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Multisensory Integration as a Window into Orderly and Disrupted Cognition and Communication

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Abstract

During our everyday lives, we are confronted with a vast amount of information from several sensory modalities. This multisensory information needs to be appropriately integrated for us to effectively engage with and learn from our world. Research carried out over the last half century has provided new insights into the way such multisensory processing improves human performance and perception; the neurophysiological foundations of multisensory function; the time course for its development; how multisensory abilities differ in clinical populations; and, most recently, the links between multisensory processing and cognitive abilities. This review summarizes the extant literature on multisensory function in typical and atypical circumstances, discusses the implications of the work carried out to date for theory and research, and points toward next steps for advancing the field.

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INTRODUCTION TO MULTISENSORY INTEGRATION

In our natural environment, we are confronted with a vast amount of sensory information. These sensory inputs originate from numerous external sources, propagate via various forms of energy, and are processed through multiple sensory systems. Despite the complexity of these information streams, the healthy brain can determine which bits of sensory information coded by different sensory systems originated from a single external source and merge this information into a single unified percept. At the same time, the healthy brain can accurately dissociate sensory information originating from disparate sources and events and appropriately segregate it into discrete percepts. As an example, you can successfully integrate your partner's auditory voice and visual facial articulations while in a noisy bar, and you can successfully refrain from integrating his or her voice with other faces in your field of view. The integration of redundant and complementary information from the different senses affords numerous perceptual and behavioral benefits. This sensory synthesis, known collectively as multisensory integration, has been reliably shown to increase perceptual accuracy and speed of response as well as increase rates of detection and discrimination (for a review, see Murray & Wallace 2011). Thus, in the example above, you not only integrate your partner's voice and facial articulations but also gain a striking increase in speech perception in doing so.

To achieve this integration, the human nervous system relies on two distinct types of information, which can roughly be referred to as more low-level influences (i.e., the physical characteristics of the incoming sensory signals) and more high-level, learned associations (Collignon et al. 2013). The primary physical stimulus characteristics that influence multisensory integration are the spatial alignment and temporal coincidence of the paired inputs and the intensity or effectiveness of the signals (Stein & Meredith 1993). In brief, the more spatially aligned and temporally coincident two stimuli are, the more likely they will be integrated and perceptually bound into a single,

fused percept. Also, the less effective the unisensory components of a multisensory pairing are, the greater the multisensory benefit, a principle known as inverse effectiveness (Meredith & Stein 1986). These spatial, temporal, and inverse effectiveness factors interact with one another at both the behavioral (e.g., Fister et al. 2016, Nidiffer et al. 2016) and neural levels (e.g., Cappe et al. 2012, Royal et al. 2009).

MULTISENSORY DEVELOPMENT IN ANIMAL MODELS

A good deal of work has been done in mammalian models to characterize basic maturational features as they relate to multisensory circuits and their functional organization. A key finding across both precocial and altricial species is a developmental chronology in which the neural representations for the individual senses appear and begin to mature prior to the emergence of multisensory representations. One of the best-studied examples of this sequence is seen in the cat, in which tactile responses are seen in somatosensory brain regions including the thalamus, superior colliculus, and somatosensory cortex at birth (Wallace & Stein 1997). Auditory responses begin to appear sometime during the first 1–2 weeks of postnatal life, and visual responses are further delayed by several weeks. The appearance and development of these unisensory (i.e., responsive to a single sensory modality) representations is then followed by the appearance of the first multisensory (i.e., responsive to two or more modalities) neurons, which continue to grow in incidence as the animal matures, reaching adult values near the beginning of sexual maturity (Wallace & Stein 1997). In more precocial species such as monkeys, although somatosensory, auditory, and visual responses are present at birth, the maturational chronology of these three sensory systems follows a similar course (Wallace & Stein 2001). In mammals, this sequence makes a great deal of ecological sense, as touch is critical in the newborn who stays in close proximity to the mother. As the behavioral repertoire increases and the animal begins to explore at a distance, the more exteroceptive senses (audition and vision) begin to mature.

Although early multisensory neurons have the ability to respond to stimuli from two or more senses, they are strikingly different from such neurons in the adult, in that they lack the ability to integrate these different inputs (Wallace & Stein 1997, 2001). Such multisensory integration is characterized by neural responses that differ significantly from those of the individual senses and that often differ greatly from a simple summation of the unisensory responses (Stein & Meredith 1993). As development progresses, an increasing allotment of neurons gain this integrative capacity, thus allowing them to dramatically transform the inputs they are receiving. The appearance of these integrative abilities seems closely yoked to the maturation of receptive field properties of these neurons. For example, early multisensory neurons (much like their unisensory correlates) have very large receptive fields, and only upon the consolidation of these receptive fields do these neurons begin to exhibit integrative abilities (Wallace & Stein 1997).

Somewhat surprisingly, our knowledge regarding the development of the neurophysiological operations of these neurons has far outstripped our knowledge regarding the maturation of the behaviors dependent upon multisensory function. For example, little evidence has been gathered to date in developing animals as to when simple multisensory-mediated behaviors such as the facilitation (i.e., speeding) of reaction times first appear and how these gains in behavioral performance relate to the development of multisensory neural circuits. Future work should seek to study these brain-behavior relationships in developing animal models. Furthermore, although a host of animal models of various human neurologic and psychiatric disease and disorders exist (and, as described in later sections, these disorders frequently are accompanied by sensory and multisensory processing differences), very little work has yet been done to characterize (multi)sensory function

in these animal models of human disease. One exciting and notable exception to this has come in a mouse model of autism with disrupted serotonergic signaling due to a mutation in the serotonin transporter (a mutation derived from humans with autism). Using a paradigm developed to assess multisensory performance in rodent models (Siemann et al. 2015), Siemann et al. (2017) found that these mutant animals failed to derive the same degree of benefit from the presence of combined visual-auditory information as wild-type animals. Such work lays the foundation for future studies focused on characterizing alterations in multisensory function in these models of human disorders (and exploring how these changes in multisensory function relate to other characteristics of the disorders).

We argue that knowledge of the basic principles of sensory and multisensory development is critical information for enriching our understanding of cognitive development in health and disease, as (multi)sensory representations are a key developmental scaffold upon which higher-order representations are formed and refined (Murray et al. 2016). Although many of the ensuing sections focus on the relationship between multisensory and cognitive abilities in adults, several allude to how changes in sensory development (such as those precipitated by sensory loss) result in altered cognitive abilities and representations. A compelling future research direction would be to relate the development of sensory and multisensory abilities to the maturation of cognitive functions (in both humans and animal models), in the hopes of better understanding how (multi)sensory development undergirds cognitive development.

