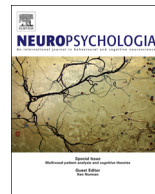




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## Interactions between space and effectiveness in human multisensory performance

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### ABSTRACT

Several stimulus factors are important in multisensory integration, including the spatial and temporal relationships of the paired stimuli as well as their effectiveness. Changes in these factors have been shown to dramatically change the nature and magnitude of multisensory interactions. Typically, these factors are considered in isolation, although there is a growing appreciation for the fact that they are likely to be strongly interrelated. Here, we examined interactions between two of these factors – spatial location and effectiveness – in dictating performance in the localization of an audiovisual target. A psychophysical experiment was conducted in which participants reported the perceived location of visual flashes and auditory noise bursts presented alone and in combination. Stimuli were presented at four spatial locations relative to fixation (0°, 30°, 60°, 90°) and at two intensity levels (high, low). Multisensory combinations were always spatially coincident and of the matching intensity (high-high or low-low). In responding to visual stimuli alone, localization accuracy decreased and response times (RTs) increased as stimuli were presented at more eccentric locations. In responding to auditory stimuli, performance was poorest at the 30° and 60° locations. For both visual and auditory stimuli, accuracy was greater and RTs were faster for more intense stimuli. For responses to visual-auditory stimulus combinations, performance enhancements were found at locations in which the unisensory performance was lowest, results concordant with the concept of inverse effectiveness. RTs for these multisensory presentations frequently violated race-model predictions, implying integration of these inputs, and a significant location-by-intensity interaction was observed. Performance gains under multisensory conditions were larger as stimuli were positioned at more peripheral locations, and this increase was most pronounced for the low-intensity conditions. These results provide strong support that the effects of stimulus location and effectiveness on multisensory integration are interdependent, with both contributing to the overall effectiveness of the stimuli in driving the resultant multisensory response.

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### 1. Introduction

Our brains are continually receiving sensory information from the environment. Each sensory system is tasked with receiving and processing this information and each accomplishes this task in different ways. Often, information from one modality is

accompanied by corresponding information in another, particularly when this information is derived from the same event. To process such stimuli more efficiently, our brains integrate this information, often in ways that result in substantial changes in behavior and perception (Calvert et al., 2004; Murray and Wallace, 2012; Stein and Meredith, 1993). Several of the more familiar and compelling examples of these multisensory-mediated changes in behavior include improvements in target detection (Frassinetti et al., 2002; Lovelace et al., 2003), improvements in target localization and orientation (Ohshiro et al., 2011; Stein et al., 1988), and

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speeding of reaction or response times (RTs; Amlot et al., 2003; Calvert and Thesen, 2004; Corneil et al., 2002; Diederich et al., 2003; Forster et al. 2002; Frens et al., 1995; Harrington and Peck, 1998; Hershenson, 1962; Hughes et al. 1994; Molholm, et al., 2002).

In an effort to “decide” what should be integrated (and what should not be integrated), the brain capitalizes on the statistical regularities of cues from the different senses that provide important information as to the probability that they are related (Alais and Burr, 2004; Altieri et al., 2015; Baier et al., 2006; den Ouden et al., 2009; Massaro, 1984; McIntosh and Gonzalez-Lima, 1998; Polley et al., 2008; Shinn-Cunningham, 2008; Wallace and Stein, 2007). Thus, multisensory integration (and its resultant behavioral and perceptual benefits) is in part determined by physical factors associated with the stimuli to be paired. Several stimulus factors have been identified as being integral to this process. Preeminent among these are the spatial and temporal relationships of the stimuli and their relative effectiveness. As a general rule, the more spatially and temporally proximate two signals are, the more likely they are to influence one another's processing. Furthermore, weakly effective sensory signals typically result in the largest multisensory gains when they are paired, a phenomenon known as inverse effectiveness.

These stimulus-dependent factors and their influence on multisensory processing have proven to be remarkably robust across a wide array of experimental measures. These include: the activity of individual neurons in animal models [*space* (Meredith and Stein, 1986a), *time* (Meredith et al., 1987), *effectiveness* (Meredith and Stein, 1986b)], neural responses in humans as measured by fMRI and PET [*space* (Macaluso et al., 2004), *time* (Macaluso et al., 2004; Miller and D'Esposito, 2005; Stevenson et al., 2010, 2011), *effectiveness* (James and Stevenson, 2012; James et al., 2009, 2012; Nath and Beauchamp, 2011; Stevenson and James, 2009; Stevenson et al., 2009; Werner and Noppeney, 2009)] and EEG [*space* (Zhou et al., 2004), *time* (Schall et al., 2009; Senkowski et al., 2007; Talsma et al., 2009), *effectiveness* (Stevenson et al., 2012)], as well as human behavior and perception [*space* (Bolognini et al., 2005; Frassinetti et al., 2002) but see (Murray et al., 2005), *time* (Conrey and Pisoni, 2006; Dixon and Spitz, 1980; Hillock et al., 2011; Keetels and Vroomen, 2005; Stevenson and Wallace, 2013; Stevenson et al., 2012a; van Atteveldt et al., 2007; van Wassenhove et al., 2007; Wallace et al., 2004), *effectiveness* (Stevenson et al., 2012b; Sumby and Pollack, 1954) but see (Chandrasekaran et al., 2011; Ross et al., 2007)]. It should also be noted here that, aside from these bottom-up factors, other higher-level factors such as task, semantic congruence, and context are likely to also be very important in dictating the final response (Foxy, 2008; Otto et al., 2013; Stevenson et al., 2014; Ten Oever et al., 2013).

