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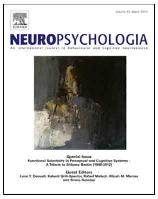

Stimulus intensity modulates multisensory temporal processing

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ABSTRACT

One of the more challenging feats that multisensory systems must perform is to determine which sensory signals originate from the same external event, and thus should be integrated or "bound" into a singular perceptual object or event, and which signals should be segregated. Two important stimulus properties impacting this process are the timing and effectiveness of the paired stimuli. It has been well established that the more temporally aligned two stimuli are, the greater the degree to which they influence one another's processing. In addition, the less effective the individual unisensory stimuli are in eliciting a response, the greater the benefit when they are combined. However, the interaction between stimulus timing and stimulus effectiveness in driving multisensory-mediated behaviors has never been explored – which was the purpose of the current study. Participants were presented with either high- or low-intensity audiovisual stimuli in which stimulus onset asynchronies (SOAs) were parametrically varied, and were asked to report on the perceived synchrony/asynchrony of the paired stimuli. Our results revealed an interaction between the temporal relationship (SOA) and intensity of the stimuli. Specifically, individuals were more tolerant of larger temporal offsets (i.e., more likely to call them synchronous) when the paired stimuli were less effective. This interaction was also seen in response time (RT) distributions. Behavioral gains in RTs were seen with synchronous relative to asynchronous presentations, but this effect was more pronounced with high-intensity stimuli. These data suggest that stimulus effectiveness plays an underappreciated role in the perception of the timing of multisensory events, and reinforces the interdependency of the principles of multisensory integration in determining behavior and shaping perception.

1. Introduction

Our daily environment is filled with an abundance of information that our different sensory systems utilize in order to allow us to successfully navigate the world. Despite the fact that many of the objects and events in our world are specified by information carried by multiple senses, we perceive these as singular and unified. In order to create such a unified percept, the brain must be able to "bind" information that belongs together and segregate information that should be separate. The binding process by which multisensory cues are actively synthesized – a process that represents a component of multisensory integration – has been the subject of much study. Collectively, this work has revealed dramatic changes associated with combining information across multiple senses; changes that frequently result in substantial benefits to behavior (Amlot et al., 2003; Frassinetti et al., 2002; Lovelace et al., 2003) and striking alterations in perception (McGurk and MacDonald, 1976; The Neural Bases of Multisensory Processes, 2012; Shams et al., 2002).

To solve this "binding or causal source problem," sensory systems rely upon the statistical properties of the different sensory signals, two of the most important of which are space and time. Multisensory (e.g., visual-auditory) stimuli that are spatially and temporally concordant tend to influence one another's processing, and may ultimately be integrated or bound, whereas those that are discordant in space and/or time tend to not influence the processing of one another (Conrey and Pisoni, 2006; Hairston et al.,

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2005; Keetels and Vroomen, 2005; Kording et al., 2007; Macaluso et al., 2004; Powers et al., 2009; Sato et al., 2007; Stevenson et al., 2012c, 2012b; van Atteveldt et al., 2007; van Wassenhove et al., 2007; Vroomen and de Gelder, 2004; Vroomen and Keetels, 2010; Wallace and Stevenson, 2014). Furthermore, it has also been shown that stimuli that are weakly effective on their own tend to give rise to the largest gains when combined (James et al., 2009; James and Stevenson, 2012b; James et al., 2012; Ross et al., 2007a; Senkowski et al., 2011; Stein et al., 2009; Stevenson et al., 2012d; Stevenson and James, 2009). Collectively, these integrative principles make a great deal of ethological sense, in that spatial and temporal proximity typically signal a common source, and in that it is highly adaptive to accentuate multisensory gain when each of the sensory signals is weak or ambiguous when presented alone.

Recently, a number of studies have focused on how temporal factors influence the nature of human multisensory perceptual judgments (Billock and Tsou, 2014; Conrey and Pisoni, 2006; Grant et al., 2004; Macaluso et al., 2004; van Wassenhove et al., 2007; Vroomen and de Gelder, 2004; Vroomen and Keetels, 2010). One useful construct associated with this work is the concept of a multisensory temporal binding window, defined as the epoch of time within which multisensory stimuli can influence one another's processing. The window within which multisensory influences can be demonstrated appears to be surprisingly broad, spanning several hundred milliseconds (Hillock et al., 2011; Hillock-Dunn and Wallace, 2012; Powers et al., 2012, 2009; Sarko et al., 2012; Stevenson et al., 2013b). In addition, these studies and others have revealed a number of other salient characteristics concerning multisensory temporal acuity. These include that it: 1) has a great deal of individual variability (Stevenson et al., 2012a; van Eijk et al., 2008), 2) differs depending upon stimulus type and task (Kasper et al., 2014; Megevand et al., 2013; Stevenson and Wallace, 2013; van Eijk et al., 2008, 2010; Vroomen and Stekelenburg, 2011), and 3) is malleable in response to perceptual training (Keetels and Vroomen, 2008; Powers et al., 2012, 2009; Schlesinger et al., 2014; Stevenson et al., 2012c, 2013a, 2013b; Vroomen et al., 2004) and across development (Hillock et al., 2011; Hillock-Dunn and Wallace, 2012; Joanne Jao et al., 2014; Johannsen and Roder, 2014; Lewkowicz, 2012; Polley et al., 2008; Shi and Muller, 2013) and aging (Bates and Wolbers, 2014; DeLoss et al., 2013; Diaconescu et al., 2013; Freiherr et al., 2013; Hugenschmidt et al., 2009; Mahoney et al., 2012, 2014; Mozolic et al., 2012; Stevenson et al., 2015).

