CHAPTER 16

Sensory Features in Autism Spectrum Disorders

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INTRODUCTION

Sensory features have been noted in persons with autism spectrum disorders (ASDs) dating back to the earliest case studies on record (Kanner, 1943), and these intriguing behaviors continue to perplex parents, clinicians, and researchers today. Kanner's case studies described both sensory fascinations (e.g., watching light reflecting from mirrors) that provided seemingly endless joy, as well as heightened sensitivities (e.g., covering ears to shield against noise) that caused distress in some children with ASD. Following several decades of scant research on sensory features, these issues have gained prominence in recent literature with the advent of new technologies, theories, and methods that have (a) more comprehensively characterized sensory phenotypes; (b) clarified associations with other features of ASD; (c) better addressed questions of pathogenesis, development, and impact; and (d) informed clinical assessment and intervention approaches. Thus, we are pleased to contribute

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this chapter to the *Handbook* and highlight new findings regarding sensory features in ASD.

DESCRIPTION, PREVALENCE, AND SPECIFICITY OF SENSORY FEATURES

Myriad terms have been used in the literature to describe the vast array of sensory experiences reported and/or behavioral manifestations evidenced by individuals with ASD. These include, but are not limited to under-, over-, and fluctuating responsiveness to various sensory stimuli (O'Neill & Jones, 1997; Schoen, Miller, & Green, 2008); hypo- and hypersensitivities (e.g., Baron-Cohen, Ashwin, Ashwin, Tavassoli, & Chakrabarti, 2009); sensory avoidances or aversions (e.g., Baranek, 2002; Dunn 2001); sensory overload (O'Neill & Jones, 1997); sensory seeking or craving behaviors (e.g., Dunn, 2001; Miller, Anzalone, Lane, Cermak, & Osten, 2007); fascinations or preoccupations with sensory aspects of the environment (e.g., Cesaroni & Garber, 1991); superior acuities or enhanced perceptions (e.g., Mottron, Burack, Iarocci, Belleville, & Enns, 2003); sensory integration deficits (e.g., Schaaf et al., 2010); sensory-perceptual distortions (Minshew & Hobson, 2008); and synesthesias and other paradoxical reactions to sensory stimuli (Asher et al., 2009; Cytowic, 2002; Iarocci & McDonald, 2006). Many phenomenological accounts (e.g., Cesaroni & Garber, 1991; Grandin & Scariano, 1986; Jones, Quigney, & Huws, 2003; Tammet, 2006; D. Williams, 1994) and empirical studies (e.g., Baranek, David, Poe, Stone, & Watson, 2006; Hirstein, Iverson, & Ramachandran, 2001; Leekam, Nieto, Libby, Wing, & Gould, 2007; Watson et al., 2011) have demonstrated that sensory features are evidenced across all modalities, including auditory, visual, somatosensory, gustatory, olfactory, and vestibular systems, and are thought to reflect underlying differences in uni- and multisensory processing, and/or integration functions. Because sensory processing functions are vital to higher order perceptual and cognitive processes, research in this area may inform theories regarding these unusual sensory features as well as other central characteristics of the disorder such as impaired social cognition and language development.

A major challenge in the ASD literature is reconciling terminology and translating across disparate fields from the basic neurosciences through more clinically applied behavioral fields. In this chapter we use the term *features* (rather than *symptoms*) to describe specific behavioral manifestations that may reflect enhancements as well as deficits in sensory processing abilities. Furthermore, although we present largely convergent findings and generalizations across behavioral and neurophysiological studies that may help to explain the pathogenesis and development of sensory features, we recognize that sensory experiences in the real world are individualized and varied. Sensory features may present differently across people with ASD, as well as across time and contexts within the same person, presumably as a result of individual capacities transacting with challenges/affordances encountered in complex physical and social environments.

Sensory features are common in persons with ASD at all ages. Although there are no epidemiological studies, smaller studies of preschool/school-aged samples have reported prevalence of sensory features ranging from ~40% to >90% (Baranek et al., 2006; Kern et al., 2006; Kientz & Dunn, 1997; Le Couteur et al., 1989; Leekam et al., 2007; O'Donnell, Deitz, Kartin, Nalty, & Dawson, 2012; Ornitz, Guthrie, & Farley, 1977; Tomchek & Dunn, 2007; Volkmar, Cohen, & Paul, 1986; Watling, Deitz, & White, 2001). Fewer studies report rates of sensory features in very young children (e.g., Ben-Sasson et al., 2007; Wiggins, Robins, Bakeman, & Adamson, 2009) or older adolescents/adults with ASD (e.g., Crane, Goddard, & Pring, 2009; Kern, Trivedi, et al., 2007).

Modality Specific Descriptions of Sensory Features

Among the most commonly reported sensory features in ASD are auditory processing problems, particularly hyperacusis (Bettison, 1996; Grandin & Scariano, 1986; Greenspan & Wieder, 1997; Reynolds & Lane, 2008; Talay-Ongan & Wood, 2000; Volkmar et al., 1986). Higher functioning individuals with ASD often report trouble filtering out background noise during conversations. It is not clear whether auditory sensitivities are more common than sensitivities in other modalities, or whether distressing auditory stimuli are less avoidable in naturalistic environments and thus more salient to observers. Differentiating auditory hypersensitivities from anxiety and fears of specific objects or situations (Green & Ben-Sasson, 2010; Pfeiffer, Kinnealey, Reed, & Herzberg, 2005) is challenging, especially since stressful situations exacerbate physiological arousal. Auditory talents including superior pitch recognition, discrimination of musical tones, or enhanced perception of specific frequencies of sounds that are not easily discernible by others (e.g., Bonnel et al., 2003) are also reported. (Psychophysical/physiological studies are presented in later sections.) Paradoxically, despite the high prevalence of hypersensitivities to sound, hyporesponsiveness (i.e., absent, delayed, or inconsistent response) to auditory stimuli, particularly spoken language, is considered a hallmark sign of ASD in young children and often results in a clinical referral. Although hearing is generally intact (Gravel, Dunn, Lee, & Ellis, 2006; Klin, 1993; Tharpe et al., 2006), conductive, sensorineural, or mixed hearing loss can co-occur with ASD (Jure, Rapin, & Tuchman, 1991; Rosenhall, Nordin, Sandström, Ahlsen, & Gillberg, 1999).

In the visual domain, a variety of strengths (e.g., detection of small details) and deficits (e.g., reduced global perception; decreased motion processing) are noted. Visual fascinations and stereotypies (e.g., wiggling fingers near eyes; watching objects flicker/spin) as well as peripheral sighting (e.g., looking out the corner of the eyes) are commonly reported (e.g., Lord, Rutter, & Le Couteur, 1994; Mottron et al., 2007). Much research has been conducted on gaze aversion due to its presumed relevance to social deficits in ASD, especially poor eye contact (see Simmons et al., 2009, for review). Studies measuring visual acuity (Kaplan, Rimland, & Edelson, 1999; Scharre & Creedon, 1992) indicate that 18% to 50% of children with ASD have difficulties with near and far acuity, fixation, binocularity, and/or strabismus; however, these deficits are insufficient to fully explain the wide-ranging visual sensitivities, fascinations, and stereotypies. One study noted enhanced visual acuity for low-level (i.e., threshold) processing (Ashwin, Ashwin, Rhydderch, Howells, & Baron-Cohen, 2009). Experiments testing luminance and texture contrast have suggested strengths in the parvocellular system (i.e., ventral visual stream that is sensitive to temporal resolution, and identification of colors, textures, and patterns; often referred to as the “what” system) and deficits in the magnocellular system (i.e., dorsal visual stream that is sensitive to spatial resolution and motion—often referred to as the “where” system) in ASD (e.g., Bertone, Mottron, Jelenic, & Faubert, 2005; Bölte, Holtmann, Poustka, Scheurich, & Schmidt, 2007; Davis, Brockbrader, Murphy, Hetrick, & O’Donnell, 2006; Milne et al., 2002; Mottron et al., 2003; Plaisted, Swettenham, & Rees, 1999; Tsermentseli, O’Brien, & Spencer, 2008; Vandenbroucke, Scholte, van Engelund, Lamme, & Kemner, 2008).

Unusual responses to somatosensory stimuli (e.g., tactile defensiveness, withdrawal from social touch, aberrant responses to pain) are central to autobiographical accounts of high-functioning persons with ASD (Grandin & Scariano, 1986; Jones et al., 2003). Despite such reports, experimental studies of tactile perception in ASD are limited in comparison to those in auditory and visual modalities, and results are mixed (see later sections for psychophysical/ neurophysiological findings). In the gustatory/olfactory modality there is even less systematic research; however, picky eating is a commonly reported behavior that may reflect both oral (taste, texture, smell) functions as well as cognitive rigidities (see Ledford & Gast, 2006, for review).