MULTISENSORY DEVELOPMENT IN HUMANS

Much like for animal models, work carried out to date in humans has shown that the ability to integrate across the senses, as well as the underlying factors influencing multisensory integration, changes dramatically across development. One clear example of this is in the perception of multisensory temporal relations. Although infants as young as four months of age are able to discriminate between synchronous and asynchronous multisensory stimuli (i.e., paired visual and auditory stimuli that are synchronous or not), they can do so only for large temporal offsets (e.g., Lewkowicz 1996). Throughout childhood and into adolescence, this multisensory temporal acuity improves, with the window of temporal offsets within which an individual perceives two sensory inputs as synchronous [commonly known as the temporal binding window (TBW)] (Dixon & Spitz 1980, Vroomen & Keetels 2010) progressively narrowing (e.g., Hillock-Dunn & Wallace 2012, Kēita et al. 2011).

Within the same developmental time frame, the strength of integration across the senses also increases. This has been classically observed within a paradigm known as the McGurk effect (McGurk & MacDonald 1976). In a McGurk task, participants are presented with an auditory utterance such as *ba* and a discordant visual articulation such as *ga*. When asked to report their perception, participants commonly report a novel percept such as *da* or *tha*. This fused percept is seen as a proxy measure for multisensory integration. Rates of such perceptual fusion have been widely shown to increase with age (e.g., McGurk & MacDonald 1976).

It has been proposed that the changes in how children perceive the physical properties of stimuli across development are inextricably and causally linked to increased rates of multisensory integration. For example, the intersensory redundancy hypothesis suggests that early in life, physical stimulus attributes of the same objects that are shared across modalities, such as temporal and spatial characteristics, as well as stimulus intensity, provide redundant information that facilitates a child's ability to perceptually differentiate co-occurring sensory events (Bahrick & Lickliter 2000). This in turn leads to increased multisensory integration. Indeed, even in adulthood, the precision of an individual's multisensory temporal perception is strongly related to his or her ability to

perceive the McGurk effect—the more precise one’s ability to accurately discriminate between synchronous and asynchronous presentations, the stronger his or her perception of the McGurk effect (Stevenson et al. 2012).

Although multisensory illusions such as the McGurk effect provide useful empirical measures of the development of multisensory integration, the perceptual and behavioral benefits associated with the maturation of multisensory integration have also been shown to increase across development. One of the best examples of this is that the benefit (i.e., gain in speech perception) associated with seeing a speaker’s face in addition to hearing his or her auditory speech increases across development and does so preferentially under noisy conditions (Ross et al. 2011).

One important transition in the development of multisensory integration is a shift from an early reliance on low-level (i.e., stimulus statistics) factors to a much heavier weighting of higher-order experiential factors (Collignon et al. 2013). The impact of these later-developing learned associations can be seen specifically in multisensory temporal acuity, where adults display a wider TBW for semantically congruent stimulus pairings (relative to incongruent pairings). That is, the system binds semantically congruent information even when the physical stimulus characteristics are quite asynchronous (Ten Oever et al. 2013).

MULTISENSORY INTEGRATION SCAFFOLDS TO COGNITION AND OTHER HIGHER-ORDER SKILLS

Based on findings from seminal work in animal models and research into early development, it has been proposed that multisensory processing provides a strong foundation for the development of perceptual representations and facilitates the acquisition of higher-order cognitive functions (e.g., Bahrick & Lickliter 2002, Bremner et al. 2012a). This theory is intuitively appealing, given the precedence of sensory development relative to the emergence of cognitive, social, and linguistic skills. As previously discussed, it is well established that sensory systems appear prenatally and that rudimentary multisensory processes are evident early in postnatal life (albeit with a protracted developmental trajectory), well in advance of higher-level cognitive and communicative processes (e.g., Bremner et al. 2012b). As highlighted earlier, the initial development of sensory and multisensory systems relies heavily on low-level statistical stimulus features (Murray et al. 2016). This developmental model, which posits a rather pivotal role for sensory processes, in particular early in life, is compatible with several existing psychological theories of cognitive development, including embodied cognition, the extended mind thesis, and enactivism (Clark & Chalmers 1998, Thompson 2005, Varela et al. 1991).

The aforementioned framework finds empirical support from a large and ever-growing literature exploring links between multisensory function and cognition across species, from animal embryos and neonates to human infants, children, and adults. Preliminary support for a formative role for the maturation of multisensory processing in the development of more complex functions came from work carried out in bobwhite quail, a species sensitive to intersensory redundancy during the prenatal and precocial periods (Lickliter & Banker 1994). Quail embryos exhibited enhanced learning and memory for a mother’s call when prenatally exposed to synchronous multisensory (i.e., mother’s song presented in conjunction with a temporally aligned patterned light stimulus) but not asynchronous or unisensory (i.e., mother’s vocalization alone) information (Lickliter et al. 2002, 2004). Subsequent work has shown that facilitative effects are achieved even with only a brief exposure to a multisensory stimulus synchronized with the onset of the mother’s call (Jaime et al. 2010) and has suggested that exposure to such multisensory stimulation may actually prepare or entrain the offspring to relevant unisensory information, for example, facilitating the quail chick’s subsequent recognition of the mother’s call in isolation (Lickliter et al. 2006).

ASD: autism spectrum disorder

DLD: developmental language disorder

Analogous results have been obtained in translational research carried out in human infants. Early linguistic development serves as an illustrative example. Language learning is a complex process that requires an infant to efficiently process and parse an incoming speech stream into distinct word forms and morphosyntactic structures, ascertain the meaning of each of these linguistic units, and over time learn how to reproduce them in a generative manner. As highlighted earlier, the incoming speech stream comprises not only dynamic auditory information but also complementary visual information from the moving mouth that boosts the efficiency of speech processing and supports word and broader language learning across the life span (e.g., Chandrasekaran et al. 2009, Massaro 1998).

Past research has shown that typically developing children attend to and integrate the visual cues that correspond with auditory speech very early in postnatal life (e.g., Lewkowicz & Hansen-Tift 2012, Patterson & Werker 2003). Typically developing infants and toddlers, for example, tend to look to the mouth—the source of linguistic multisensory redundancy—during pivotal periods in early language learning, such as when they are latching onto their native language and when they are experiencing an acceleration or burst in word learning (de Boisferon et al. 2018, Lewkowicz & Hansen-Tift 2012). The extent to which they do so has been linked with their early speech perception, prelinguistic vocal development, and broader spoken language learning (e.g., Bahrack et al. 2018, Teinonen et al. 2008, Tenenbaum et al. 2015).

Beyond this example of language acquisition, which plays an instrumental role in bootstrapping the development of various cognitive abilities, the maturation of multisensory processing has been linked with a host of other discrete perceptual and cognitive abilities, from selective attention and memory to tempo and numerical discrimination to associative learning, sequence detection, abstract rule learning, and face and affect discrimination, as well as more generalized cognitive development (Bahrack et al. 2002, 2018; Flom & Bahrack 2007, 2010; Frank et al. 2009; Gogate & Bahrack 1998; Jordan et al. 2008; Lewkowicz 2004). Thus, findings from research carried out over the course of several decades lend strong empirical support to the theory that multisensory maturation scaffolds the development of higher-order skills.

