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Article *in* Autism Research · April 2016

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COMMENTARY

Toward an Interdisciplinary Approach to Understanding Sensory Function in Autism Spectrum Disorder

Carissa J. Cascio, Tiffany Woynaroski, Grace T. Baranek, and Mark T. Wallace

Heightened interest in sensory function in persons with autism spectrum disorder (ASD) presents an unprecedented opportunity for impactful, interdisciplinary work between neuroscientists and clinical practitioners for whom sensory processing is a focus. In spite of this promise, and a number of overlapping perspectives on sensory function in persons with ASD, neuroscientists and clinical practitioners are faced with significant practical barriers to transcending disciplinary silos. These barriers include divergent goals, values, and approaches that shape each discipline, as well as different lexical conventions. This commentary is itself an interdisciplinary effort to describe the shared perspectives, and to conceptualize a framework that may guide future investigation in this area. We summarize progress to date and issue a call for clinical practitioners and neuroscientists to expand cross-disciplinary dialogue and to capitalize on the complementary strengths of each field to unveil the links between neural and behavioral manifestations of sensory differences in persons with ASD. Joining forces to face these challenges in a truly interdisciplinary way will lead to more clinically informed neuroscientific investigation of sensory function, and better translation of those findings to clinical practice. Likewise, a more coordinated effort may shed light not only on how current approaches to treating sensory processing differences affect brain and behavioral responses to sensory stimuli in individuals with ASD, but also on whether such approaches translate to gains in broader characteristics associated with ASD. It is our hope that such interdisciplinary undertakings will ultimately converge to improve assessment and interventions for persons with ASD. ***Autism Res*** *2016, 0: 000–000.* © 2016 International Society for Autism Research, Wiley Periodicals, Inc.

Keywords: sensory processing; sensory integration; multisensory; autism; collaboration

Introduction

As interest in sensory function in autism spectrum disorder (ASD) has grown among researchers across diverse fields, the potential to form truly interdisciplinary collaborations is brimming, but has yet to be fully realized. Clinical practitioners and neuroscientists both actively address sensory function in persons with ASD, but as yet both groups work largely independently of one another [see Baum, Stevenson, & Wallace, in press; Schaaf & Lane, 2015 for reviews from each perspective]. A collaborative, interdisciplinary approach will undoubtedly enhance both groups' efforts, but there are significant practical barriers to transcending disciplinary silos. While neuroscientists and clinical practitioners have a number of overlapping perspectives on sensory function in persons with ASD, there are important differences that define their disciplinary landscapes. Our goal is to describe these differences, as well as to highlight the commonalities, across disciplines with the hope that it will foster conversation and facilitate further interdisciplinary work in this area.

Sensory neuroscience encompasses myriad approaches, but here, to keep the discussion tractable, we focus on human psychophysics and neuroimaging. Likewise, we focus on occupational therapy (OT), a clinical discipline with expertise in the assessment and treatment of sensory challenges that affect the everyday lives of persons with ASD, while acknowledging that many other clinical disciplines are also relevant. We highlight divergent goals, values, approaches, and terminology, as well as shared perspectives that constitute a conceptual framework spanning the two disciplines. We review findings from recent interdisciplinary studies of sensory processing in ASD, point to some pressing needs for future research, and offer specific recommendations to guide such cross-disciplinary endeavors.

Divergent Goals, Values, Approaches, and Terminology

Although there is growing overlap in perspectives across disciplines, as will be described below, the majority of

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Received July 29, 2015; accepted for publication January 18, 2016

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Published online 00 Month 2016 in Wiley Online Library (wileyonlinelibrary.com)
DOI: 10.1002/aur.1612

neuroscientists focus primarily on research, whereas the majority of OTs focus primarily on clinical practice. As such, each field has a set of core values and goals that influences its work at every level, from theory to practice. In drawing these contrasts, we do not wish to suggest that the tenets of one field are more or less valuable, or that these distinctions are absolute, as clinician-scientists with formal research training may operate with a foot in both worlds. However, as very few professionals have extensive formal training in both fields, we expect that an improved understanding of the importance of each field's fundamental goals, values, approaches, and lexicons will facilitate interdisciplinary efforts.