Sensory Response Patterns Across Modalities

Although experimental research often targets unimodal sensory processes, sensory features in ASD are well documented across all sensory modalities and may aggregate into response patterns (e.g., Baranek et al., 2006; Dunn, 1997; Miller et al., 2007). Recognizing that other patterns may exist, we categorize sensory features into four distinct behavioral patterns that have been most commonly reported and empirically validated across modalities: (1) hyporesponsiveness; (2) hyperresponsiveness; (3) sensory interests, repetitions, and seeking behaviors; and (4) enhanced perception. Grouping features by behavioral response patterns may elucidate pathogenesis and facilitate understanding of generalized mechanisms supporting multimodal sensory processes, as well as inform intervention planning.

Hyporesponsiveness is characterized by a lack of, less intense, or delayed response to sensory stimuli (e.g., Baranek et al., 2006; Ben-Sasson et al., 2007; Dunn, 1997). For example, a child may show no behavioral orienting to a novel sound or may have a diminished response to pain. Hyperresponsiveness is characterized by an exaggerated, aversive, or avoidant response to sensory stimuli (e.g., Baranek, Boyd, Poe, David, & Watson, 2007; Dunn, 1997; Reynolds & Lane, 2008). For example, a child may show discomfort to grooming activities or cover ears in response to certain sounds. Sensory interests, repetitions, and seeking behaviors are characterized by a fascination with or craving of sensory stimulation, which is intense and may be repetitive in nature (e.g., Ausderau et al., in revision; Dunn, 1997; Freuler, Baranek, Watson, Boyd, & Bulluck, 2012). For example, a child may show a fascination with flickering lights or rubbing textures. Enhanced perception is characterized by superior acuity, awareness, and/or discrimination of specific sensory stimuli or specific elements of stimuli (e.g., Happé & Frith, 2006; Mottron, Dawson, Soulières, Hubert, & Burack, 2006).

While these four sensory patterns are distinct, they may coexist with significant heterogeneity (Baranek et al., 2006; Ben-Sasson et al., 2007; Ben-Sasson et al., 2009; Hilton, Graver, & LaVesser, 2007; Lane, Young, Baker, & Angley, 2010; Liss, Saulnier, Fein, & Kinsbourne, 2006). Phenomenological reports (Cesaroni & Garber, 1991; Grandin & Scariano, 1986; D. Williams, 1994) have provided corroborating evidence of fluctuating and coexisting sensory response patterns in some persons with ASD. For example, an individual may show distress to certain sounds, textures, or sights, while ignoring other stimuli that appear more intense in their psychophysical properties. Studies have particularly noted the co-occurrence of hypo- and hyperresponsiveness in children with ASD (e.g., Ben-Sasson et al., 2007). For example, Baranek et al. (2006) reported that 38% children with ASD, ages 2–6.5 years, evidenced significantly high levels of both coexisting patterns, and this was in contrast to a group of children with developmental disabilities that showed only 2% with high levels of both hyper- and hyporesponsiveness. Both sensory patterns are associated with sensory seeking behaviors, which may serve some arousal modulation functions (Dunn, 1997; Liss et al., 2006). Hyporesponsiveness appears to be a very early developing feature (e.g., Freuler et al., 2012) and is thought to be more unique to ASD as compared to neurotypical and developmental disabilities control groups (Baranek et al., 2013; Ben-Sasson et al., 2009; Greenspan & Wieder, 1997; Hirstein et al., 2001; Rogers & Ozonoff, 2005), particularly at lower mental ages and verbal abilities. Enhanced perception is not significantly correlated with hyporesponsiveness (Ausderau et al., in revision), but is hypothesized to lead to hyperresponsiveness (aversion, avoidance, distress) perhaps due to sensory overload (Mottron et al., 2006). Enhanced perception tasks distinguish high functioning adolescents/adults with ASD when compared with neurotypical controls (Mottron et al., 2006; Mottron, Dawson, & Soulières, 2009); however, this pattern is difficult to measure and detect in very young or nonverbal children.

Unusual sensory features are associated with a variety of conditions, including other developmental disabilities (e.g., Ermer & Dunn, 1998; Rogers, Hepburn, & Wehner, 2003), which challenges the specificity of sensory features to ASD. Utilizing appropriate developmental controls to sort out characteristics uniquely associated with ASD from those associated with intellectual disability in general, some studies (Baranek et al., 2006;

Lord, 1995; Rogers et al., 2003) found that parents endorsed sensory symptoms at a significantly higher rate for preschoolers with ASD than for those with nonspecific developmental delays, whereas others (Stone & Hogan, 1993) did not. Further differentiating results by sensory patterns helps to clarify that sensory hyporesponsiveness (versus hyperresponsiveness) may be more specific to children with ASD than to children with other developmental disabilities (Baranek et al., 2006; Ben-Sasson et al., 2007; Rogers et al., 2003). The large heterogeneity of sensory features represented in persons with ASD and the co-occurrence of seemingly paradoxical sensory response patterns has led some researchers to investigate the existence of specific subtypes among children with ASD (Ausderau et al., under review; Lane et al., 2010; Liss et al., 2006). Subtypes may provide more homogeneous sensory phenotypes that could be useful to elucidate the pathogenesis of co-occurring features, as well as potentially inform more specific interventions.

NEUROPSYCHOLOGICAL PERSPECTIVES ON SENSORY FEATURES

Although theories of social cognition and theory of mind (e.g., Adolphs, 2001; Baron-Cohen, Leslie, & Frith, 1985) have provided reasonable explanations of deficits in social interaction and communication in ASD, they have not sufficiently explained the presence of unusual sensory features. Executive dysfunction theories propose that certain behavioral characteristics (e.g., rigidities, compulsive behaviors, rituals, etc.) may be due to poor cognitive flexibility, including planning, inhibition, and set-shifting components (Ozonoff, Strayer, McMahon, & Filloux, 1994). Although some sensory features are related to behavioral rigidities (e.g., Baranek, Foster, & Berkson, 1997; Boyd et al., 2010), one study found no significant associations between sensory features and measures of executive function (Boyd, McBee, Holtzclaw, Baranek, & Bodfish, 2009). Specific problems with attention disengagement and attention shifting have also been implicated in ASD (Allen & Courchesne, 2001; Courchesne et al.,1994; Landry & Bryson, 2004; Van der Geest, Kemner, Camfferman, Verbaten, & van Engelund, 2001) and provide explanations for why some children overfocus on certain sensory stimuli and fail to respond to other sensory stimuli, but more research is needed.

Other neuropsychological approaches have focused on how sensory-perceptual functions may impact generalized cognitive processes. For example, weak central coherence theory gives one plausible explanation for the strong detail (as opposed to gestalt) oriented processing style demonstrated in individuals with ASD (Happé & Frith, 2006). Other researchers have clarified that people with ASD are capable of global processing, but have superior local processing, or enhanced perception (Mottron et al., 2006; Mottron & Burack, 2001). Complexity of stimuli may be another source of variation across studies with some researchers arguing that persons with ASD display heightened abilities with lower level sensory-perceptual tasks, but as stimuli become increasingly complex, performance becomes more disrupted (e.g., Bertone, Mottron, Jelenic, & Faubert, 2003; D. L. Williams, Goldstein, & Minshew, 2006). Although these theories may account for some sensory features (e.g., heightened sensitivities; intense focus on sensory aspects) in ASD, they do not fully explain the wide heterogeneity across individuals or co-occurrence of sensory response patterns.

PSYCHOPHYSICAL AND PHYSIOLOGICAL PERSPECTIVES ON SENSORY FEATURES

Diverse methods are used in ASD to examine the underlying physical events and hypothesized neural substrates that may account for unusual behavioral responses to sensory stimuli. Psychophysical methods are used to study the detection, discrimination, and integration of sensory information as it affects perception and behavior. Electrophysiological methods are used to examine the perception, regulation, and integration of sensory information in the brain. Electrodermal responses (EDR) and cardiac measures are used to evaluate the effect of sensory stimuli on the body's arousal and self-regulation systems. We focus on generalized mechanisms (psychophysical, psychophysiological, and neurophysiological) that may particularly explain constellations of similar types of sensory features across modalities (i.e., sensory response patterns). One caveat is that much more physiological research has been conducted on auditory, visual, and multisensory processing than on touch, smell, or taste in ASD (see Marco, Hinkley, Hill & Nagarajan, 2011, for review).

