



Invited Review

The construct of the multisensory temporal binding window and its dysregulation in developmental disabilities



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ABSTRACT

Behavior, perception and cognition are strongly shaped by the synthesis of information across the different sensory modalities. Such multisensory integration often results in performance and perceptual benefits that reflect the additional information conferred by having cues from multiple senses providing redundant or complementary information. The spatial and temporal relationships of these cues provide powerful statistical information about how these cues should be integrated or “bound” in order to create a unified perceptual representation. Much recent work has examined the temporal factors that are integral in multisensory processing, with many focused on the construct of the multisensory temporal binding window – the epoch of time within which stimuli from different modalities is likely to be integrated and perceptually bound. Emerging evidence suggests that this temporal window is altered in a series of neurodevelopmental disorders, including autism, dyslexia and schizophrenia. In addition to their role in sensory processing, these deficits in multisensory temporal function may play an important role in the perceptual and cognitive weaknesses that characterize these clinical disorders. Within this context, focus on improving the acuity of multisensory temporal function may have important implications for the amelioration of the “higher-order” deficits that serve as the defining features of these disorders.

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1. Introduction

We live in a world rich with information about the events and objects around us. This information comes in a variety of different forms; forms that we generally ascribe to our different senses. Although neuroscience has generally approached the study of sensory processes on a modality-by-modality basis, our perceptual view of the world is an integrated and holistic one in which these sensory cues are blended seamlessly into a singular perceptual Gestalt. Such a multisensory perspective cries out for an intensive investigation of how information from the different senses is combined by the brain to influence our behaviors and shape our perceptions, a field that has emerged over the past 25 years and which is now growing at an impressive pace.

Rather than simply acknowledging the necessity of merging information from the different senses in order to build our perceptual reality, it must also be pointed out that the synthesis of multisensory information confers powerful behavioral and perceptual advantages (for recent reviews see Calvert, Spence, and Stein (2004); King and Calvert (2001); Stein and Meredith (1993); Stein et al. (2002a)). Indeed, the driving evolutionary forces that undoubtedly led to multisensory systems are the powerful adaptive benefits seen when information is available from more than a single sense. For example, in animal behavior, the presence of cues from multiple senses has been shown to result in improvements in stimulus detection, discrimination and localization that manifest as faster and more accurate responses. In a similar manner, human studies have revealed multisensory-mediated performance benefits in a host of behavioral and perceptual tasks. Several of the more salient of these include the speeding of simple reaction times under paired visual–auditory stimulation and increased intelligibility of a speech signal when presented in a multisensory (i.e., audiovisual) context within a noisy environment (Bishop & Miller, 2009; Erber, 1975; Girin, Schwartz, & Feng, 2001; Grant & Walden, 1996; Grant, Walden, & Seitz, 1998; MacLeod & Summerfield, 1987; Robert-Ribes et al., 1998; Stevenson & James, 2009; Sumbly & Pollack, 1954).

A great deal of work has gone into examining the neural correlates of these multisensory-mediated changes in behavior and perception. These studies have detailed the presence and organization of a number of cortical and subcortical structures within which information from multiple senses converges, and the neural integration that accompanies this convergence in both humans (Amedi et al., 2005; Baum et al., 2012; Bishop & Miller, 2009; Beauchamp et al., 2004; Beauchamp, 2005; Calvert et al., 1999, 2001; Calvert, Campbell, & Brammer, 2000; Calvert, 2001; Cappe et al., 2009, 2010; De Gelder, Vroomen, & Pourtois, 2004; Foxe et al., 2000, 2002; James et al., 2011; Kim & James, 2010; Kim, Stevenson, & James, 2012; Laurienti et al., 2002, 2003; Lloyd et al., 2003; Macaluso et al., 2004; Martuzzi et al., 2007; Molholm et al., 2002; Murray et al., 2005; Nath & Beauchamp, 2011, 2012; O'Doherty, Rolls & Kringelbach, 2004; Powers, Hevey, & Wallace, 2012; Romei et al., 2009; Stevenson, Geoghegan, & James, 2007; Stevenson & James, 2009; Stevenson, Kim, & James, 2009; Stevenson et al., 2010, 2011, 2012, 2012a; Wallace & Murray, 2011; Werner & Noppeney, 2009, 2010a, 2010b, 2011) and animals (Allman & Meredith, 2007; Allman, Keniston, & Meredith, 2008; Alvarado et al., 2007, 2008, 2009; Benevento et al., 1977; Carriere et al., 2007; Jiang et al., 2001; Kadunce et al., 1997; Meredith & Stein, 1986b, 1983; Meredith, Wallace, & Stein, 1992; Meredith,