A natural extension of this scaffolding theory suggests that disruptions in foundational sensory function, particularly early in life, are likely to produce cascading effects on development across a number of domains (e.g., Bahrack 2010, Cascio et al. 2016). Research into clinical populations, including children and adults with autism spectrum disorder (ASD), developmental language disorder (DLD) and dyslexia, primary sensory impairments, and other neurodevelopmental and/or neurogenic conditions, has provided significant insights into the critical role of multisensory function for cognitive, linguistic, and/or social development.

ALTERED MULTISENSORY FUNCTION IN CLINICAL CONDITIONS: LINKS TO COGNITION AND BROADER SYMPTOMATOLOGY

Autism Spectrum Disorder

Changes in sensory and multisensory function have now been well established in one of the most pervasive and commonly studied developmental disorders, ASD. Autism has been classically defined by difficulties with social communication coupled with restricted interests and repetitive behaviors, but the most recent diagnostic guidelines now include atypical sensory processing (Am. Psychiatr. Assoc. 2013). Although only recently recognized diagnostically, these sensory issues have been noted since the original description of autism (Kanner 1943) and are among the most commonly reported features associated with the disorder (Le Couteur et al. 1989). A growing body of literature has established that these issues are apparent across a wide range of sensory modalities and, most germane here, include impairments in multisensory integration (for a review, see

Baum et al. 2015), including audiovisual (Feldman et al. 2018), audiotactile (Russo et al. 2010), and visuo-haptic (Cascio et al. 2012) integration.

One of the most commonly used paradigms to examine multisensory integration in autism is the previously described McGurk effect (McGurk & MacDonald 1976). Across numerous studies, autistic individuals¹ are reported to perceive the illusion at significantly reduced rates (e.g., de Gelder et al. 1991, Irwin et al. 2011), a finding validated in a recent meta-analysis (Zhang et al. 2019).

Interestingly, however, the finding of reductions in multisensory integration is less consistent in studies using a multisensory illusion comprising simple flashes and beeps, the sound-induced flash illusion (Shams et al. 2000). Across four studies utilizing this low-level illusion to date, half have found significantly reduced multisensory integration for autistic individuals relative to controls (Foss-Feig et al. 2010, Stevenson et al. 2014b), and half have failed to detect between-group differences (Keane et al. 2010, van der Smagt et al. 2007).

There are two possible explanations for this difference in consistency of findings between the McGurk effect and the sound-induced flash illusion. First, there may be differences between multisensory impairments when processing social or linguistic stimuli relative to nonsocial, nonlinguistic stimuli. Although this pattern has been seen within some individual studies, a recent meta-analysis suggested that the overall effect sizes for between-group differences observed with social versus nonsocial stimuli were not significantly different (Feldman et al. 2018). Thus, the possibility of a disparity in the magnitude of multisensory integration deficits across different stimulus types is an interesting and still-unresolved topic in the field.

A second possibility is that the developmental trajectory of multisensory integration is delayed or disordered. Within the four studies to date that have used the sound-induced flash illusion to study multisensory integration in autism, the two studies testing children found significant reductions for participants with autism relative to typically developing controls (Foss-Feig et al. 2010, Stevenson et al. 2014b), whereas the two studies testing adults failed to find differences (Keane et al. 2010, van der Smagt et al. 2007). Additionally, two studies to date have examined the developmental trajectory of multisensory integration using the McGurk effect, with one showing that autistic individuals show greater impairments early in development and catch up during adolescence (Taylor et al. 2010) and the other showing that autistic individuals show levels of multisensory integration equivalent to their typically developed peers early in development but fail to exhibit the usual increase in multisensory integration observed across development (Stevenson et al. 2014a). A recent quantitative synthesis of the literature of audiovisual integration in persons with ASD has confirmed that between-group effect sizes of multisensory deficits are larger in younger children (Feldman et al. 2018). However, without further study, it remains unresolved whether these differences reflect delayed versus disordered developmental trajectories.

Beyond multisensory illusions, autistic individuals also show reduced multisensory integration in tasks involving speech. The gains in comprehension typically seen for combined audiovisual speech (Sumbly & Pollack 1954) have been shown to be diminished in autistic individuals. In particular, studies parametrically varying the signal-to-noise ratio of audiovisual stimuli have shown

¹Although researchers and clinicians often feel more comfortable using person-first language such as “individuals with autism,” autistic individuals have endorsed identity-first language that incorporates autism as a component of their identity over person-first language (61% versus 28%) (Kenny et al. 2015). While autistic individuals themselves bear the full ability to choose which terminology is used, these preferences also coincide with those of parents of autistic children (51% versus 22%) (Kenny et al. 2015) and self-advocates (Brown & Autistic Self Advocacy Netw. 2016, Sinclair 1999). As such, we will respect this preference and use this language throughout this manuscript.

that autistic individuals show the greatest reduction in multisensory gain at noise levels similar to those at which typically developed individuals exhibit the greatest multisensory enhancement (Foxe et al. 2013, Stevenson et al. 2017a). A single yet well-powered study also examined multisensory enhancements in speech perception across childhood and adolescence, finding that autistic individuals exhibited significant reductions in multisensory integration that were more pronounced earlier versus later in development (Foxe et al. 2013). These findings, taken as a whole, suggest that disrupted multisensory integration may play an important contributory role in the social communication symptoms and language learning difficulties seen in individuals with ASD.

As previously mentioned, there are multiple low-level stimulus factors that guide the integration of incoming sensory information, including the temporal coincidence of sensory signals. Such physical stimulus cues are used early in development to scaffold the maturation of more advanced perceptual and cognitive abilities. Multisensory temporal processing in autistic individuals has been the topic of intense study in recent years, with these studies typically showing autistic individuals to have less precise multisensory temporal processing (for a review, see Stevenson et al. 2016). A lack of temporal precision has been postulated to cascade into impairments in multisensory integration and social communication in this clinical population (e.g., Bahrnick & Todd 2012, Wallace & Stevenson 2014), and a recent study has directly linked multisensory temporal precision with the ability to integrate multisensory speech cues (measured by the McGurk effect) and the behavioral gains experienced in response to multisensory speech (Stevenson et al. 2018b). In short, less precise temporal processing is associated with decreased integration as well as disruptions in speech perception. Indeed, a recent meta-analysis quantified the associations between disrupted multisensory integration and clinical autism symptomatology, demonstrating that multisensory impairments, particularly those exhibited in response to social stimuli, are moderately to strongly correlated with clinical symptoms associated with ASD, including but not limited to impaired social communication (Feldman et al. 2018).

In addition to their impacts on speech perception, impairments in multisensory temporal processing have recently been linked to measures of higher-order language processing. One study used a preferential-looking paradigm to assess synchrony perception and reported that autistic children who preferentially looked toward synchronous audiovisual presentations exhibited higher receptive language abilities (Patten et al. 2014). In a second study, eye-gaze measures suggested that the ability to detect long asynchronies was impaired in autistic individuals, and at these long asynchronies, the proportion of time attending to the synchronous presentations was significantly predictive of both receptive and expressive language (Righi et al. 2018). These two findings begin to connect impairments in the perception of multisensory speech with deficits in higher-order language processing, including expressive language.