Stimulus Detection

A number of psychophysical studies examined sensory thresholds (i.e., lowest intensity level at which the participant perceives the stimulus) in persons with ASD. Studies of taste and smell detection thresholds have not found significant group differences between groups with ASD and controls (Bennetto, Kuschner, & Hyman, 2007; Suzuki, Critchley, Rowe, Howlin, & Murphy, 2003; Tavassoli & Baron-Cohen, 2012a). In the tactile modality, findings have varied and depend upon the specific types of stimuli and ages of samples studied. Some researchers failed to find significant differences between children with ASD and typically developing controls for ability to detect and discriminate roughness of textures (O'Riordan & Pasetti, 2006) or tactile vibratory input (Güçlü, Tanidir, Mukaddes &, Unal, 2007). Cascio et al. (2008) found that adults with ASD showed more sensitivities to vibration and thermal pain (forearm and palm) than neurotypical controls, but light touch detection thresholds, nonnoxious warm/cool detection, and pleasantness ratings for textures were similar between groups. Contrastingly, Blakemore et al. (2006) reported that adults with ASD had superior detection of some high frequency (not low frequency) vibratory stimuli as compared to neurotypical controls. More research is needed to reconcile discrepancies across studies, particularly the extent to which reported problems in stimulus detection reflect peripheral, subcortical, and/or cortical processing differences.

Detection of auditory stimuli is measured by auditory brainstem response (ABR), also known as brainstem auditory evoked response (occurring within ∼20 ms after presentation of a rapid series of clicks), provides a method for determining whether auditory information is being detected by the central nervous system at the entry point into the brainstem (de Regnier, 2008). Evidence in ASD is inconsistent (e.g., Courchesne, Courchesne, Hicks, & Lincoln, 1985; Kwon, Kim, Choe, Ko, & Park, 2007; Rosenhall, Nordin, Brantberg, & Gillberg, 2003; Tharpe et al., 2006) and depends somewhat upon the type of stimuli presented, namely, simple nonspeech stimuli such as clicks (e.g., Klin, 1993; Rapin & Dunn, 2003) versus more complex stimuli such as speech (e.g., Russo, Nicol, Trommer, Zecker, & Kraus, 2009). For individuals with ASD who have average intelligence and language skills, ABRs elicited by clicks appeared normal, but deficient brainstem encoding was evident in subgroups of school-aged children for speech sounds with noise and varied pitch contours (Russo et al., 2008). Other evidence from young (24–45 months) children with ASD revealed significantly prolonged latencies to click stimuli compared to normative data (Roth, Muchnik, Shabtai, Hidesheimer, & Henkin, 2012). Longitudinal studies are needed to test neurodevelopmental hypotheses that early sensory processing differences for simple sensory stimuli may attenuate over time but nonetheless have potentially negative and cascading effects for processing of more complex speech stimuli.

Sensory Discrimination

Sensory discrimination studies focus on a person's ability to differentiate between distinct sensory stimuli with respect to their stimulus characteristics (e.g., frequency, duration, location, intensity). Higher order perceptual processes (e.g., object and speech recognition) and cognitive functions depend upon intact lower level sensory processing functions (Bomba & Pang, 2004; Fitch & Tallal, 2003); thus many ASD studies have investigated the integrity of sensory discrimination functions across modalities. Findings depend upon the modalities tested, and the age and intellectual levels of the participants included. For example, children with ASD were found to be less accurate than controls in olfactory discrimination tasks (Suzuki et al., 2003) as well as taste discrimination tasks for sour and bitter (but not sweet and salty) (Bennetto et al., 2007). However, for high-functioning adults with ASD, olfactory adaptation following prolonged exposure to an odor was found to be normal (Tavassoli & Baron-Cohen, 2012b). Heightened sensory discrimination abilities have been noted in several experiments for auditory (Bonnel et al., 2003; Heaton, Davis & Happé, 2008), visual (e.g., Ashwin et al., 2009), and tactile (e.g., Blakemore et al., 2006; Cascio et al., 2008) modalities, at least for high-functioning adolescents/adults with ASD. Tommerdahl, Tannan, Cascio, Baranek, and Whitsel (2007) found heightened baseline tactile sensitivities with concomitant deficits in vibrotactile spatial adaptation and temporal order judgments among adults with ASD, suggesting aberrant short-range (cortico-cortical) connectivity within the somatosensory cortex (see Mountcastle, 2005). Taken together, findings related to perceptual enhancements may reflect overconnected local processing networks (short range) in individuals with ASD, perhaps sometimes at the expense of impaired long range neural connectivity that is important to more integrative functions and attention (e.g., Gomot et al., 2006; O'Riordan, Plaisted, Driver, & Baron-Cohen, 2001).

Evoked potentials and event-related potentials (ERPs) are electroencephalography (EEG) measures that record sequential cortical activity across time following presentation of sensory, cognitive, or motor events (de Regnier, 2008). Short-latency ERP components usually reflect modality-specific early sensory neural processing, whereas long-latency ERPs reflect higher-level cognitive processes that may involve multisensory integration (Bomba & Pang, 2004). EEG studies with persons with ASD have mostly examined the auditory modality (for reviews see Marco et al., 2011; Samson, Mottron, Jemel, Belin, & Ciocca, 2006). Although behavioral findings suggest that high-functioning children and adolescents with ASD demonstrate relative strengths in processing simple auditory stimuli such as pure tones (e.g., Bonnel et al., 2003; Heaton, 2003), EEG studies have generally demonstrated weaknesses in selective attention and processing, particularly for complex auditory input with multiple sound sources as required for language processing (e.g., Jansson-Verkasalo et al., 2003; Teder-Salejarvi, Pierce, Courchesne, & Hillyard, 2005). The most consistently reported finding is a decreased P3 amplitude to novel auditory stimuli (e.g., Čeponienė et al., 2003; G. Dawson, Finley, Phillips, Galpert, & Lewy, 1988; Donkers et al., in press; Kemner, Verbaten, Cuperus, Camfferman, & van Engeland, 1995; Lincoln, Courchesne, Harms, & Allen, 1993); this is hypothesized to reflect differences in attention allocation or salience evaluation. More studies are needed to determine to what extent early sensory processing differences (e.g., attenuation of P1/N1 to standard tones) found in some EEG studies (e.g., Bruneau, Roux, Adrien, &, Barthélémy, 1999; Donkers et al., under review) may impact later processing functions (discrimination, attention allocation, etc.), and/or multisensory integration.

EEG studies also use mismatch negativity (MMN) paradigms to measure automatic change detection independent of voluntary attention; this method is passive and thus well suited for young children or less verbal populations such as ASD. In MMN studies, subjects are exposed to a series of repeating, identical stimuli with distinct, mismatching stimuli interspersed occasionally to determine if deviant sounds are distinguishable from the identical ones. Reports of MMN amplitude and latency in response to auditory stimuli in children with ASD are conflicting. Some studies have indicated higher MMN amplitudes and shorter latencies (e.g., Ferri et al., 2003), supporting the idea that children with autism have some heightened sensitivities. Others reported lower MMN amplitudes and longer latencies (Seri, Cerquiglini, Pisani, & Curatolo, 1999), which may support deficits in auditory memory encoding needed for accurate discrimination (e.g., Oram Cardy, Flagg, Roberts, & Roberts, 2005).

Relatively few EEG studies have examined visual discrimination in ASD. In contrast to findings in the auditory domain, P3 amplitude differences were generally not found between ASD and neurotypical controls during simple visual target detection tasks (Ciesielski, Courchesne, & Elmasian,1990; Courchesne et al., 1985; Pritchard, Raz, & August, 1987); however, studies using oddball paradigms have shown either abnormally small occipital P3 responses (e.g., Kemner, Verbaten, Cuperus, Camfferman, & van Engeland, 1994; Kemner et al., 1995) or prolonged latencies (right hemisphere) to novel visual stimuli (Sokhadze et al., 2009) in persons with ASD. The prolonged latencies may reflect right hemisphere cortical overprocessing, which was also suggested in an EEG study of short-latency somatosensory evoked potentials following median nerve electrical stimulation (Miyazaki et al., 2007).