Goals, Values, and Approaches of the Neuroscientist in a Research Setting

The primary goal of neuroscientists is to use the scientific method to accurately describe sensory function in ASD and its neural basis. As such, central values include reductionism and objectivism. To achieve this goal, neuroscientists hold tightly to fidelity and rigor in stimulus control and delivery and in response measurement. In psychophysical experiments, research participants are asked to sustain attention to carefully controlled stimuli and react accurately and quickly to target stimuli or stimulus properties, while otherwise remaining quiet and sedentary. Performance is usually measured in accuracy and/or reaction time and is often coupled with non-invasive measures of neural response (e.g., with EEG or fMRI). This experimental approach lends itself well to precise, objective measurement and can provide significant insights into differences in how the brain responds to a given sensory stimulus, but because ecological validity is often sacrificed for tight stimulus control, translation presents a challenge and measured responses are not easily linked to everyday function.

Goals, Values, and Approaches of the Occupational Therapist in a Clinical Setting

Rather than describe sensory function, the primary goal of the OT is to assess how sensory differences, along with other individual factors, may impact daily life for persons with ASD, and how interventions may be implemented to influence sensory function or accommodate sensory dysfunction. The ultimate goal is to facilitate engagement and support participation in health-promoting "occupations" (i.e., engagement in meaningful daily life activities). Thus, central values include the therapist–client relationship, purposeful activity, and participation. To achieve their goals, OT practitioners adhere to theoretical frameworks, ethical principles, and evidence-based practice guidelines. Interventions are necessarily personalized to the goals and needs of clients, whereas the tight control of variables that an experimental setting requires is not a primary objective. For example, in a sensory integration framework for ASD treatment, goals may include helping the child to maintain attention and regulate emotional responses to sensory input, or to coordinate sensory input with motor responses during functional activities such as play or self-care. This focus on active engagement is in contrast to the quiet, sedentary environment used by neuroscientists to isolate responses to a given sensory stimulus. Outcomes are measured through standardized and non-standardized tests, clinical observations, and caregiver reports/interviews, and often tracked via individualized treatment plans. This clinical approach is ecologically strong and rich in context, but because client needs are prioritized, it does not necessarily include precise quantification of sensory functions or direct correlation with neural mechanisms.

Differences in Terminology

Differences in terminology pose another practical barrier to interdisciplinary dialogue and collaboration. For the purposes of illustrating the problem, we consider differences in defining "multisensory integration" across fields. For OT, multisensory integration refers to the organization of various types of sensations necessary to support performance in daily activities (e.g., writing, eating, socializing). Since such activities typically involve motoric action (i.e., praxis), the tactile, proprioceptive, and vestibular modalities are considered integral. An example of a sensory integration goal in a clinically oriented investigation may thus be "improved praxis and tactile processing for putting on socks independently," operationalized as the pre–post treatment change in the level of independence achieved in putting on socks as quantified by a behaviorally anchored clinical rating scale [Schaaf et al., 2014].

In contrast, neuroscientists define multisensory integration as the influence of one sensory system on another that results in a behavioral or perceptual change (e.g., the visual influence of a moving mouth on perception of a spoken syllable). Thus, the emphasis is on characterizing specific changes in perception in response to particular sensory combinations, not on holistic performance in actions of daily life. For example, in psychophysical studies conducted by neuroscientists, multisensory integration may be operationalized as the gain in processing speed or accuracy for stimuli presented in multisensory (e.g., audiovisual) versus unisensory (e.g., auditory or visual only) contexts. Although it is beyond the scope of this commentary to propose a common lexicon, we use this striking example to illustrate the pressing need for members of both fields to provide clear conceptual and

operational definitions for terminology when engaging in cross-disciplinary scientific communication.