As alluded to earlier, deficits in multisensory integration in ASD are not limited to audiovisual integration but are also observed for other modality pairings, including visuo-tactile/proprioceptive integration. For example, autistic individuals show weaker perception of the rubber-hand illusion (Cascio et al. 2012). In the rubber-hand illusion, the participant's hand is obscured from view while a visible rubber hand is placed to the side of the participant's hand. Both the real and rubber hand are simultaneously stroked with a brush, which induces a perceptual shift of the location of the participant's hand in the direction of the rubber hand as well as a growing sense of ownership of the rubber hand (Botvinick & Cohen 1998). This decrease in perception of the rubber-hand illusion suggests that autistic individuals are less likely to integrate proprioceptive (Minshew et al. 2004) and visual information (Glazebrook et al. 2009) relative to their typically developed peers. Importantly though, multisensory integration and its role in the development of a sense of body ownership and self-differentiation have been linked to a number of cognitive abilities that are impaired in autism, including social referencing, imitation, and empathy

(Chaminade et al. 2005, Gallese 2003). Indeed, autistic children who exhibited weaker rubber-hand illusions were also more likely to exhibit higher levels of impairment in empathy (Cascio et al. 2012).

The presence of impairments in multisensory temporal processing and multisensory integration and of decrements in higher-order cognitive and communicative operations such as speech perception, receptive and expressive language, and empathy highlights the pervasive impact that sensory impairments may have on development. At the same time, these findings may point toward novel targets for remediation, as is discussed in the section titled Conclusion and Future Directions. We would like to emphasize here the fact that it cannot yet be concluded that these associations are causal, given that the work to date has largely been concurrent and correlational in nature, pointing to the need for more longitudinal and experimental studies in the near future.

Dyslexia

Alterations in multisensory processing are not limited to persons with ASD but are also observed in other clinical populations, including individuals with dyslexia, a specific learning disorder characterized by difficulties with reading that interfere with an individual's academic, social, and vocational success (Am. Psychiatr. Assoc. 2013). There are numerous theories regarding the psychological and neurobiological basis of dyslexia. Many of these posit that the disorder may be rooted in disruptions in various cognitive processes, including associative learning (Gascon & Goodglass 1970), temporal processing (Zurif & Carson 1970), selective attention (Pelham & Ross 1977), rule learning (Manis et al. 1987), attention shifting (Hari & Renvall 2001), or—in what is arguably the prevailing theory at present—phonological processing (e.g., Carroll & Snowling 2004, Wagner 1986).

Other work has posited a strong sensory foundation to dyslexia. Indeed, the first account of dyslexia attributed reading difficulties to a visual deficit or word blindness (Morgan 1896); several subsequent hypotheses have centered on purported deficits in visual attention, visual perceptual processing (Eden et al. 1996), or generalized dysfunction within the auditory system (Hämäläinen et al. 2013). It is notable, though, that one of the earliest hypotheses put forth asserted that dyslexia was rooted not in unisensory differences but rather in a multisensory disturbance, in particular atypical audiovisual integration (Birch & Belmont 1964, 1965).

Such a multisensory emphasis makes intuitive sense, in that reading is inherently a multisensory process wherein one is tasked with mastering the cross-modal correspondence between visual orthographic tokens and phonological forms. A growing literature now lends empirical support to the theory that atypical multisensory function may disrupt this process. Specifically, poor readers show reduced recognition of mismatched orthographic and phonologic forms of words and pseudowords (Fox 1994), atypical neural responses to congruent versus incongruent letter-sound combinations as indexed via electroencephalography (Froyen et al. 2011, Mittag et al. 2013) and functional magnetic resonance imaging (Blau et al. 2009, 2010), and reduced cross-modal activation of cortical areas associated with orthographic processing (i.e., the visual word form area) in response to tasks that tap phonological processing (Desroches et al. 2010).

On measures of broader multisensory function, individuals with reading impairments have been reported to display reduced visual influence on speech perception when presented with mismatched McGurk stimuli, at least under some listening conditions (Hayes et al. 2003); poorer audiovisual temporal acuity (Hairston et al. 2005); less gain in reaction times in response to multisensory versus unisensory stimuli (Harrar et al. 2014); and a reduced boost in perceptual accuracy with access to visual cues on speech-in-noise tasks relative to controls (van Laarhoven et al. 2018, Ziegler et al. 2009). Thus, there is evidence to suggest that individuals who struggle to read show

SLI: specific language impairment

DCD: developmental coordination disorder

impairments not only in phoneme-grapheme mapping but also in more generalized multisensory integration (for a fairly recent review of this literature, see Hahn et al. 2014).

Contemporary research has provided new insights into the neural substrates and possible developmental consequences of multisensory disruptions in persons with dyslexia. Specifically, a number of studies point toward the superior temporal sulcus and the larger temporoparietal region, a known hub of multisensory integration, as sites of disruption in persons with reading disorders (e.g., Blau et al. 2010, Rüsseler et al. 2018). Aspects of multisensory processing (specifically sensitivity to audiovisual synchrony) have further been observed to account for unique variance in reading accuracy in adults with dyslexia, even after controlling for several previously identified predictors of reading ability (including working memory, processing speed, associative learning, and cognitive flexibility) (Francisco et al. 2017). In addition, these multisensory measures have been shown to predict future reading outcomes, even before dyslexia can be reliably diagnosed (Karipidis et al. 2018). One hypothesis regarding the mechanistic basis of dyslexia, rooted in work carried out in animal models, posits that increased neural noise stemming from amplified cortical excitability may account for impairments in phonological processing and difficulties with acquiring cross-modal grapheme-phoneme mappings via its effects on multisensory temporal processing (Hancock et al. 2017). This intriguing hypothesis warrants consideration in future research.

Other Neurodevelopmental Disorders

Disruptions in multisensory function have now been observed in a number of additional neurodevelopmental disorders. Accumulating evidence indicates, for example, that in comparison with typically developing peers, children who are diagnosed with specific language impairment (SLI, now also referred to as DLD or simply language disorder), or who have a developmental history of SLI, show decreased selective attention to audiovisual speech and reduced sensitivity to temporal synchrony in audiovisual speech, as evident in studies employing a broad range of biobehavioral methods, including psychophysics, eye tracking, and electroencephalography/event-related potentials (Kaganovich et al. 2014; Pons et al. 2013, 2018). Persons with SLI additionally have difficulty identifying and integrating the visual speech cues that correspond to the auditory speech signal (Norrix et al. 2006, 2007). Relative to controls, they experience a lesser degree of gain in perceptual accuracy in noisy listening conditions with access to audiovisual versus auditory-only speech (Huyse et al. 2015).