Sensory Gating

Sensory gating refers to the brain's capacity to regulate its sensitivity to stimuli (Davies, Chang, & Gavin, 2009) and is commonly measured through either prepulse inhibition (PPI) (i.e., attenuation of the startle response to an intense auditory, visual, or tactile stimulus, usually preceded by a weaker stimulus) (Yuhas et al., 2011), or P50 ERP suppression (i.e., stimulus filtering, or a reduced response to sensory input presented following an initial conditioning stimulus, which can be intra- or cross-modal) (Kisley, Noecker, & Guinther, 2004; Oranje, Geyer, Bocker, Kenemans, & Verbaten, 2006). When sensory gating fails, processing of irrelevant or distracting stimuli may occur, leading to sensory overload, and disrupting attention and higher order cognitive processing (Seri, Pisani, Thai, & Cerquiglini, 2007). The degree of inhibition reflects the degree of sensorimotor gating, thus hypo- and hyperresponsive behavioral patterns could be related to ineffective gating. Adults with ASD have demonstrated reduced PPI, supporting a hypothesis of hyperresponsiveness to auditory stimuli (McAlonan et al., 2002). Adolescents with ASD have shown significantly prolonged startle latencies, but fewer impairments in PPI as compared to adolescents with fragile X syndrome with and without autism (Yuhas et al., 2011). Evidence from P50 suppression studies have failed to find evidence of sensory gating abnormalities in individuals with ASD compared to typical controls across age groups (e.g., Kemner, Oranje, Verbaten, & van Engeland, 2002; Magnée, Oranje, van Engeland, Kahn, & Kemner, 2009; Myles-Worsley et al., 1996; Orekhova et al., 2008). More studies are needed to resolve discrepancies in findings of sensory gating studies, explicate developmental factors influencing maturation of sensory gating mechanisms, and examine potential associations with clinical/behavioral measures of sensory response patterns in ASD.

Multisensory Integration and Perception

Most naturally occurring environmental stimuli engage multiple senses at any given moment. Multisensory integration (MSI) refers to the process of condensing and managing information from multiple modalities, and is integral to a person's ability to experience perceptual coherence and generate appropriate responses within the ongoing stream of environmental events (e.g., Iarocci & McDonald, 2006). Persons with ASD are reported to have a variety of sensory features that appear to implicate differences in MSI (e.g., Russo et al., 2010; Russo, Mottron, Burack, & Jemel, 2012), such as difficulty processing and using visual feedback in environments with excessive auditory stimulation (Iarocci, Rombough, Yager, Weeks, & Chua, 2010), synesthesias (i.e., stimulation of one sensory modality results in an experience perceived by a second sensory pathway, such as perceiving musical tones as different colors) (Cytowic, 2002), and deficits integrating interoceptive (e.g., proprioceptive) and exteroceptive (e.g., visual) feedback (e.g., Mostofsky & Ewen, 2011). MSI functions may be different or more effortful in children than adults as a function of cortico-cortical development that supports more automatic processing (Brandwein et al. 2011; Molholm et al., 2002).

Several groups have proposed that some sensory features in ASD may be the result of difficulties simultaneously filtering and processing sensory information from multiple modalities (Foss-Feig et al., 2010; Iarocci & McDonald, 2006; O'Neill & Jones, 1997; Russo et al., 2010). The extent to which simple versus complex (e.g., Bebko, Weiss, Denmark, & Gomez, 2006; Minshew, Goldstein, & Siegel, 1997) and amodal (e.g., spatial pattern) versus modality-specific (e.g., color, sound frequency) (e.g., Bahrick & Lickliter, 2004) aspects of sensory stimuli are being integrated and processed efficiently by individuals with ASD is debated. Individuals with ASD have demonstrated deficits in higher level MSI using complex auditory-visual stimuli, such as the McGurk effect (which involves the ability to combine visual lip reading and auditory phoneme perception stimuli) (Bebko et al., 2006; Mongillo et al., 2008). E. G. Smith and Bennetto (2007) reported that, even when trained to use the visual feedback provided by lip reading in the McGurk task, children with ASD still failed to integrate visual with auditory speech stimuli. In contrast, some studies of basic-level MSI revealed typical integration abilities in children with ASD for nonlinguistic, simple stimuli (Bebko et al., 2006; van der Smagt, van Engeland, & Kemner, 2007). Likewise, studies of low-level MSI using the flash-beep illusion (i.e., pairing of presentations of multiple auditory tones with one visual stimulus to create an illusory perceptual experience of multiple visual flashes) showed no differences between children with ASD and typically developing controls (van der Smagt et al., 2007), although, one study (Foss-Feig et al., 2010) found that children with ASD had a wider temporal window in which the illusion continued to be produced (as compared to typical controls). Also, there are neurophysiological reports of timing differences between ASD and controls in integrative auditory-somatosensory tasks (Russo et al., 2010). New advances in technology, particularly with functional neuroimaging, are rapidly increasing our knowledge of these issues in persons with ASD, at least for high-functioning, verbal, and older populations. More research is needed with young children and less verbal populations.

Among individuals with ASD, integrative processing that requires an extended period of time may reflect inefficient MSI, leading to problems responding to specific modalities in the presence of input from other modalities, particularly when stimuli in either modality are rapidly changing. These findings also reinforce the neuropsychological theories described earlier with respect to a local rather than global processing bias in ASD, perhaps due to a failure to integrate multisensory information in the brain. A plausible explanation is provided by the temporal-binding hypothesis (i.e., that the timing of cross-modal integration of sensory and spatiotemporal information from the same event or contexts is impaired in ASD) (Alcantara, Weisblatt, Moore, & Bolton, 2004; J. Brock, Brown, Boucher, & Rippon, 2002; E. G. Smith & Bennetto, 2007), which may be related to neural underconnectivity (e.g., Just, Cherkassky, Keller, Kana, & Minshew, 2007).

Researchers have also investigated a hypothesized association between MSI and attention in autism, with some findings in support (e.g., Talsma & Woldorff, 2005) and some against (e.g., Zimmer & Macaluso, 2007). Results may vary depending upon whether tasks involve selective versus divided attention, with MSI problems more apparent during divided attention tasks in persons with ASD (Koelewijn, Bronkhorst, & Theeuwes, 2010; Magnée, de Gelder, van Engeland, & Kemner, 2011). This finding does not support a primary MSI deficit in ASD, but instead suggests difficulty in dividing attention across multiple modalities of information.

Autonomic Responses

The autonomic nervous system, comprised of the sympathetic (SNS; arousal and fight-flight) and parasympathetic (PNS; homeostasis and recovery) branches, promotes adaptation and self-regulation in response to internal and external sensory stimuli. Sensory hyper- or hyporesponsive behavioral patterns among individuals with ASD are often hypothesized to reflect excessive or inadequate SNS activation (Schoen et al., 2008) and/or difficulty restoring homeostasis after a stressor (deficit in PNS functions) (Schaaf, Miller, Seawell, & O'Keefe, 2003). Electrodermal response (EDR; skin conductance) measures detect changes in SNS activation via sweat gland activity (M. E. Dawson, Schell, & Filion, 2007). Studies have consistently found EDR/skin conductance differences between individuals with ASD in relative to neurotypical controls; however, results are inconsistent with respect to the prevalence of overresponse and difficulty habituating to repeated stimuli (e.g., Barry & James, 1988; Chang et al., 2012) versus underresponse indicated by low or delayed responses to stimuli (e.g., Schoen, Miller, Brett-Green, & Nielson, 2009; Stevens & Gruzelier, 1984; van Engeland, 1984). Schoen and colleagues (2008, 2009) found that high-functioning children with ASD demonstrated significantly lower electrodermal responses than control groups (neurotypical children and those with sensory modulation disorders) across all sensory domains (auditory, visual, tactile, olfactory, vestibular). However, EDR findings were not significantly correlated with clinical sensory features as measured by the Sensory Profile (Dunn, 1999), a parent questionnaire. Additional analyses suggested two subgroups within ASD, including a high-arousal group (higher skin conductance/electrodermal magnitudes, faster latencies, and slower habituation) that was more hyperresponsive behaviorally, and a low-arousal group (lower skin conductance/electrodermal magnitudes, slower latencies, and faster habituation) that was behaviorally more hyporesponsive. In contrast, Chang et al. (2012) found that high-functioning children with ASD (relative to controls) had higher skin conductance at baseline and recovery, and demonstrated significantly higher EDR to presentations of a standard auditory tone, but not to a siren recording. Among the group with ASD, electrodermal measures were positively, significantly correlated with caregiver report of hyper- and hyporesponsiveness as measured by the Sensory Processing Measure Home Form (Parham, Ecker, Miller-Kuhaneck, Henry, & Glennon, 2007). The contrasting findings across EDR studies might be due to the presence of subgroups (e.g., overresponsive versus underresponsive) or perhaps general dysregulation of sensory modulation processes among children with ASD (Chang et al., 2012).

Vagal tone, also known as respiratory sinus arrhythmia, is estimated from measures of heart rate variability adjusted for respiratory rate, and taps PNS activity via vagal nerve (Fox & Stifter, 1989). High PNS activity as measured by variability in heart rate is indicative of an ability to adapt and cope with changing stimuli, whereas low PNS activity is related to a poor ability to physiologically adapt to changes. Very little is known about vagal tone patterns of children with ASD. One study found low vagal tone and cardiac baroreflex sensitivity at rest, suggesting parasympathetic deficits, along with high heart rate and blood pressure at rest, suggesting sympathetic overactivity (Ming, Julu, Brimacombe, Connor, & Daniels, 2005). In contrast, another study found no differences in vagal tone or EDR among children with ASD, compared to typical controls, following exposure to a social stressor (Levine et al., 2012). Considering the evidence pointing to heterogeneity of sympathetic responses among children with ASD, it seems reasonable to expect subgroups of parasympathetic responsiveness as well in this population.

