Sensory symptoms in autism: A blooming, buzzing confusion?

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Abstract

Autism is most well known for the way that it affects how a person interacts and communicates with others. But autism can affect behavior in other important and debilitating ways, such as in an intense desire for sameness and in sensory systems that work too well or not well enough. Researchers have largely overlooked the latter "sensory symptoms" but their prominence in forthcoming diagnostic criteria calls for systematic investigation. Here, I review existing theoretical accounts of autism and also introduce a new proposal that employs Bayesian methods to identify the nature of the (altered) computations involved in autistic sensation and perception. Specifically, I suggest that sensory symptoms may be due to fewer prior constraints or attenuated "priors". The possibility that autistic people perceive the world as it "really is" rather than as imbued by prior experiences could explain the range and idiosyncrasy of sensory sensitivities and their difficulties dealing with new experiences.

Difficulties making friends, repetitive behaviors and problems with communication are often the first things that come to mind when one thinks about autism. But there is a collection of less well-known "sensory symptoms" that also characterize autistic[1] individuals, which can be as equally – and sometimes more – debilitating on their everyday lives, as clinicians, educators, parents and autistic people themselves attest. These symptoms were noted by Kanner (1943) and Asperger (1944/1991) in their original descriptions of the condition and were the subject of the earliest experimental studies (Hermelin & O'Connor, 1970; Hutt, Hutt, Lee, & Ounsted, 1964; Ornitz & Ritvo, 1968). Yet the relevance of these symptoms both in terms of our understanding of autism and their impact upon the lives of individuals is only now being fully realized. For the first time they are included as a symptom within the proposed diagnostic criteria for autism (DSM-5; American Psychiatric Association, 2012), with the implication that they are part of the "core" of autism.

There is still much to learn about these symptoms. This article provides an overview of what we know so far and outlines a new explanatory account of the sensory and other non-social symptoms of autism.

Understanding the nature and extent of sensory symptoms in autism

The findings from both first-hand reports of sensory symptoms (e.g., Grandin, 2009; O'Neill & Jones, 1997; Williams, 1994) and studies using parent-report questionnaires such as the widely-used Sensory Profile (Dunn, 1999) suggest that sensory symptoms vary enormously in autism and are often idiosyncratic in nature. They range from *hyper*sensitivity to incoming stimuli, including strong reactions to loud and "impulsive" sounds (e.g., dogs barking, vacuum cleaners), bright lights, the touch of others or one's own clothes, and strong smells (like perfume), to *hypo*sensitivity to such stimuli, including failing to orient to sounds and dampened response to pain. Autistic individuals

[1] The term "autistic individuals" is the preferred language of some people on the spectrum (see Sinclair, 1999). In this paper, I use this term as well as person-first language to respect the wishes of all individuals on the spectrum.

also show "sensory seeking" behaviors – a craving of, and interest in, sensory experiences that are prolonged or intense – including a fascination with spinning or brightly colored objects, and intense looking at flickering light, specific objects or people.

These symptoms are common, occurring in the majority of autistic individuals regardless of intellectual ability (e.g., Leekam, Nieto, Libby, Wing, & Gould, 2007), manifest across modalities – vision, hearing, touch, smell, and taste – and can often oscillate between extremes *within the same individuals* (Ben-Sasson et al., 2009; Rogers & Ozonoff, 2005). They also appear to be more strongly related to other "non-social symptoms", such as repetitive behaviours and interests, motor stereotypies and so-called resistance to change, than the social symptoms of autism (e.g., Mandy, Charman, & Skuse, 2012).

The potential consequences of sensory atypicalities vary widely. Some sensory experiences can be pleasurable, while others can cause catastrophic distress, "sensory overload" or evoke challenging or self-injurious behaviour. They can also have negative consequences on individuals' social participation and degree of autonomy. For example, a child with extreme sensitivity to food odors who refuses to eat in the school cafeteria, might in turn reduce the time spent with his/her peers, while an adult who is hypersensitive to bright lights and noise might be prevented from going about daily activities like grocery shopping. The few existing studies addressing the impact of sensory sensitivities support anecdotal reports, suggesting that sensory symptoms are related to social (Hilton et al., 2010) and affective symptoms (Ben-Sasson et al., 2008), impact upon classroom behaviour (Ashburner, Ziviani, & Rodger, 2008) and interfere with family life (Bagby, Dickie, & Baranek, 2012).

Despite being well documented by clinicians and autistics, sensory symptoms until now have failed to capture the sustained attention of researchers. There is therefore a dearth of systematic knowledge of the nature and degree of such symptoms, how they manifest differently at distinct points in development and, critically, how they change over time. This lack of knowledge has serious implications for how clinicians make diagnostic decisions regarding these symptoms and how autistics, parents, and practitioners seek to remediate them.

One major challenge in addressing these questions pertains to the measurement of sensory symptoms. Observational studies are difficult to conduct largely due to the limited opportunity for children to show responses to sensory events within short time frames. Many studies have therefore relied on questionnaire measures. Yet the use of some such instruments can be problematic because they are not designed specifically for autism (Dunn, 1999), are not sufficiently sensitive for measuring symptom changes over time, and can often only be used within a specified age range (Baranek et al., 2006). Moreover, the existing questionnaires were not developed on the basis of solid theoretical models regarding the underlying basis for the overt sensory symptoms in autism.

This latter point presents a deeper challenge: precisely what explains the presence, heterogeneity and idiosyncrasy of such symptoms in autism?