Emerging research suggests that differences in audiovisual temporal acuity may also be present early in life in children with other intellectual and developmental disabilities, including infants with Down syndrome and fragile X syndrome (D'Souza et al. 2016). Multisensory disruptions of a different nature (i.e., in the integration of visual, proprioceptive, somatosensory, and auditory information) have been implicated in developmental coordination disorder (DCD), a condition characterized by core deficits in sensorimotor control, a capacity that is reliant upon an intact awareness of the body and its relation to the external environment (Mon-Williams et al. 1999, Schoemaker et al. 2001). The commonality of these findings may be due to the frequent co-occurrence of the conditions reviewed thus far (i.e., ASD, DLD, dyslexia, DCD, Down syndrome, and/or fragile X syndrome) (Matson 2015, Reilly 2009, Visser 2003). Such findings raise the possibility that these multisensory disturbances are not disorder specific but rather are reflective of a more generalized mechanism that impacts neurodevelopment. Thus, there is a need for future research to ascertain the extent to which multisensory processing profiles converge versus diverge across different disorders, as well as to explore the extent to which various features of multisensory function relate to core and related symptoms.

NEUROPSYCHIATRIC CONDITIONS

Alterations in Multisensory Function and Links to Schizophrenia

SZ: schizophrenia

As defined by the National Institute of Mental Health, schizophrenia (SZ) is a chronic and severe mental disorder that affects how a person thinks, feels, and behaves. One of the hallmark features of the disorder is the frequent presence of delusions and hallucinations, characteristics that are strongly anchored in sensory function. How the sensory features of the disease relate to many of its cognitive aspects, such as disordered thinking, deficits in attention and memory, and disturbances in executive function, remains poorly understood. Nonetheless, some work has begun to elucidate the interrelations between sensory and multisensory function and cognitive abilities in the context of SZ.

Numerous studies have detailed the sensory characteristics of SZ and have illustrated processing changes in a variety of sensory modalities (e.g., Behrendt & Young 2004, Javitt 2009). Auditory hallucinations are perhaps the best recognized of the sensory features of SZ, with neuroimaging evidence showing that such hallucinations are frequently accompanied by activity changes in the areas of the brain linked to the perception of speech, including areas of the superior temporal and inferior frontal cortices (Jardri et al. 2011). Although auditory hallucinations are most frequently associated with SZ, hallucinations have been seen in a number of senses. This, coupled with the presence of sensory features across multiple modalities (and often in the same individuals), suggests that it may be fruitful to view the sensory-based changes in SZ not on a sense-by-sense basis but rather more from a pansensory or multisensory perspective. Thus, rather than stemming from processing changes within a specific sense, these could be a result of more generalized differences that impact all sensory systems or could be a result of specific weaknesses in the ability to integrate information across the senses. Indeed, deficits in sensory integration are considered a neurological soft sign of disease in SZ (Heinrichs & Buchanan 1988) and have been associated with positive symptoms such as hallucinations (Postmes et al. 2014). However, it must be cautioned that the term sensory integration has been used with limited specificity in this past work.

A growing number of studies have now shown deficits specific to the integration of sensory cues from different modalities in SZ. The major finding from these studies has been an apparent weakness in the ability to obtain behavioral and perceptual benefits from combined audiovisual cues, with an emphasis on speech-related stimuli (Pearl et al. 2009, Ross et al. 2007). Probing further, these studies suggest that deficits are most pronounced when audiovisual speech stimuli are embedded in noise (Ross et al. 2007). Extending these findings was work showing that multisensory differences were observed even in response to simple tasks measuring reaction times to paired audiovisual targets. Though control participants show a significant speeding under multisensory conditions, such benefits were found to be substantially reduced in the SZ population (Williams et al. 2010). In the perceptual arena, prior work has shown that those with SZ are less susceptible to the McGurk illusion (Pearl et al. 2009). Probing the possible neurophysiological correlates of these differences in multisensory function, electroencephalographic studies have found that the neural signatures associated with multisensory-mediated behavioral gains are significantly compromised in those with SZ (Stekelenburg et al. 2013).

One area of intense research focus in regard to multisensory differences in SZ is temporal processing, wherein there is emerging evidence that those with SZ integrate multisensory stimuli over different time intervals when compared with non-SZ individuals (Foucher et al. 2007). This work, much of it focused on the construct of the multisensory TBW (operationalized above), was predicated on initial reports of poor acuity in judging the temporal relationship between paired auditory, visual, and audiovisual stimulus pairs in persons with SZ (Foucher et al. 2007). Building off of this work, Stevenson et al. (2017b) found audiovisual temporal acuity differences

in individuals with SZ relative to controls that could not simply be attributed to differences in unisensory (i.e., auditory alone, visual alone) processing. Perhaps more importantly, these changes in multisensory temporal acuity were predictive of hallucination severity, connecting changes in multisensory temporal function to one of the core clinical features of SZ. Structural and functional imaging work further connects these domains by showing striking overlap, specifically in regions along the superior temporal sulcus, in activation patterns associated with multisensory temporal function and positive sensory symptoms of SZ (Kim et al. 2003, Surguladze et al. 2001, Szycik et al. 2009).

Much work still needs to be done to understand how changes in sensory and multisensory function relate to changes in cognitive abilities in SZ. Although both sensory and cognitive features are common characteristics of the disease, their mechanistic interrelationships need to be elucidated. As highlighted earlier, sensory and multisensory systems are theorized to form the foundation for perceptual and cognitive representations. Accordingly, the integrity of the sensory information reaching these representations and the manner in which it is integrated could be powerful determinants of healthy (and pathological) cognitive function.

Multisensory Integration in Healthy and Pathological Aging and Links to Cognition

Acuity and performance within the individual sensory systems almost inevitably declines with aging. Although outside the scope of this review, these changes in unisensory function have been strongly associated with cognitive decline. Age-related changes in unisensory performance and perception create an interesting challenge (and perhaps an interesting opportunity) for multisensory systems. On the one hand, as with unisensory systems, multisensory systems and the networks that support multisensory function may also decline with aging. Alternatively, multisensory-mediated performance gains may increase as acuity within the individual senses declines (Tye-Murray et al. 2010). Such a prediction is in keeping with the so-called principle of inverse effectiveness, in which multisensory gain increases as unisensory salience or reliability decreases (Stein & Meredith 1993). Statistical optimality-based accounts of multisensory performance offer a similar prediction (Alais & Burr 2004, Ernst & Banks 2002).