Further studies are needed to unravel the complexities presented in physiological studies of children with ASD, particularly with regard to how parent-report and behavioral measures of sensory response patterns are associated with physiological findings. Few studies have investigated how physiological findings may be aligned or associated with caregiver report and behavioral measures of sensory features among individuals with ASD. Chang et al. (2012) found that caregiver-reported hypo- and hyperresponsiveness were associated with EDR, while Donkers et al. (in press) demonstrated that sensory seeking behaviors (as measured by clinical behavioral assessments) were associated with atypical EEG response (i.e., attenuation of P1/N1 to standard tones). Discrepancies across studies may reflect differences in stimulus types (e.g., tones versus speech), or be a result of unimodal versus panmodal investigations. Additionally, inconsistent findings may be due to differences in sampling characteristics such as language ability or IQ (Samson et al., 2006) or potential subtypes of individuals with ASD. Methods that require individuals with ASD to withstand demands related to physiological measures (e.g., EEG) or require increased cognitive abilities (e.g., provide pain ratings) may not be feasible in children with extreme sensory features (Donkers et al., in press) or those that are lower functioning, leading to the exclusion of children with stronger neurophysiological disruptions.

DEVELOPMENTAL PERSPECTIVES ON SENSORY FEATURES

Although sensory systems (e.g., auditory, tactile, vestibular) have formed by the second gestational trimester, and basic sensory functions (e.g., reflexes to touch, hearing higher pitched sounds, visual detection of motion and light sensitivity) are reliably evidenced in newborns (e.g., Simion, Regolin, & Bulf, 2008; Starr, Amlie, Martin, & Sanders, 1977), the sensory systems continue to mature at varying rates, and refine their functional integration and differentiation throughout childhood via meaningful engagement with the physical and social environment (e.g., Gottlieb, 1976; Turkewitz & Kenny, 2004). Sensory processing is dependent upon the integrity of neural systems, and is essential to support lower order (e.g., sensory) as well as higher order cognitive functions (e.g., perception, action, learning) (e.g., Budinger, Heil, Hess, Scheich, 2006; Woldorff et al., 1993). Developmental timing in cortical maturation of certain sensory functions may have adaptive advantages. For example, young infants' visual responsiveness is limited to low spatial frequencies, which may help to organize their responses to their sensory environment (i.e., reduce total amount of stimulation to be processed), thereby supporting the development of more efficient perceptual and cognitive integration capacities (see Lewkowicz, 2002, for a review of intersensory perceptual development). Thus, if infants' sensory experiences are either too limited or too unrestricted during sensitive periods of development, a sensory system may fail to develop optimally (Turkewitz & Kenny, 2004). This may lead to atypical sensory responsiveness, which may transact with other domains of development and contribute to a variety of risk processes that have cascading effects over time.

Neurobiological accounts of ASD suggest that there are disruptions in neural architecture that may arise very early in utero, and result in changes in short-range and long-range neural connectivity (e.g., Belmonte et al., 2004) that is important for adequate processing of sensory information as well as many other social and cognitive functions. These neurodevelopmental disruptions may reflect multiple risk factors (e.g., genetics, neurophysiology, environment) that transact with various developmental risk processes over time (e.g., altered engagement and social interactions) (G. Dawson, 2008), and potentially give rise to a variety of phenotypic expressions (including sensory features) in ASD that may manifest differently at different points in development. Several researchers have posited that impairments in earlier developing systems (e.g., sensory orienting), particularly during very sensitive periods of brain development, may have secondary consequences in later developing systems (e.g., joint attention, language) (e.g., Baranek et al., in press; Loveland, 2001; Mundy & Neal, 2001; Waterhouse, Fein, & Modahl, 1996). Further, co-occurring deficits (e.g., in social and nonsocial domains) may reciprocally influence each other over time (G. Dawson, 2008; E. Williams, Costall, & Reddy, 1999), but it is difficult to empirically test such transactions, particularly longitudinally.

Attentional processes play a role in several stages of sensory processing, including selection of, filtering of, and switching to relevant sensory stimuli. Components of visual attention, including alertness, orienting, executive attention, and sustained attention, develop significantly in the first few years of life as a result of the maturation of the underlying subcortical and cortical neural substrates that support these skills (see Colombo, 2001, for a review). In particular, attentional orienting to stimuli seems to be slower and less flexible in ASD (e.g., Courchesne et al., 1994; Landry & Bryson, 2004; Renner, Klinger, & Klinger, 2006;

Wainwright & Bryson, 1996), as early as 9 to 12 months of age (Bryson et al., 2007; Osterling & Dawson, 1994; Zwaigenbaum et al., 2005). The overlap in timelines between the development of the orienting/executive attention networks and the emergence of behavioral manifestations of sensory features (particularly hyporesponsiveness) may have implications for understanding pathogenesis of these features.

The emergence, developmental course, and stability of sensory features across the lifespan for individuals with ASD are not well understood. The earliest manifestations of sensory features during infant development have been detected through various methods including retrospective parental reports or clinical case studies (e.g., Dahlgren & Gillberg, 1989; Watson et al., 2007), retrospective video analysis studies (e.g., Baranek, 1999a; Freuler et al., 2012; Osterling & Dawson, 1994), and prospective studies usually with high-risk samples such as infant siblings of children with ASD (Bryson et al., 2007; Zwaigenbaum et al., 2005). These studies have shown that both high-risk infant siblings and infants from low-risk samples later diagnosed with ASD show predominantly hyporesponsive sensory patterns (e.g., failure to orient to social and nonsocial stimuli, low activity levels) and some unusual sensory focused behaviors and repetitions (e.g., rubbing hands repetitively on an object, unusual mouthing/sniffing, visual fixations) by 6 to 12 months of age (e.g., Bryson et al., 2007; Dahlgren & Gillberg, 1989; Freuler et al., 2012; Guinchat et al., 2012; Osterling & Dawson, 1994; Zwaigenbaum et al., 2005), and that these behaviors may even precede some of the social and communication features of ASD in some cases. Hyperresponsive behaviors (e.g., touch aversion, intense reactions to stimuli) are also occasionally noted by 9–12 months (Baranek, 1999a; Bryson et al., 2007; Zwaigenbaum et al., 2005), but seem to increase in their frequency of being reported/observed in the early toddler and preschool years (e.g., Guinchat et al., 2012; Zwaigenbaum et al., 2005), potentially as a result of parents becoming more aware of their atypicality and/or association with a clinical diagnosis (Lord, 1995).

It is difficult to separate out sensory features from regulatory and temperamental differences in infancy since these constructs are related (M. E. Brock et al., 2012; Clifford et al., 2012; Garon et al., 2009). Unusual sensory reactivity, particularly hyperresponsiveness, is often reflected in more difficult temperament (e.g., withdrawal from stimuli; negative affect) and in self-regulation problems (e.g., sleep disturbances; inconsolable crying), all of which have been commonly recalled by parents of children with ASD in the first 2 years of life (e.g., Bryson et al., 2007; Dahlgren & Gillberg, 1989; Greenspan & Wieder, 1997; Guinchat et al., 2012; Werner, Dawson, Munson & Osterling, 2005; Wing, 1969; Young, Brewer, & Pattison, 2003), even in cases with late-onset or regressive autism (Werner & Dawson, 2005). Collectively, these infant studies indicate that a pattern of behavioral hyporesponsiveness to sensory stimuli and regulatory difficulties may be emerging in the first year of life, followed closely by, or perhaps in tandem with, hyperresponsive and sensory seeking patterns.