Shared Perspectives

Perspective 1: Atypical Behavioral Responses to Sensory Stimuli are a Consequence of Atypical Neural Processing of Sensory Input in Individuals With ASD

Despite these differences in goals, values, approaches, and terminology, neuroscientists and clinical practitioners have a number of shared perspectives regarding sensory function in ASD. First, both neuroscientists and OTs generally assume that atypical behavioral responses to sensory stimuli in persons with ASD result, at least in part, from differences in the structure and/or function of brain regions responsible for the processing of sensory information. These presumed neural differences are thought to lead to altered sensation and/or perception, which in turn are thought to give rise to atypical behavioral response patterns, such as hyper- or hyporesponsiveness to, or unusual interest in, sensory stimuli.

Perspective 2: Differences in Sensory Function May Explain Higher-Level Deficits in Individuals With ASD

Second, both OT and neuroscience adopt a hierarchical framework for conceptualizing sensory function, such that basic sensory representations provide a foundation for higher-level cognitive, linguistic, social, and adaptive abilities that impact an individual's ability to engage and participate in meaningful life activities. Historically, OT interventions based on Ayres' influential sensory integration model [Ayres, 1979] emphasized an across-modalities perspective, with proximal senses (vestibular, tactile, proprioceptive) forming a developmental foundation upon which more distal senses (visual, auditory) and more complex functions (perception, attention, cognition, praxis) depend. In contrast, neuroscience has historically placed a greater emphasis on describing structure and function within-modalities.

More recently, though, the OT and neuroscience fields have begun to converge in their approach to understanding this hierarchy of sensory function. Multisensory neuroscience has yielded new insights into how the statistical characteristics of combined stimuli, such as their spatial and temporal relationship, influence the manner in which they are integrated by the nervous system, as well as how more complex processes, such as attention, shape basic sensory integration [Murray & Wallace, 2011]. Similarly, newer formulations in OT recognize the importance of multisensory integration for coherent perception and action, emphasizing the contextual nature of real-world human experiences. As within neuroscience, both sensory and cognitive factors are considered in how a person with ASD responds to, and modulates, incoming sensory information to support participation in daily life [American Occupational Therapy Association, 2014].

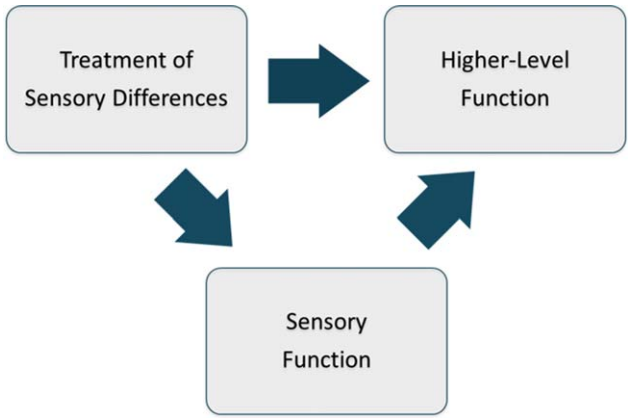

Figure 1. A proposed interdisciplinary framework for conceptualizing sensory function in ASD. Targeted treatment of basic or "foundational" sensory differences in ASD should yield effects on sensory function, and translate to improvements in "higher-level" abilities in individuals with ASD. Sensory function may be measured by neuroscientific and/or clinical measures or, ideally, both. Higher-level functions include the full range of cognitive, linguistic, social, and adaptive abilities that impact an individual's ability to engage and participate in meaningful life activities.

Perspective 3: Sensory Function May Be Malleable With Treatment

Both OTs and neuroscientists operate with the belief that sensory function in individuals with ASD is susceptible to environmental influences and is thus malleable with treatment. In accordance with the previously stated perspective, improvements in sensory function should then translate to effects on higher-level deficits associated with ASD. The broader interdisciplinary community of clinicians working with individuals with ASD is focused largely on these "higher-level" abilities, such as social interaction and engagement, language and communication, and/or other adaptive behaviors, on which sensory differences are believed to produce cascading effects. Based on the aforementioned set of shared perspectives, we have proposed a framework by which we might conceptualize sensory function in ASD (depicted in Fig. 1).

Inroads, Challenges, and Future Directions

At present, there are varying degrees of support for these three perspectives, and thus for the conceptual framework, that we have set forth. Here, we review the evidence to date and provide some concrete suggestions for future interdisciplinary efforts.