In recent years, studies have set out to examine multisensory function in the context of normal aging and age-related disorders such as dementia and Alzheimer's disease (AD). Results of research on the typical aging process suggest that older individuals on average experience larger performance gains under multisensory conditions when compared with younger adults (e.g., Laurienti et al. 2006, Peiffer et al. 2007). These changes in multisensory function have been linked with the declines in perceptual sensitivity that accompany aging (e.g., Setti et al. 2013, Tye-Murray et al. 2016). However, as a general rule, these performance improvements appear to be limited to the pairing of very simple stimuli such as flashes and beeps. As stimulus and task complexity increases, these larger multisensory gains often disappear, and multisensory performance deficits become the norm, notably for the binding of speech-related audiovisual signals (Stevenson et al. 2015). Such a shift from performance gains to performance decrements may be explained by the accumulating evidence for changes in multisensory temporal function in aging (e.g., Bedard & Barnett-Cowan 2016, Chan et al. 2014). These changes are manifest as a widening window within which multisensory signals are integrated (the TBW), a widening that tends to covary with a reduction in the overall magnitude of multisensory integration for synchronous multisensory stimuli (Stevenson et al. 2018a). Given that the width of the TBW grows with stimulus complexity, this could explain the contrast between gains and deficits in the elderly related to stimulus complexity. One global possibility that could explain this decrease in multisensory temporal acuity in aging is the

generalized slowing that has been seen in many studies of aging individuals (Salthouse 1996). Although this is a possible contributing factor, many of the studies of age-related changes in the width of the TBW have found these increases to be preferentially seen in tests of audiovisual (i.e., multisensory) binding. Stated a bit differently, differences in unisensory acuity are insufficient to explain the changes that are seen in multisensory temporal function, suggesting that generalized slowing is not a driving factor.

The evidence cited above focuses on audiovisual interactions largely because such interactions are most readily related to cognition, given their strong relationship to speech comprehension, language processes, and executive function. However, evidence for altered multisensory function in aging has been seen across a host of stimulus combinations, including visual-vestibular interactions (e.g., Ramkhalawansingh et al. 2017). Changes in visual-vestibular integration are important because of the likely role they play in the increased incidence of falls in the elderly (Setti et al. 2011). One area of research opportunity that has yet to be pursued in the aging arena is the covariation of changes across the various multisensory stimulus pairings. For example, are changes in audiovisual integration and visual-vestibular integration highly correlated? Such studies will provide greater mechanistic insight into the aging brain.

Changes in multisensory abilities across the life span are likely tied to changes in cognitive function, although the direction of this relationship is difficult to decipher. Given the previously articulated view that (multi)sensory systems scaffold the construction and maintenance of perceptual and cognitive representations, one might predict that sensory-based changes resulting from aging would ultimately lead to cognitive changes. Such a causal relationship has been difficult to establish, despite the wealth of correlative evidence linking sensory and cognitive decline and calls for the use of more targeted experimental research designs in subsequent work. Furthermore, the unique contributions of changes in multisensory function (as opposed to broad-based sensory changes) have yet to be established. Given that multisensory function necessitates integration across large neural networks, however, it seems likely that differences in multisensory abilities will track more closely with changes in cognitive domains when compared with changes in unisensory abilities.

Finally, there is a rapidly growing body of evidence suggesting that multisensory interactions are mediated by a combination of bottom-up (i.e., sensory encoding) and top-down (i.e., attentional, decisional) factors (Choi et al. 2018, Rohe & Noppeney 2018). Such an organization raises the question of how aging affects each of these contributors to the final multisensory product. Asking the question more concretely, might the impact of aging on top-down processes precede its impact on bottom-up processes, and how may such differential effects be teased out?

Although only a few studies have sought to characterize multisensory function specific to diseases of aging and have shown selective deficits in multisensory abilities in mild cognitive impairment and AD (Festa et al. 2017, Wu et al. 2012), remediation work in these diseases is increasingly multisensory focused (for a review, see Sánchez et al. 2013). These approaches, which are being used now in many conditions in which there is evidence for multisensory dysfunction, are predicated on the ideas that exposure to multisensory settings can train integrative networks to better process sensory information and that this emphasis on enhanced integration will translate to benefits in higher-order cognitive domains.

SENSORY LOSS AND CROSS-MODAL PLASTICITY

Vision Loss, Cross-Modal Plasticity, and Impact on Cognition

Multisensory function is likely to play a key role not only in the neurodevelopmental and neuropsychiatric conditions detailed in the above sections but also in circumstances of sensory loss,

in which large-scale brain reorganization typically takes place. For example, loss of vision, either complete or partial, is accompanied by marked reorganizational changes in the brain, which attempts to compensate for the loss of visual information. Although this cross-modal plasticity is most extensive when the vision loss occurs in early life, there is evidence for substantial plasticity even when the loss occurs in adulthood. A common theme in many studies of cross-modal plasticity is that portions of the deprived visual representations are recruited by other sensory modalities, with the most evidence for auditory and somatosensory inputs entering into regions of the visual brain. Such plastic changes create a very different organization framework within which multisensory interactions can take place.

Although there may be mechanistic similarities, a useful distinction in these studies of vision loss separates the effects of complete from partial loss. Such a distinction is particularly appropriate for the current topic, as partial vision loss results in striking changes in multisensory function that are not seen (at least for visual-nonvisual interactions) in the absence of vision. Hence, studies of blindness generally focus on cross-modal plasticity and document both the anatomical and functional recruitment of areas such as visual cortex for nonvisual sensory functions as well as enhanced abilities in the remaining senses that are posited to be a result of the recruitment of visual regions (Fine & Park 2018, Renier et al. 2014). Recent work in this area illustrates the utility of describing visual cortical regions not based on their visual properties but rather based on their task specificity. Perhaps the best example of this is the so-called visual word form area, originally described based on its responses to visually presented words (Dehaene & Cohen 2011). However, more recent work with the congenitally blind has shown this area to respond to words presented via Braille, as well as to words rendered into soundscapes as learned and discriminated via auditory sensory substitution devices, suggesting that this area is specialized for the processing of word forms regardless of the modality in which they are presented (Striem-Amit et al. 2012).

More germane to multisensory function are circumstances in which vision is impaired but some residual visual abilities remain. In such circumstances, the nonimpaired senses provide redundant information that can supplement the weak cues provided through vision. These conditions of low vision are perhaps best viewed through the lens of conceptual models of multisensory function such as cue reliability and maximum likelihood estimation (Alais & Burr 2004, Ernst & Banks 2002), in which the product of a multisensory interaction is dependent on the relative reliability of the sensory signals. According to such frameworks, in conditions such as low vision, the addition of information from a second sense (such as audition) has the potential to substantially boost visual performance (Targher et al. 2012, 2017). Such benefits provide an important foundation from which to explore the possibility of low vision rehabilitation based in multisensory training (Bolognini et al. 2005).

Although research into the links between multisensory function and low vision and cognitive abilities in children and adults at present is limited, recent evidence from two large US national data sets suggests strong associations between vision loss and cognitive decline in older adults (Chen et al. 2017). The presence of such links raises the possibility that training protocols intended to optimize multisensory performance could provide not only benefits for vision but also some degree of protection against age-related cognitive decline in those with poor vision.