Although these studies have illustrated the central importance of time in dictating human multisensory interactions, other studies have focused on the roles of space (Bertelson and Radeau, 1981; Ghose and Wallace, 2014; Kadunce et al., 2001; Krueger et al., 2009; Macaluso et al., 2004; Mahoney et al., 2015; Meredith and Stein, 1986, 1996; Radeau and Bertelson, 1974; Royal et al., 2009, 2010; Sarko et al., 2012; Vroomen et al., 2001; Wallace et al., 2004) and effectiveness (James and Stevenson, 2012a; James et al., 2012; Kim and James, 2010; Kim et al., 2012; Leone and McCourt, 2013; Liu et al., 2013; Nath and Beauchamp, 2011; Stevenson and James, 2009; Werner and Noppeney, 2010; Yalachkov et al., 2015). Collectively, we have learned a great deal from these studies about how stimulus-related factors shape the multisensory process, but most have treated time, space and effectiveness as independent contributors to the final multisensory product. In fact, these stimulus factors are complexly intertwined, with manipulations in one having effects upon the other. For example, simply changing the spatial location of an identical stimulus will impact the effectiveness of that stimulus given the differences in spatial acuity for different regions of space (Nidiffer et al. (2015) (in this issue); Stein et al., 1989). Reinforcing the importance of examining these interactions in more detail, recent neurophysiological studies in animal models have shown that manipulating one aspect of a multisensory stimulus (e.g., spatial location) has consequent effects in both the temporal and effectiveness dimensions (Carriere et al., 2008; Ghose and Wallace, 2014; Krueger et al., 2009; Royal et al., 2009). Indeed, this work has suggested that stimulus effectiveness may play a more preeminent role than space and time in dictating multisensory interactions at the neural level. Extending this work into the domain of human performance, recent studies have shown a strong interdependency between time and space (Keetels and Vroomen, 2005; Krueger et al., 2009; Stevenson et al., 2012c). For example, Keetels and Vroomen (2005) showed that judgments concerning the order of auditory and visual stimuli were more precise when they were presented in disparate spatial locations. Stevenson et al. (2012d) showed that individuals were more likely to perceive auditory and visual stimuli as synchronous when they were presented at peripheral relative to foveal locations.

The present study seeks to expand upon these previous findings by examining for the first time the interaction between the temporal relationship of paired audiovisual stimuli and their relative effectiveness. Specifically, we tested the impact that manipulations of stimulus effectiveness (accomplished via changes in stimulus intensity and defined as rate of perceived synchrony) have on the ability of an individual to report audiovisual stimulus asynchrony. Our results illustrate that the relative effectiveness of the paired stimuli do in fact modulate how they are perceived in time. Furthermore, these studies revealed complex interactions between time and effectiveness in dictating the final behavioral outcome.

2. Methods

2.1. Participants

Participants included 51 Vanderbilt undergraduate students (21 male, mean age=18.9, STD=1, age range=18–21) who were compensated with class credit. All recruitment and experimental procedures were approved by the Vanderbilt University Institutional Review Board (IRB). Data from participants who did not accurately report the perception of synchrony even when the auditory and visual presentation was objectively simultaneous (0 ms stimulus onset asynchrony; SOA) at least 50% of the time were excluded from further analysis (N=5). Data from one additional subject was excluded for responding synchronous for all trials irrespective of SOA resulting in 45 subjects being included in all data analysis. The present study is part of a larger study investigating the interrelationship of stimulus effectiveness, and stimulus spatial and temporal factors (Nidiffer et al. (2015) (in this issue); Stevenson et al., 2012c).

2.2. Stimuli

Visual and auditory stimuli were presented using E-Prime version 2.0.8.79 (Psychology Software Tools, Inc; PST). Visual stimuli were presented on a Samsung Sync Master 2233RZ 120 Hz monitor arranged so that subjects were seated at a distance of 46 cm. All visual stimuli were white circles measuring 7 mm in diameter, or approximately 1° of visual angle. Visual stimuli were presented at 0° azimuth (in front of the subject) slightly above a fixation cross. Visual stimuli were presented at two luminance levels, 7.1 cd/m^2 (low) and 215 cd/m^2 (high) on a black background of 0.28 cd/m^2. Luminance values were verified with a Minolta Chroma Meter CS-100. Visual stimulus durations were 10 ms, with timing confirmed using a Hameg 507 oscilloscope with a photovoltaic cell.

Auditory stimuli were presented via a speaker mounted on the

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