2002; Perrault et al., 2005; Royal, Carriere, & Wallace, 2009; Schroeder et al., 2001; Schroeder & Foxe, 2002; Stein & Meredith, 1990, 1993; Stein, Meredith, & Wallace, 1993; Stein & Wallace, 1996; Stein, 1998; Stein et al., 2002b, 2009; Wallace, Meredith, & Stein, 1992, 1993, 1998; Wallace & Stein, 1994; Wallace, Wilkinson, & Stein, 1996; Wallace et al., 2006; Wallace & Murray, 2011). In addition, a great deal of recent work has gone into describing the modulatory influences that a “non-dominant” modality can have on information processing within the “dominant” modality, such as examining how visual information can affect the processing of sounds within auditory cortex (Hackett & Schroeder, 2009; Zion Columbic et al., 2013). Indeed, these observations have spurred a debate as to whether or not the entire cerebral cortex (and by extension the entire brain) can be considered “multisensory” (Driver & Noesselt, 2008; Schroeder & Foxe, 2005). Collectively, these studies have greatly illuminated our understanding of how information from the different senses interacts to influence neural and network responses, and how these responses are ultimately correlated with behavior and perception.

1.1. A “principled” view into multisensory processing

Along with detailing how neuronal, behavioral and perceptual responses are altered under multisensory conditions, prior work has also revealed key operational characteristics regarding these multisensory interactions. Perhaps most important among these was the general finding that the physical characteristics of the stimuli that were to be combined are important determinants of the end product of a multisensory interaction. First studied at the level of the individual neuron, these stimulus factors include the characteristics of space, time and effectiveness. In regards to space and time, multisensory (e.g., visual–auditory) stimuli that are spatially and temporally proximate typically result in the largest enhancements in neuronal response (Meredith, Nemitz, & Stein, 1987; Meredith et al., 1992; Meredith & Stein, 1986a, 1996; Royal et al., 2009; Wallace et al., 1996, 2004). In addition, stimuli that are weakly effective when presented on their own result in proportionately larger enhancements when combined (James, Stevenson, & Kim, 2012; Meredith & Stein, 1983; Stein, Stanford, & Rowland, 2009). These basic integrative principles make a great deal of intuitive sense in that space and time are powerful statistical indicators of the likelihood that stimuli arise from the same event, and in that a highly-salient or effective stimulus is one modality needs little amplification. Recent work has added to our understanding of the role that these stimulus factors play in multisensory interactions by highlighting their interdependency (Carriere, Royal, & Wallace, 2008; Ghose & Wallace, 2014; Krueger et al., 2009; Royal et al., 2009; Sarko et al., 2012; Sarko, Ghose, & Wallace, 2013). Thus, one cannot view space, time and effectiveness as independent entities, since manipulations of one, for example spatial location, will also impact the effectiveness of those stimuli and the temporal firing patterns associated with them.

Following the description of these principles at the neuronal level, a number of studies have followed up on this work in the behavioral and perceptual realms, and have shown that these principles often extend into these domains as well. Thus, behavioral and perceptual facilitations have been shown to be greatest for stimuli that are close together in space and time (Alais et al., 2010; Bertelson & Radeau, 1981; Colonius & Diederich, 2004, 2010, 2011; Colonius, Diederich, & Steenken, 2009; Conrey & Pisoni,

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