Correlational studies provide some evidence for maturational development impacting the degree to which sensory features manifested behaviorally. Some reported that hyperresponsiveness may become more prominent (e.g., Liss et al., 2006; Talay-Ongan & Wood, 2000) as a function of increasing chronological age; others suggested hyperresponsiveness may decrease with greater mental abilities irrespective of chronological age (Baranek et al., 2007). Hyporesponsiveness has been found to decrease as a function of age (particularly mental age) in preschool/school age samples (Baranek et al., 1997; Baranek et al., in press; Kern, Trivedi, et al., 2007; Kern, Garver, et al., 2007). It is also possible that development is nonlinear, and changes reflect different functions at different developmental periods. A recent meta-analysis suggested that severity of sensory features, specifically hyperresponsiveness and sensory-seeking patterns, increases with chronological age from toddlerhood through the early school years, and subsequently decreases (Ben-Sasson et al., 2009). Although the severity of sensory features may vary over time depending on many other factors to be further explored (e.g., cortical maturation, intervention effects, coping abilities, etc.), there is evidence that sensory differences among individuals with ASD persist throughout life (Ben-Sasson et al., 2009; Kern et al., 2006). Crane and colleagues (2009) reported that although the modality affected and the severity level of symptoms varies, 94.4% of adults with ASD indicate some sensory features. The nature and direction of change over time in sensory features remains uncertain due to limitations in research design (e.g., cross-sectional rather than longitudinal) and differences in measurement tools (e.g., measures of general development or autism symptoms rather than sensory symptoms per se). More longitudinal studies are needed to expand our understandings of the developmental nature of sensory features and their transactions with other aspects of development including social, emotional, language, motor, and cognitive skills.

ASSOCIATIONS WITH OTHER FEATURES OF ASD

Studies have linked specific sensory features to social-communication deficits, the presence of restricted and repetitive behaviors, and atypical motor features among individuals with ASD. Often these co-occurring features are conflated and difficult to unravel experimentally.

Social-Communication

Sensory features are evident across social and nonsocial contexts for persons with ASD (Baranek et al., in press; Hilton et al., 2007; Liss et al., 2006). Some studies indicate that verbal and nonverbal communication deficits in children with ASD may overshadow some of their difficulties with sensory experiences. For example, Nader, Oberlander, Chambers, and Craig (2004) found that although caregivers often perceived children with ASD as being hyporesponsive to pain, detailed observational scales coded during routine venipuncture procedures revealed that these children had heightened pain responses relative to typically developing children.

Several studies have shown negative correlations between the degree of sensory features, particularly hyporesponsiveness, and social-communication abilities (Lane et al., 2010; Watson et al., 2011). Specifically, difficulty orienting to both social and nonsocial sensory stimuli, often reported in very young children with ASD, may negatively impact development of joint attention (Baranek et al., in press; G. Dawson et al., 2004) and subsequent opportunities for language acquisition (e.g., Watson et al., 2011). Deficits found in temporal processing of complex auditory stimuli (Jansson-Verkasalo et al., 2003; Teder-Salejarvi et al., 2005), auditory memory encoding (Seri et al., 1999), and temporal synchrony (Bahrick, Lickliter, & Flom, 2004) may have particular implications for language functions.

Phenomenological accounts from highly verbal individuals with ASD (e.g., Grandin & Scariano, 1986; D. Williams, 1994) also provide insights into how complex multisensory environments, particularly in social situations, may become overstimulating, resulting in decreased ability to filter relevant information from conversations and increasing tendencies for social withdrawal. Laboratory studies indicating physiological overarousal (Barry & James, 1988; McAlonan et al., 2002), heightened sensitivities (Cascio et al., 2012; Gomot, Giard, Adrien, Barthélémy, & Bruneau, 2002), and/or deficits in multisensory integration (e.g., Hardan et al., 2008) provide some support for such interpretations, but few have shown correlations with clinical measures of hyperresponsiveness (e.g., Chang et al., 2012). Tactile hyperresponsiveness has also been documented in several behavioral (Baranek et al., 1997) and physiological studies (Cascio et al., 2008), and has been linked with social withdrawal. One theory posits that early neurodevelopmental disruptions in an affiliative social touch system involving C-touch (CT) afferents (i.e., unmyelinated tactile mechanoreceptors distributed primarily in the hairy skin) may be implicated (Olausson et al., 2002; Vallbo, Olausson, & Wessberg, 1999; Wessberg, Olausson, Fernstrom, & Vallbo, 2003), but studies directly testing these hypotheses are needed (Cascio et al., 2008).

Restricted and Repetitive Behaviors

Restricted and repetitive behaviors (RRBs) are conflated and difficult to parse out from sensory features, particularly for the category of sensory seeking behaviors that may be intense, repetitive, and overfocused on sensory feedback from object manipulations (e.g., sighting closely while twiddling string) or body movements (e.g., body rocking). Furthermore, sensory features, especially hyperresponsiveness to sensory stimuli (Green & Ben-Sasson, 2010), as well as RRBs (Turner, 1999), have been linked to hyperarousal, perhaps to serve a homeostatic function or to alleviate anxiety. Moreover, studies have shown correlations with developmental maturation such that lower IQ or lower mental age is associated with both RRBs (Bishop, Reichler, & Lord, 2006; Bodfish, Symons, Parker, & Lewis, 2000) and sensory features (Baranek et al., 2007; Boyd et al., 2010) in ASD. To deal with these issues, studies have begun to adjust for IQ and remove duplicate questionnaire items, yet they still find that degree of sensory features is associated with the severity of RRBs among children with ASD (Boyd et al., 2009; Chen, Rodgers, & McConachie, 2009; Gabriels et al., 2008). With regard to specific sensory response patterns, hyperresponsiveness has been correlated with rigid and inflexible behaviors (Baranek et al., 1997) as well as stereotypies, compulsions, and rituals/sameness behaviors (Boyd et al., 2010), while sensory-seeking behaviors positively correlated only with rituals/sameness behavior (Boyd et al., 2010). Contrasting findings suggest that RRBs are associated with hyporesponsiveness (in the tactile modality) and sensory seeking (Foss-Feig, Heacock, & Cascio, 2012). More research is needed to uncover shared mechanisms that may underlie the manifestation of both sensory features and RRBs.

Motor Features

Atypical motor features such as difficulties with postural control, dyspraxia, and dyscoordination (David et al., 2009; Dziuk et al., 2007; Gepner, Mestre, Masson, & de Schonen, 1995) are common in ASD but are not considered as core impairments. Evidence that motor difficulties may be linked with deficits in higher order sensory processing (i.e., integration of multisensory information in complex neural systems, rather than simple detection by unimodal first-order analysis of sensory information in the brain) includes studies that have found compromised postural stability among individuals with ASD compared with typical controls, particularly under conditions when one sensory system (e.g., somatosensory input) is altered (Minshew, Sung, Jones, & Furman, 2004; Molloy, Dietrich, & Bhattacharya, 2003). Typical development of postural stability emerges as the integration of vestibular, proprioceptive, and visual information become refined with experience and maturation (Shumway-Cook & Woolacott, 1985).

Dyspraxia is likely related to impairments in imitation of body positions and movements in individuals with ASD (I. M. Smith & Bryson, 1994), which may reflect disturbances in the integration of somatosensory (i.e., tactile and proprioceptive) with visual information. Research suggests that imitation of body movements is more impaired than object imitation in young children with ASD (DeMyer et al., 1972; Stone, Ousely, & Littleford, 1997); thus, generating or using internal somatosensory representations of visually modeled actions may be more difficult than reproducing actions that provide ongoing visual cues. However, recent findings suggested that accuracy of proprioceptive learning (i.e., decoding of elbow position) was similar for adolescents with ASD and neurotypical controls, indicating that peripheral proprioceptive signals or lower level neural representations of limb positions did not account for motor coordination difficulties in ASD (Fuentes, Mostofsky, & Bastian, 2011). A more plausible explanation for motor difficulties may be impairment in higher level integration of proprioceptive with other sensory information, such as visual, vestibular, and tactile sensations as they change in time and space. In support, Izawa et al. (2012) found that children with ASD had an abnormal bias toward reliance on internal proprioceptive feedback over external visual feedback, which may have implications for learning novel movements, as well as acquiring internal models of action from social imitation.

FUNCTIONAL IMPACT AND ADAPTIVE OUTCOMES

Adaptive functioning (e.g., daily-living skills, social skills, school functioning, etc.) is often compromised among individuals with ASD (Baker, Lane, Angley, & Young, 2008; O'Donnell, Deitz, Kartin, Nalty, & Dawson, 2012), even in the presence of average cognitive ability (e.g., Klin et al., 2007). Research suggests that the overall degree of sensory features (Rogers et al., 2003) as well as specific sensory response patterns (Ashburner, Ziviani, & Rodger, 2008; Baranek et al., 1997) or subtypes (e.g., Ausderau et al., under review; Lane et al., 2010) may be related to difficulties with adaptive functioning. Specifically, sensory hyporesponsiveness and sensory-seeking patterns have been associated with maladaptive behavior (Baker et al., 2008; Liss et al., 2006; Reynolds, Bendixen, Lawrence, & Lane, 2011).