Although these factors have largely been studied in an independent manner in this prior work (e.g., exclusive manipulation of the spatial relationship of the paired stimuli), there is an intuitive interdependency between them that has not been thoroughly explored. For example, manipulating the absolute spatial location of multisensory stimuli impacts the relative effectiveness of these stimuli because of, for example, changes in the sensory acuity of the peripheral organs. Indeed, recent neurophysiological (Carriere et al., 2008; Krueger et al., 2009; Royal et al., 2009) and psychophysical (Cappe et al., 2012; Macaluso et al., 2004; Stevenson et al., 2012) studies have begun to shed light on the nature of these interdependencies.

These studies serve as motivation for the current study, which seeks to examine the interdependency of spatial location and stimulus effectiveness in dictating one aspect of human performance – target localization. The work is predicated on the evidence that manipulations of the location of visual or auditory stimuli results in changes in the accuracy related to detecting the location or

changes in the location of the stimuli (Bock, 1993; Carlile et al., 1997; Mills, 1958, 1960; Yost, 1974). Therefore, our hypothesis was that changing the location of a stimulus should result in changes in the effectiveness of that stimulus. In turn, the magnitude of behavioral gains from multisensory presentations should reflect this change of effectiveness across space in a manner mirroring inverse effectiveness, providing insights into how space and effectiveness interact to dictate multisensory responses. To explore this hypothesis, we tested individuals' ability to localize visual, auditory, and paired audiovisual targets as a function of both stimulus location and stimulus intensity. By examining localization accuracy and RTs, we then characterized the multisensory gains seen in responses to these different stimulus combinations (Stevenson et al., 2014). Testing the principles of multisensory integration together and investigating interactions between them would lend support to the notion that the principles are strongly interrelated, and provide novel mechanistic insights into the nature of such interactions.

## 2. Methods

### 2.1. Participants

Participants included fifty-one Vanderbilt undergraduate students (21 male, mean age=18.9, STD=1, age range=18–21 and were compensated with class credit. All recruitment and experimental procedures were approved by the Vanderbilt University Institutional Review Board. Exclusionary criteria, applied prior to in-depth data analysis, included a failure to detect foveal stimuli (at 0°) above 80% rate (N=5), or the failure to report foveal, synchronous stimuli as synchronous at a 50% rate (N=5). Finally, one subject was excluded for repeatedly pressing a single button on the response box for the entirety of the experiment. This study is part of a larger study investigating the interaction of spatial, temporal, and effectiveness factors on multisensory processing (Krueger Fister et al., this issue; Stevenson et al., 2012).

### 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 two Samsung Sync Master 2233RZ monitors at 100 Hz arranged so that each monitor crossed the circumference of circle centered on the participants nasium at a distance of 46 cm at 0°, 30°, 60°, and 90° azimuth, with all presentations in the right visual field (Fig. 1a, b). All visual stimuli were white circles measuring 7mm in diameter, or approximately 1° of visual angle. Visual stimulus durations were 10 ms, with timing confirmed using a Hameg 507 oscilloscope with a photovoltaic cell. Visual stimuli were presented at two luminance levels, 7.1 cd/m<sup>2</sup> (low) and 215 cd/m<sup>2</sup> (high) with a black background of 0.28 cd/m<sup>2</sup>, measured with a Minolta Chroma Meter CS-100. Visual stimuli were presented at each spatial location (4) and each salience level (2), for a total of eight visual-only conditions.

Auditory stimuli were presented via four separate speakers mounted on the top of the two monitors at 0°, 30°, 60°, and 90° azimuths angled toward participant, matching the visual presentations. Speakers were mounted 2 cm, or 2.5° above their respective visual presentation. Auditory stimuli consisted of a frozen white-noise burst generated at 44,100 Hz with the Matlab *rand* function with a 5 ms rise/fall cosine gate. Auditory stimulus duration was held constant at 10 ms, with timing confirmed using a Hameg 507 oscilloscope. Auditory stimuli were presented at two intensity levels, 46 dB SPL (low) and 64 dB SPL (high), with a background noise at 41 dB SPL, measured with a Larson Davis sound level meter, Model 814. Auditory stimuli were presented at each spatial location (4) and each salience level (2), for a total of eight auditory-only conditions.

Audiovisual (AV) conditions consisted of pairs of the auditory and visual stimuli described above. Presentations were always spatially coincident, and salience levels were always matched (high-high and low-low). AV conditions were presented at each spatial location (4) and each salience level (2) for a total of eight AV conditions. Additionally, a “blank” no stimulus condition was also included in which no auditory or visual stimulus was presented while all aspects of the trial remained consistent. In total 25 unique conditions were presented, eight visual only, eight auditory only, eight AV, and one blank. In addition to these trials that are relevant to this report, additional presentations including temporal synchrony variations of these stimuli were also included. These modulations are reported elsewhere (Stevenson et al., 2012) and are incorporated in these analyses only in the exclusionary criteria listed above.

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