Perspective 1: Clear Headway in Characterizing Sensory Function and Some Progress in Linking Neural and Behavioral Atypicalities in Individuals With ASD

Great progress has been made in characterizing sensory differences in ASD [Ausderau et al., 2014; Baranek, Little, Parham, Ausderau, & Sabatos-Devito, 2014; Baum et al., in press; Schaaf & Lane, 2015], undoubtedly contributing to the recognition of sensory features in the most recent revision of the diagnostic criteria [American Psychiatric Association, 2013]. Much of this progress has come from neuroscience or clinical research teams working in isolation, but some attempts have been made to bridge these two perspectives in research. Studies seeking to correlate clinical assessments of sensory reactivity and/or unusual sensory interest with psychophysical and brain-based measures (i.e., EEG and fMRI) have uncovered connections between experimental/neural and clinical measures of sensory function in ASD [e.g., Cascio, Gu, Schauder, Key, & Yoder, 2015; Donkers et al., 2013; Green et al., 2015; Ludlow et al., 2014; Marco et al., 2012; Woynaroski et al., 2013]. Such findings help us to understand how performance on controlled laboratory tasks relates to behavioral reactivity, and point toward possible avenues for intervention to influence or accommodate challenging sensory differences in individuals with ASD.

However, the picture in regards to anticipated links between neural and clinical measures of sensory function is quite complex. Such links are sometimes not observed [e.g., Woynaroski et al., 2013], are weaker than expected [e.g., Brandwein et al., 2015; Haigh, Minshew, Heeger, Dinstein, & Behrmann, 2015; Hardan et al., 2008], or are difficult to interpret conceptually, such as an association between sensory seeking behavior and visual accuracy [e.g., Stewart et al., 2015]. One possible explanation for the frequent failure to find theoretically based associations is that our present measurement system/s are problematic (i.e., are not quantifying constructs in a way that is reliable and/or valid). Second, it is possible that the theory on which the anticipated associations are based is in need of modification.

Regarding the first possibility, most neuroscientifically oriented studies to date that have incorporated clinical measures of sensory function have relied nearly exclusively on parent- or self-report measures. These measures can be administered very easily, are available for a broad range of age and functioning levels, and provide insight into generalized responses to a much wider range of sensory experiences than can be presented in a laboratory setting. However, such questionnaires are not typically constructed to isolate the behavioral patterns within single sensory modalities (e.g., auditory hyperresponsiveness), which we might expect would most readily be mapped to a psychophysical or neural outcome variable (e.g., decreased auditory thresholds). The breadth of these parent/self-port measures also often reflects attentional and affective aspects of perception and behavioral response that are less likely to correlate directly with basic sensory processes assessed in the controlled laboratory setting [Tavassoli, Hoekstra, & Baron-Cohen, 2014].

Some studies have incorporated observational measures of sensory function. For example, the Sensory Processing Assessment [SPA; Baranek, 1999] has been used successfully to link both brain structure [Pryweller et al., 2014] and function [Donkers et al., 2013] with clinical indices of sensory response patterns in children with ASD. However, observational measures are considerably more labor-intensive than parent- and self-reports, and available observational measures are primarily geared toward developmentally younger children with ASD and thus may not be valid for older and/or higher functioning individuals who most commonly comprise the samples of psychophysical and neuroimaging studies. As such, the development and validation of new observational measures represents an important direction for future research.

It is additionally worth noting that psychophysical and neuroimaging approaches present unique challenges in this population, as they generally impose heavy demands on sustained attention, verbal comprehension of task instructions, and motor response, all of which are impacted by ASD. This limits the range of the spectrum that can be studied with these experimental paradigms. Care should be taken by neuroscientists to control for these limitations even in high functioning samples, and to seek alternative experimental paradigms or to adapt existing ones for use in a broader range of individuals with ASD. One example of the latter approach used an adapted psychophysical task in combination with an observational measure of sensory function, revealing a dissociation between reported versus observed sensory responses in younger/less verbal children with ASD [Cascio, Lorenzi, & Baranek, 2013].