Participation in activities in the home and community (e.g., helping prepare meals, attending school clubs, visiting neighbors) promotes development and learning (Dunst, Bruder, Trivette, Raab, & McLean, 2001; Humphry & Wakeford, 2006). Research suggests that children with ASD participate less frequently, with less variety, and with fewer individuals in activities as compared to typically developing children and those with other developmental disabilities (e.g., Hilton, Crouch, & Israel, 2008; Orsmond & Kou, 2011); however, studies demonstrating how specific sensory features affect participation, either negatively (Bagby, Dickie, & Baranek, 2012; Hochhauser & Engel-Yeger, 2010; Schaaf, Toth-Cohen, Outten, Johnson, & Madrid, 2011) or positively (Little, 2012), are just emerging. For example, enhanced perception abilities may contribute to success in some tasks, such as doing puzzles, among children with autism (Little, 2012).

Studies have reported that hyperresponsive sensory patterns especially interfere with activities in the home (e.g., mealtimes, grooming) and community (e.g., going out to restaurants, entertainment venues) for families of children with ASD (Baranek et al., 1997; Dickie, Baranek, Schultz, Watson & McComish, 2009; Hochhauser & Engel-Yeger, 2010; Jasmin, Courture, McKinley, Fombonne, & Gisel, 2009; Lane et al., 2010; Little, 2012; Marquenie, Rodger, Mangohig, & Cronin 2010). Although a number of studies have focused on the limited social participation among school-age children and adolescents with ASD (Potvin, Snider, Prelock, Kehayia, & Wood-Dauphinee, 2012; Solish, Perry, & Minnes, 2010), it may be that the unpredictability of sensory stimuli in unfamiliar social contexts, coupled with children's social-communication limitations, impacts their participation. Sensory stimuli associated with activities in the home versus community may be more predictable and manageable for families (Bagby et al., 2012; Schaaf et al., 2011). Furthermore, children's maturational levels and autism severity likely interact with sensory features to impact activity participation (Little, 2012), lending support for a transactional view of the complexities involved in children's participation across contexts.

APPROACH TO CLINICAL ASSESSMENT

Professionals across a wide range of disciplines (e.g., occupational therapists, physical therapists, speech-language pathologists, audiologists, psychologists, and physicians, etc.) may assess sensory processing abilities (e.g., modulation, discrimination, or integrative functions) in individuals with ASD across contexts such as home, school, work environment, and clinic. Various tools are available, depending on the purpose of the assessment (e.g., initial assessment/diagnosis, eligibility for services, intervention planning, progress monitoring, and outcome evaluation). Although most individuals with ASD do not have a primary sensory deficit such as a hearing or vision loss, the appropriate professionals should assess these functions, resolving any concerns before further evaluating sensory processing functions. The assessment of sensory features among individuals with ASD necessitates a thorough understanding of the purpose of the assessment, nature of concerns, and potential impact of the disorder on important areas of functioning (e.g., social communication, adaptive behavior, etc.). Specific behavioral manifestations of sensory features, including strengths and weaknesses, need to be assessed appropriately if such concerns appear to be impacting daily functioning or social participation.

A top-down approach (American Occupational Therapy Association, 2002; Coster, 1998) would begin by focusing on the most global level of assessment such as social participation, which is an essential consideration for individuals with ASD and their families. This approach would then systematically address more specific aspects of engagement (i.e., activities and tasks) and followed by specific impairments (e.g., sensory processing deficits). Use of sensory assessment tools in a strictly bottom-up approach runs the risk of focusing on sensory deficits while neglecting the transactional relationship between the impairment level (i.e., sensory processing deficits) and the more global participation level. A combination of interviews (client and caregiver), structured and unstructured skilled clinical observations, and standardized assessments may provide a holistic perspective and guide an individualized and contextually relevant intervention plan.

Clinical Assessments/Behavioral Measures

A number of clinical caregiver report measures and behavioral assessments have been developed to characterize sensory features in individuals with ASD and/or other populations, and these assessments are often aligned with specific sensory processing conceptual frameworks. Theoretical perspectives that inform the clinical assessment of sensory features among individuals with ASD include but are not limited to the Optimal Engagement Band (Baranek, Reinhartsen, & Wannamaker, 2000), Dunn's Model of Sensory Processing (Dunn, 1997), and Miller and colleagues' Proposed Nosology of Sensory Integration (2007). Although assessment measures may aid in understanding strengths and weaknesses for diagnostic purposes or intervention planning, few have been developed or tested systematically for their sensitivity to change (positive or negative) and validity as outcome measures of intervention. Goal attainment scaling (GAS) is one method used to set individualized goals in collaboration with family members, and can be monitored over time to assess progress (Mailloux et al., 2007). Systematic monitoring of meaningful goals aligns with current recommendations of the American Academy of Pediatrics (2012) regarding therapies for children with developmental and behavioral disorders.

A comprehensive assessment of sensory features may obtain an inventory of sensory experiences across modalities and/or patterns, or focus on a specific construct (e.g., hyperresponsiveness) or modality (e.g., tactile). An exhaustive review of the psychometric properties of clinical caregiver report measures and behavioral assessments is beyond the scope of this chapter (see Baranek, Parham, & Bodfish, 2005, for more details). Clinical caregiver report measures (presented in alphabetical order) include the Sensory Experiences Questionnaire Version 3.0 (SEQ-3.0; Baranek, 2009), a 105-item assessment developed for children with ASD and other developmental disorders, ages 2 through 12 years. The SEQ-3.0 measures the frequency of behaviors associated with four sensory response patterns (i.e., hyporesponsiveness; hyperresponsiveness; sensory interests, repetitions, and seeking behaviors; and enhanced perception) as well as modalities (i.e., auditory, visual, tactile, gustatory, vestibular) across social or nonsocial contexts. In addition to using a Likert scale (i.e., 1 = never/almost never to 5 = always/almost always) of frequency of behaviors, the SEQ-3.0 has eight items that allow the caregiver to provide qualitative responses related to their children's sensory features. The Sensory Processing Measure (SPM; Parham et al., 2007) is a norm-referenced questionnaire for parents or teachers of children ages 5–12 years. It is designed to detect atypical behaviors in sensory processing, praxis, and social participation. A preschool version, the SPM-P, is for children ages 2–5 years (Miller-Kuhaneck, Ecker, Parham, Henry, & Glennon, 2010), which provides scores for social participation, praxis, five sensory systems (visual, auditory, tactile, proprioceptive, and vestibular), and a total sensory composite. The Sensory Profile (SP; Dunn, 1999), normed with typically developing children aged 3 to 10 years, is a 125-item questionnaire that uses a 5-point Likert scale (i.e., 1 = never/almost never to 5 = always/almost always) to measure reactions to various sensory situations and some behavioral/emotional consequences of sensory reactivity. An Infant/Toddler SP (Dunn, 2002), Adolescent/Adult SP (self-report) (Brown & Dunn, 2002), and a short form (SSP; McIntosh, Miller, Shyu, & Dunn, 1999) are also available. Scores are obtained for four quadrants: low registration, sensory seeking, sensory sensitivity, and sensory avoiding.

A variety of behavioral assessments are available for testing specific sensory features or processing; however, few were developed for assessment of sensory features among individuals with ASD, and the psychometric properties of many continue to be investigated. The Sensory Integration and Praxis Tests (SIPT; Ayres, 1989) include 17 subtests designed to detect dysfunctional sensory processes (e.g., visual perception, tactile perception, vestibular-proprioceptive functions) in children ages 4 to 9 years. The Sensory Over-Responsivity Scales: Assessment and Inventory (SensOR; Schoen et al., 2008) measures sensory overresponsivity in seven sensory domains (i.e., tactile, auditory, visual, proprioceptive, olfactory, gustatory, vestibular) in ages 3 through 55 years through both an examiner-administered performance evaluation ($n = 53$ items) and a caregiver self-rating scale ($n = 76$ items). The Sensory Processing Assessment (SPA; Baranek, 1999b) is a brief behavioral measure designed to assess sensory response patterns for children with ASD and related developmental disorders ages 9 months through 6 years. The SPA uses a semistructured play-based format to assess approach-avoidance patterns with sensory toys, orienting responses to social and nonsocial sensory stimuli, and habituation to repeated stimuli. The Tactile Defensiveness and Discrimination Test—Revised (TDDT-R; Baranek, 1998) is a structured behavioral assessment with five subtests administered in a game-like fashion to measure tactile processing in preschool and school-aged children.

CONSIDERATIONS FOR INTERVENTION

Intervention approaches should be highly individualized and aim to maximize engagement in meaningful activities and social participation in the community that are critical to support long-term health, wellness, and quality of life (e.g., Bober, Humphry, Carswell, & Core, 2001). Individualized interventions ideally should align with the goals of the client or family, consider strengths as well as weaknesses, and be contextually relevant, theoretically sound, and congruent with existing clinical and empirical evidence.