Hearing Loss, Cochlear Implants, and Multisensory Abilities

Much like for vision loss, a substantial amount of work has documented cross-modal plasticity associated with hearing loss (for a review, see Sharma & Glick 2016). The emphasis of this work has been on those with profound sensorineural hearing loss, which occurs both congenitally and at

later stages of life through a variety of audiologic or neurologic insults. As with vision loss, loss of hearing is accompanied by major alterations in the anatomical and functional properties of auditory brain regions (most notably auditory cortex) and by significant recruitment of auditory cortex by inputs from other sensory modalities. Only recently has attention turned to such cross-modal changes in the context of moderate hearing impairment, wherein electrophysiological evidence shows that visual cross-modal reorganization of auditory cortex begins even in the early stages of hearing loss (Campbell & Sharma 2014).

One difference with hearing loss as compared to vision loss has been the remarkable benefits offered by the cochlear implant (CI), a neuroprosthetic device that restores some degree of hearing function to improve access to environmental sounds, augment speech perception, and support language acquisition in the profoundly deaf (Kral et al. 2019). The CI takes auditory input captured by a microphone and sends a processed signal to electrodes implanted within the inner ear. Although highly degraded, these electrical signals are often sufficient to support speech comprehension, generally after a period of training. One important and until recently relatively understudied aspect of CI function is the additional information conveyed by the visual system through the lip movements of the speaker. As highlighted earlier, in normal hearing subjects these visual cues can substantially amplify the audible signal, particularly in noisy environments. Thus, it seems highly likely that with the degraded auditory input provided by the implant, CI users will be even more reliant upon these visual cues. However, until recently, it was believed that lip reading could impede functional reorganization by not allowing the novel auditory inputs to reinnervate auditory cortex (Champoux et al. 2009, Sandmann et al. 2012).

A number of studies have now examined audiovisual function in CI users (for a recent review, see Stevenson et al. 2017c), beginning with an early study claiming that CI users were better multisensory integrators (Rouger et al. 2007). This work includes studies of deaf animal models implanted with these devices. The major findings from this work provide substantial evidence for plastic changes in auditory and visual cortical regions as well as more widespread network reorganization following implantation (Giraud et al. 2001, Strelnikov et al. 2015), links between audiovisual temporal function and implant outcomes (Butera et al. 2018, Jahn et al. 2017), and improvements in spatial localization following multisensory training (Isaiah et al. 2014). Findings from this work, as well as recent neuroimaging work using functional near-infrared spectroscopy (Anderson et al. 2017), do not appear to support the assertion that lip reading impedes cortical reorganization in CI users. Future work is needed in this area, especially because training for CI users, in particular treatment geared toward newly implanted children and adults, continues to be based on older ideas and frequently blocks access to visual speech cues. In contrast, a more multisensory-based perspective suggests that treatments providing access to redundant cross-modal cues would facilitate multisensory development and yield more optimal speech and language outcomes for this clinical population.

Collectively these findings strongly point to a greater emphasis in future rehabilitative work focused on multisensory function in which training objectives would emphasize the use of combined concordant visual and auditory cues as tools to build more robust and veridical multisensory representations. The potential cognitive benefits of such approaches cannot be understated, as hearing loss has been strongly associated with cognitive declines, most notably in the elderly (Lin et al. 2013, Loughrey et al. 2018). Indeed, great opportunity would appear to exist in the prevention of cognitive decline in those with moderate hearing loss, in whom multisensory-mediated training approaches may slow the erosion of cognitive abilities. This final point also emphasizes the need for more research into multisensory function in the context of hearing aids, a pervasive assistive technology where little is known about how such auditory amplification impacts multisensory performance and abilities (Gieseler et al. 2018).

CONCLUSION AND FUTURE DIRECTIONS

Research carried out over the last half century has greatly advanced our understanding of the nature of multisensory integration across species and across the life span. The results of this work provide new insights into how organisms process sensory input, the neurophysiological foundations of multisensory function, the time course for multisensory development, and the innumerable links between multisensory processing and cognitive abilities. This large and ever-growing literature has implications for theory, research, and clinical practice in disorders and diseases in which known multisensory processing changes exist.

The findings we have reviewed collectively lend increasing empirical support to the theory that multisensory function has strong links with cognition, language, communication, and a host of other higher-level abilities. However, we cannot yet conclude confidently that multisensory disruptions are truly foundational to the aforementioned constructs, as the bulk of the extant literature has employed research designs that do not permit inferences regarding causal effects (e.g., intact group comparisons and/or correlational approaches). Further work using well-controlled experimental designs with an eye toward delimiting causal relations is needed to disentangle the extent to which multisensory differences drive cognitive development and vice versa.

Compelling findings into the dynamic relation between multisensory function and cognition are forthcoming from innovative research in the area of developmental robotics, a field at the intersection of engineering and robotics, cognitive and developmental psychology, and neuroscience (e.g., Cangelosi & Schlesinger 2018, Lungarella et al. 2003). Research in this sector is leveraging advanced technology and machine learning approaches to explore the interplay between multisensory function and cognitive development. Results of such investigations provide further support for the findings described in earlier sections, suggesting that spatially and/or temporally aligned information from multiple modalities—auditory, visual, tactile, and proprioceptive—guides our attention, influences the manner in which we explore and engage with our environment, and shapes our perceptual representations to facilitate the acquisition of higher-order skills including object and self-recognition, word learning, and social behaviors such as imitation and cooperation. In addition, this work reinforces the role of top-down processes such as executive control in multisensory function (e.g., Al-azzawi et al. 2018, Arsenio & Fitzpatrick 2005, Metta & Fitzpatrick 2003, Torres-Jara et al. 2005, Wang & Xin 2018, Zhang & Weng 2010). This type of work will undoubtedly yield new insights into the mechanisms by which multisensory experience bootstraps broader cognition and learning, and by which cognitive processes influence one's interaction and engagement with the environment to impact sensory experience.

The breadth of disruptions in multisensory integration implicated across clinical populations suggests that measures of multisensory function hold promise for future application in clinical practice, perhaps for predicting outcomes in children with or at risk for neurodevelopmental disorders and/or measuring the progression of typical aging or the impact of neurogenic conditions. A number of limitations, however, currently preclude a recommendation for widespread measurement of multisensory function in clinical settings. A primary challenge at present is a lack of standardized and norm-referenced measures of multisensory processing. Furthermore, several of the most commonly used measures, such as psychophysical and neuroimaging approaches, are relatively high demand and/or high cost and thus do not necessarily lend themselves readily to use in some populations, in particular those who are very young, those who are less cognitively able, and those who have limited language or communication ability. It is notable, as well, that most existing measures are heavily weighted toward the measurement of fairly restricted aspects of multisensory function—largely the processing and/or integration of auditory and visual information, which is easiest to manipulate for experimental purposes but which may not reflect the

full range of multisensory deficits tied to cognition and broader adaptive function. Thus, there is a pressing need to develop and validate a standardized battery of measures that will permit more comprehensive assessment of multisensory function across the life span and range of functioning levels.

