Thelen & Murray, 2013).

Despite these advances in our understanding of multisensory memory and its impact on visual recognition, it is still not clear whether or not auditory object discrimination also benefits from (single-trial) multisensory memories. Some research would emphatically contend that auditory memory is grossly inferior to visual memory (Cohen, Horowitz, & Wolfe, 2009). Memory performance in a recognition task was impaired for sounds that had been paired with a corresponding image during the preceding study phase, as well as when the stimuli for the task were either speech stimuli or clips of music, which were considered to be richer in their content. The only situation wherein recognition memory for sounds was better than that for images was when the images were highly degraded. In terms of a putative explanation, Cohen et al. went so far as to suggest the following: "*. . .auditory memory might be fundamentally different/smaller than visual memory. We might simply lack the capacity to remember more than a few auditory objects, however memorable, when they are presented one after another in rapid succession.*" (p. 6010 of Cohen et al., 2009).

By this account, benefits of multisensory contexts on subsequent unisensory auditory discrimination may not be expected. If true, this would dramatically curtail potential applications of this paradigm to remediation or training situations; a central issue for the development of multisensory rehabilitation strategies across the lifespan (Johansson, 2012; White-Traut et al., 2013). By contrast, an alternative interpretation of the results of Cohen et al. (2009) may be warranted. This is based on an extension of the principle of inverse effectiveness (Altieri, Stevenson, Wallace, & Wenger, 2013; Stein & Meredith, 1993; Stevenson et al., 2014). This interpretation would instead suggest that greater benefits would be observed in the sensory modality wherein information is less effective in eliciting a given behavior. If memory is generally less efficient in the auditory modality, then relatively greater gains from multisensory contexts would be expected. In accordance, Yuval-Greenberg and Deouell (2009) observed that visual information has a greater impact on auditory object identification than vice-versa. Likewise, selective delay-period activity on a delayed match-to-sample task was observed in intracellular recordings from monkey infero-temporal neurons not only when the animal performed a visual-to-visual task, but also when it performed either a visual-to-auditory or auditory-to-visual task (Gibson & Maunsell, 1997). This kind of neural response provides an indication that memory representations can be formed across the senses, and can also be activated by input from either sense alone. Likewise, functional imaging in humans is increasingly documenting the involvement of visual cortices in the categorical processing of sounds either via predictive coding (Vetter, Smith, & Muckli, 2014) or multisensory learning (von Kriegstein & Giraud, 2006; see also Schall, Kiebel, Maess, & von Kriegstein, 2013; Sheffert & Olson, 2004).

It thus remains to be established (1) if auditory object discrimination is affected by single-trial multisensory memories and if so whether this is to the same degree as that observed in the visual modality, and (2) if there is a systematic relationship between memory performance in the visual and auditory modalities. Given these outstanding issues, the present study assessed the efficacy of multisensory exposures on auditory object discrimination during the completion of a continuous recognition task requiring the discrimination of initial from repeated sound object presentations. On the one hand, establishing such an

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