A variety of intervention approaches (e.g., sensory-based therapies, parent-mediated interventions, developmental/behavioral programs, alternative therapies) targeting sensory features in children with ASD have proliferated in clinical settings. There is much less research conducted on efficacy of interventions for sensory processing issues relative to interventions for other core features of ASD (e.g., social-communication skills), and very few large-scale randomized controlled trials exist. Furthermore, although these intervention approaches differ with respect to structure, process, and intended outcomes, they are often discussed as if they are equivalent (e.g., sensory-based therapy is often erroneously labeled as "sensory integration therapy"). Thus, practitioners and families are often confronted with making therapeutic decisions in the face of a limited evidence base and surrounding controversies in the literature (American Academy of Pediatrics, 2012; May-Benson & Koomar, 2010). A systematic critique is presented elsewhere (see Baranek, 2002); however, we describe some of the more common sensory-based approaches below and acknowledge that many other approaches are available. Regardless of the intervention used, interventionists should consider the evidence base for the interventions and systematically evaluate outcomes (positive and negative) for their clients. Due to the heterogeneous nature of ASD, children's responses to differential treatments are likely to be quite individualized and varied.

Sensory stimulation approaches involve administration of specific protocols or activities, controlled by an intervener, in a time-limited manner (e.g., wearing a weighted vest for touch pressure input, swinging for vestibular input, sitting on a therapy ball for proprioceptive input, or brushing for tactile input). Expected outcomes usually focus on improving attention, decreasing self-stimulatory behavior, and increasing self-regulation; these have been studied using single-system research designs or alternating treatment group designs, resulting in mixed findings and usually for short-term effects (e.g., Devlin, Healy, Leader, & Hughes, 2010; Fertal-Daly, Bedell, & Hinojosa, 2001; Schilling & Schwartz, 2004; Van Rie & Heflin, 2009). Two randomized controlled trials (RCTs) using a massage protocol reported some improvements in tactile modulation and reductions in problem behaviors, perhaps related to improved sleep after massage (Escalona, Field, Singer-Strunck, Cullen, & Harshorn, 2001; Field et al., 1997). A small RCT used the Grandin Hug Machine (touch pressure) for 6 weeks and reported some reduction in self-perceived anxiety and decreased arousal/reactivity in children with ASD (Edelson, Edelson, Kerr & Grandin, 1999). Auditory integration programs involve complex applications of auditory stimuli (e.g., filtered auditory input delivered through headphones or other listening systems) and target a variety of outcomes including sensory modulation, improved language, and adaptive functioning; these have been tested in small scaled group comparison designs or RCTs, with mixed and/or inconclusive findings reported (e.g., Bettison, 1996; May-Benson & Teasdale, 2012; Mudford et al., 2000; Rimland & Edelson, 1995; for reviews see Baranek, 2002; Dawson & Watling, 2000).

In contrast to intervener-imposed sensory stimulation protocols, an alternative approach uses teaching and/or coaching individuals with ASD (usually with mental ages over 8 years) to cognitively notice their behavioral states and use sensory strategies to manage self-regulation (e.g., Alert Program; M. S. Williams & Shellenberger, 1994); however little research is available. Another approach is to modify sensory environments to improve performance, but studies with ASD samples are rare. Kinnealey et al. (2012) conducted a single subject study ($n = 4$ adolescents; 3 with ASD) and reported some positive effects of sound absorption and softer light modifications on attention to academic tasks and self-reported comfort in the classroom.

Ayres's sensory integration therapy (Ayres, 1972, 2005; Parham & Mailloux, 2010) is a long-term, individualized therapy that requires specialized training (usually by occupational therapists) to elicit active child engagement through "just-right challenges." It is delivered in individual 30–60 minute sessions, one to two times per week, for 6–12 months' duration and takes place in a large therapy room containing multisensory equipment such as swings, climbing structures, and textured materials. A fidelity instrument is available (Parham et al., 2011). Aims are to directly enhance sensory integration and praxis abilities in order to impact broader, developmental social participation and adaptive outcomes. ASD studies have primarily used single-subject designs or alternating treatments group designs (Case-Smith & Bryan, 1999; Linderman & Stewart, 1999; Smith, Press, Koenig, & Kinnealey, 2005; Watling & Dietz, 2007), with mixed evidence regarding improvements in various outcomes (e.g., engagement, play, socialization, behavior regulation, stereotypic behavior). RCT studies with children with ASD are emerging (Pfeiffer, Koenig, Kinnealey, Sheppard, & Henderson, 2011; Schaaf, Hunt, & Benevides, 2012); these limited studies report some individualized gains using goal attainment scaling as well as standardized measures.

Recent trends involve moving intervention out of the clinic to natural contexts. These caregiver-mediated approaches coach caregivers to recognize children's sensory features and problem-solve the dilemmas that arise in daily routines when living with a person with ASD (e.g., Baranek et al., in preparation; Dunn, Cox, Foster, Mische-Lawson, & Tanquary, 2012). Engagement in school- or community-based activity programs, such as exercise, yoga, swimming, martial arts, or horseback riding, are recommended by some clinicians to supplement intervention programs in an effort to enrich sensory or movement experiences that may enhance self-regulation or improve behavior. As with other interventions, efficacy research is limited (Hartshorn et al., 2001; Koenig, Buckley-Reen, & Garg, 2012).

In summary, interventions to address sensory features in ASD differ greatly in format, process, and intended outcomes. Although emergent research has validated the potentially detrimental effects of sensory processing problems for persons with ASD and their families, more research using rigorous designs and with larger samples is needed to test and compare effects of specific approaches. Future studies should clearly identify and carefully describe the specific intervention being tested, as well as the rationale for the expected outcomes. Skills that are not directly addressed and integrated meaningfully in the context of natural daily routines are less likely to improve. The dearth of efficacy studies warrants that practitioners select and monitor interventions for sensory processing problems carefully and target meaningful outcomes (e.g., functional activities, social participation, etc.) that are specific to each individual with ASD.

CONCLUSIONS

Sensory features in ASD have gained prominence in the literature over the past decade, and the field is burgeoning with more descriptive, correlational, and experimental studies to elucidate the nature of these issues. Research in the areas of attention, perception, and multisensory integration has enhanced our understanding of sensory processing differences (both strengths and weaknesses) that manifest in persons with ASD, and could facilitate the discovery of specific endophenotypes underlying both sensory features and other core features of ASD. The ubiquity of sensory features across the lifespan, and evidence of strong associations with social-communication deficits as well we repetitive behaviors in ASD, further supports their inclusion in current diagnostic nosologies as core features. Unlike the fourth edition of the *Diagnostic and Statistical Manual of Mental Disorders* (*DSM-IV*; American Psychiatric Association [APA], 2000), which largely excluded sensory features (i.e., sensory symptoms were considered associated features), the *DSM-5* (APA, 2012) includes sensory symptoms (i.e., hyper-or hyporeactivity to sensory input or unusual interest in sensory aspects of environment) as diagnostic features of ASD.

We recognize that sensory features are early developing, pervasive, and panmodal, and they affect people with ASD individually and differentially throughout their lifetimes. Yet, there is still a need for more rigorous and systematic research, particularly with respect to issues of pathogenesis, heterogeneity, developmental trajectories, and functional impact of sensory processing problems. More studies are required to determine neural mechanisms underlying specific sensory response patterns, and how sensory processes transact with other domains over time to enhance or inhibit development. We need to further differentiate the extent to which sensory processing abilities in persons with ASD are similar or different from other clinical disorders or to typically developing individuals at different stages of development. Intriguing questions also remain with regard to the overlap of seemingly paradoxical sensory response patterns; thus more research on subtypes and their neurobiological and genetic linkages is required. Very few studies include physiological and behavioral/clinical methods concurrently, and those that do have had difficulty fully reconciling discrepant findings. Finally, there has been limited progress on developing valid assessment tools and translating scientific findings into more effective interventions to address sensory processing issues in ways that are most beneficial in people's lives.

New methodological and technological advances show promise to advance research in this area; however, progress continues to be hampered by limited funding, inconsistent terminologies, professional controversies, and insufficient collaborations among basic and clinical science disciplines, as well as among researchers and practitioners. It is important to move forward sensibly, strategically, and collaboratively, involving all stakeholders (individuals with ASD, families, primary care providers, therapists, educators, advocates, and researchers including basic scientists, neuroscientists, applied and translational scientists, as well as funding agencies, etc.) in evolving the theoretical, scientific, and clinical knowledge base in this field.

CROSS-REFERENCES

Chapters 4 and 5 address issues of autism in infants and young children and school-age children, respectively. Chapter 15 addresses motor control and learning. Aspects of multidisciplinary intervention are discussed in Chapter 26. Comprehensive treatment programs are addressed in Chapter 30 and evidence-based treatments in Chapter 42.

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