The development and validation of more exhaustive multisensory measures will facilitate further investigations into the links between disordered multisensory integration, cognition, and communication in the context of the growing use of a dimensional conceptual framework through which to understand the biological basis of normal and atypical brain-behavior relations (i.e., Research Domain Criteria or RDoC) (Insel et al. 2010). Dimensional approaches recognize that, while a diagnosis of a particular disorder necessitates the presence of a specific constellation of concurrent symptoms, individual symptoms themselves are commonly represented on a spectrum across other disorders and in the general population. The RDoC perspective is intended to better tap the mapping between individual phenotypic characteristics (that are often shared across disorders and that may often manifest at subclinical levels) and their underlying biological (and genetic) basis. Thus, to understand the mechanisms underlying a particular symptom, including difficulties with multisensory integration and impairments in cognition, a promising approach is to measure these symptoms (commonly referred to as traits in nonclinical samples) across disorders and within the general population.

Indeed, research taking this approach has begun to provide a view into the associations between multisensory processing and cognition that exist even in persons with typical developmental and health histories. For example, subclinical autistic traits have been shown to relate to multisensory temporal processing (Donohue et al. 2012, Yaguchi & Hidaka 2018). Likewise, characteristics of autism have been linked to atypical multisensory integration as indexed via the rubber-hand illusion (Palmer et al. 2013) and the McGurk effect (Ujiie et al. 2015), as well as to cognitive and communicative functions that have been shown to be associated with multisensory integration within persons diagnosed with autism, such as speech perception (Stewart & Ota 2008, Yu et al. 2011). The application of such dimensional approaches thus shows significant promise for exploring the interplay between multisensory integration and cognition going forward.

Preclinical investigations clarifying the nature of multisensory profiles and more precisely elucidating the links between multisensory function and higher-order skills will lay a foundation for translational research structured to develop more effective and efficient interventions for clinical populations. The breadth of disruptions in multisensory function observed across neurodevelopmental disorders and neurogenic conditions and demonstrated links with clinical symptomatology suggest that treatments targeting multisensory function may hold some promise for facilitating cognitive development and preserving/strengthening cognitive function. Such approaches are founded in the growing evidence detailing marked plasticity in multisensory processes and their associated brain representations, as well as the growing acknowledgment of links between multisensory function and cognition (e.g., De Nier et al. 2018; Powers et al. 2009, 2012). Well-controlled clinical trials that systematically test the efficacy of candidate interventions on proximal aspects of multisensory function as well as progressively more distal skills will provide much-needed insights into the extent to which targeted treatments may translate to more optimal cognitive and communication outcomes. Studies incorporating research design elements and analytic approaches that permit testing of the subgroups for whom, and the mechanisms by which, novel sensory-based treatments work have the greatest potential to advance us toward more personalized treatment planning for clinical populations displaying multisensory differences.

In attempting to better understand the relationship between multisensory function and cognition, there is a need to explore and elucidate shared neurobiological mechanisms. Neural oscillations represent one brain mechanism by which multisensory treatments may impact distal

outcomes in clinical populations. There is increasing evidence in support of a fundamental role for these oscillations in the integration of information across the senses, in particular in the processing and transfer of information, at scales ranging from very local circuit computations through communication across broad areas of the cerebral cortex (Buzsáki & Draguhn 2004). Furthermore, the importance of oscillations for a host of cognitive processes has been well established. Linking between multisensory and cognitive functions, oscillations have been put forth as a potential mechanism underlying the visual amplification of speech signals (Schroeder et al. 2008), and neurophysiological work in animal models has shown that nonvisual inputs into auditory cortex have the ability to reset the phase of ongoing neuronal oscillations, providing a powerful multisensory-mediated gain control mechanism (Lakatos et al. 2007). Building from the role of these brain rhythms in multisensory function and potential links to cognition, oscillations and the associated oscillatory hierarchy have been shown to be altered in a variety of clinical conditions, including autism (Simon & Wallace 2016) and SZ (Uhlhaas & Singer 2010). Much of this work has been focused on relating changes in oscillatory amplitude, frequency, and coupling to the primary clinical features of these disorders, such as social communication in autism (Cornew et al. 2012) and hallucinations in SZ (Spencer et al. 2004). In contrast, little work has been done to explore the relationship between oscillatory changes in sensory and multisensory brain networks and changes in the cognitive domains that often represent the hallmark clinical features. As multisensory perceptual binding represents a key integrative process strongly dependent upon brain oscillations, exploring such relations seems a fruitful area of future inquiry, not only for the mechanistic insights likely to be derived but also for the potential to apply this knowledge to design better interventions that target oscillatory function.

In conclusion, the most promising future direction is in building a stronger knowledge base that details the relationships between multisensory and cognitive abilities, in both health and disease. Scientists working within both the multisensory space and the realm of cognition have developed (or are working to develop) comprehensive batteries that seek to characterize various constructs within their respective large functional domains. However, these efforts appear to be proceeding largely in parallel. Our perspective is that future work carried out with an eye toward interrelationships between sensory and cognitive constructs will lend stronger support to the notion that multisensory function scaffolds the development and maintenance of cognitive representations and point toward important targets of novel interventions aiming to ameliorate cognitive dysfunction.

SUMMARY POINTS

1. Research into links between multisensory function and cognitive abilities is growing at a rapid rate.
2. Seminal studies in animal models unveiled some of the neurophysiological operations that support multisensory function, with an emphasis on several key stimulus-dependent or bottom-up principles that guide these operations.
3. Developmental research indicates that multisensory function begins to emerge early, with rudimentary skills present even in the first few months of postnatal life, but shows a protracted trajectory with maturational changes evident throughout adolescence and early adulthood.
4. A strong theoretical framework has been espoused suggesting that multisensory function scaffolds the development of cognitive abilities and other higher-order skills. According

to this framework, disruptions in multisensory function may produce cascading effects on cognitive domains.

5. Disturbances in multisensory function are implicated in a number of neurodevelopmental disorders, including autism spectrum disorder, dyslexia, developmental language disorder, and more.
6. In addition, alterations in multisensory function accompany a number of neuropsychiatric conditions such as schizophrenia and age-related conditions such as dementia and Alzheimer's disease, as well as following sensory loss.
7. Differences in multisensory processing have been linked to a broad range of cognitive abilities in these disorders and are often accompanied by atypical neural structure and function centered on known multisensory hubs such as the superior temporal sulcus.
8. Findings from the extant literature collectively lend some empirical support to the cascading effects theory, suggesting that multisensory markers may have clinical utility for predicting future clinical symptomatology and/or may serve as important targets for interventions.
9. There is a great deal of evidence showing marked plasticity for multisensory processes and associated brain substrates. This evidence, coupled with the growing acknowledgment of links between multisensory function and cognition, points toward the possibility that multisensory-focused interventions may have the ability to not only impact sensory and integrative function but also provide benefits for distal functions such as cognition and communication.

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Fairly recent review of findings for multisensory temporal processing in individuals with developmental disabilities.