In regards to the second possible explanation, our belief that neural responses to sensory stimuli should map onto behavioral responses to sensory stimuli does warrant closer scrutiny. Behavioral response patterns to sensory stimuli could also result from neural differences in arousal or higher order functions, such as attention, that can greatly shape sensory function. Furthermore, aberrant neural responses to sensory stimuli may not necessarily manifest as atypical behaviors, since compensatory or adaptive responses may develop over time.

Perspective 2: Emerging Evidence Relating Sensory Function to "Higher-Level" Deficits in ASD

Several studies have further established links between measures of sensory function and "higher-level" abilities,

such as attention, social skills, communication, and spoken language, in children with ASD [Brandwein et al., 2015; Mongillo et al., 2008; Sabatos-Devito, Shipul, Bullock, Belger, & Baranek, 2016; Watson et al., 2011; Woynaroski et al., 2013]. For example, integration of auditory and visual stimuli has been found to covary with communication symptom severity [Woynaroski et al., 2013] and social skills [Lang et al., 2012; Mongillo et al., 2008] in individuals with ASD. These findings provide some support for the assumption that atypical sensory function contributes to the broader range of deficits observed in individuals with ASD.

These results are, however, only correlational versus causal in nature. Furthermore, few systematic, prospective studies have established temporal precedence for the association between sensory differences and higher order cognitive, linguistic, or social ability in ASD. Thus, the proposal that sensory differences produce cascading effects on other domains of deficit in ASD would be greatly bolstered by longitudinal studies demonstrating that early sensory differences precede and predict later impairments in cognitive, social, linguistic skill in individuals with ASD.

Perspective 3: A Relative Lack of Evidence that Treatment Improves Sensory Function in Individuals With ASD

At present, there is controversy over the strength of empirical support for the efficacy of sensory-based interventions in children with ASD [see Case-Smith, Weaver, & Fristad, 2015; Lang et al., 2012 for recent reviews]. Although several studies have been conducted, methodological limitations preclude a high level of confidence that most reported effects are causally related to the treatment/s. Recent studies with improved internal validity provide some increasing support for the notion that treatment may improve sensory function and/or higher-level abilities in children with ASD [e.g., Baranek et al., in press; Schaaf et al., 2014]. However, larger replication studies that use observational and neurophysiological measures to augment parent-report, and that ensure that assessors are blind to treatment assignment, are needed to expand upon promising findings. Thus, the "treatment" aspect of our proposed framework is presently still tenuous, and represents one of the most pressing needs for future research.

What we need most are more well-controlled (i.e., internally valid) studies of treatment for sensory function in individuals with ASD. Such studies could best test the framework that we have proposed here by: (a) measuring early effects of candidate interventions on targeted sensory function/s, as comprehensively measured by a combination of neuroscientific and clinical measures; (b) measuring later effects of the candidate intervention on higher-level abilities, as measured by a comprehensive neuropsychological battery; and (c) statistically testing whether any later effects of treatment observed on "higher-level" abilities that affect participation in life activities are mediated by the earlier effects of treatment on basic sensory function. Such studies, carried out by a broad interdisciplinary team informing all aspects of the study, would greatly increase our confidence in the assumptions that we espouse and the framework for consideration of sensory function that we have set forth.

Recommendations and Conclusions

The practical and conceptual differences that we have highlighted here illustrate the obstacles to cross-disciplinary collaboration and communication, but the complementarity between fields also suggests enormous synergistic potential for future interdisciplinary work. We conclude with a call for experts from various disciplines to work together to test our shared perspectives: the presumed link between behavioral and neural sensory atypicalities in ASD, the foundational role of sensory differences in higher-order deficits in ASD, and the malleability of sensory function with exposure or treatment. We envision the outcomes of successful cross-disciplinary collaboration to be better translation of empirical findings to clinical practice, as well as improved assessment and intervention for persons with ASD.

Acknowledgments

TW is supported by CTSA award No. KL2TR000446 from the National Center for Advancing Translational Sciences. The contents of this publication are solely the responsibility of the authors and do not necessarily represent the official views of the National Center for Advancing Translational Sciences or the National Institutes of Health.

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