Explaining the sensory symptoms of autism

Many early theoretical accounts firmly placed sensory atypicalities as the root cause of autistic symptomatology – that fundamental atypicalities in sensory processing could lead to problems in the development of other skills, such as language and social awareness. Early accounts suggested that autistic individuals were in a "chronically high state of arousal" (Hutt et al., 1964, p. 908), where the overstimulation of sensory receptors and the "blocking" of sensory pathways resulted in dampened responses to incoming stimuli, increases in repetitive movements (e.g., flapping, rocking) and social withdrawal. Other accounts proposed that the sensory *and* non-social symptoms were attributable to a functional state of sensory deprivation or underarousal (Rimland, 1964), difficulties in multisensory integration (Hermelin & O'Connor, 1970), or problems modulating incoming sensory input due to an imbalance between neural excitation and inhibition (Ornitz & Ritvo, 1968).

More recently, many theorists (Frith, 1989; Minshew, Goldstein, & Siegel, 1997; Mottron, Dawson, Soulières, Hubert, & Burack, 2006; Plaisted, 2001) have focused on explaining the non-social weaknesses and strengths in autism, including especially the perceptual talents shown by autistic individuals on tasks of embedded figures, block construction and visual search (see Simmons et al., 2009). Frith's "weak central coherence" hypothesis (1989; Happé & Frith, 2006) first suggested that a processing style that afforded "privileged access to parts and details" (Frith & Happé, 1994, p. 122) could account for the non-social symptoms in autism – the weaknesses *and* the strengths – and resulted in a failure to process stimuli in context. On this account, problems in "top-down modulation" could lead to hypersensitivity to sensory stimuli, including cases of perfect pitch in autism, and a local information processing style could result in the characteristic "insistence on sameness".

Alternatively, other theorists have suggested that enhanced bottom-up sensory-perceptual processes should best explain autistic perception. Plaisted (2001) has proposed that autistic individuals' perceptual atypicalities result from enhanced discrimination, possibly due to enhanced lateral inhibition in perception. Similarly, Mottron et al. (2006) have suggested that superior low-level perceptual processing is characteristic of autistic perception and that such perceptual processes in autism are autonomous from higher-level, top-down influences. In support of these claims, laboratory studies have demonstrated *heightened* sensitivity in autism to low-level information in visual (e.g., superior discrimination of orientation of simple luminance-defined gratings), auditory (e.g., superior pitch discrimination and auditory discrimination ability), and tactile (e.g., enhanced sensitivity to vibrotactile stimulation) domains (see Simmons et al., 2009). Echoing others (e.g., Belmonte et al., 2004; Plaisted, 2001, Rubenstein & Merzenich, 2003), Mottron and colleagues (see

Bertone et al., 2005) have suggested that "sensory magnification" in autism might result from an imbalance in inhibitory and excitatory connectivity between local neural networks in sensory regions.

These accounts, however, remain limited both by the striking disparity between self-reported sensory sensitivities and objective (e.g., threshold) measures of such atypicalities and the lack of specification of the nature of underlying processes. Furthermore, these accounts center almost exclusively on *hyper*sensitivity in autism, construed largely as an enhanced ability to perceive sensory stimuli. What is needed, however, is a comprehensive account of the nature and degree of sensory symptoms in autism – hypersensitivity, hyposensitivity and sensory seeking behaviors.

Unexpected, unpredictable and uncontrollable

One other characteristic of autistic sensation and perception is unaccounted for by existing theoretical accounts. Kanner reported an apparent paradox, that "it is not the noise or motion itself that is dreaded ... [as] the child himself can happily make as great a noise as any that he dreads and move objects about to his heart's content". In seeking to resolve this paradox, Kanner noted that "the disturbance comes from the noise or motion that intrudes itself, or threatens to intrude" (1943, p. 245). In other words, it is the unexpected and the unpredictable that is unsettling for autistic individuals; sensory information that is external to him/herself and therefore beyond his/her control.

My colleague and I (Pellicano & Burr, 2012) took this uncertainty as our starting point in a new theory of the sensory symptoms of autism. Our theory uses the tools of Bayesian decision theory, a principled framework for deriving inferences in the face of uncertain information. We suggest that sensory symptoms might be caused by important differences in what an autistic person *expects* about incoming sensory signals and therefore how s/he *interprets* their significance.

Information entering our senses (the retina, for example) is inherently ambiguous (due to natural variations in lighting and viewpoint). This uncertainty is due both to *noise* in the external stimulus and to internal (neural) noise. It has long been suggested that to resolve this uncertainty the brain must form perceptual hypotheses – or "best guesses" – about the structure of the world (Gregory, 1997; Helmholtz, 1860). To do so, the observer constructs a percept, automatically and unconsciously, based upon (ambiguous) incoming sensory information *and* available knowledge due to past experience. On this view, prior knowledge is essential for disambiguating ambiguous sensory evidence to achieve a coherent percept.

Bayesian models formalise the notion of "perception as inference" by combining existing knowledge (known as the *prior* or the bias regarding the cause of an event based on previous experience) with incoming sensory evidence (the *likelihood* of perceiving an event) to infer the most probable interpretation of the environment (the *posterior probability distribution*) (Kersten, Mamassian, & Yuille, 2004; Mamassian, Landy, & Maloney, 2002). The brain generates hypotheses, based on prior knowledge or "implicit assumptions" *and* noisy sensory signals, which helps us to make predictions about the possible causes of such information and, ultimately, make sense of what we see.

Priors help in the interpretation of ambiguous information. Consider the shaded pictures in Figure 1. The particular perception of these images – either as a bump lit-from-above (convex) or a dent lit-from-below (concave) – depends on the direction in which the light source is assumed to originate. Adults typically perceive this image as a bump because they use additional information gained from prior experience with the environment to resolve the ambiguity; that is, they implicitly assume that the light-source probably originates from above, a "light from above" prior (Adams et al., 2004). Priors like this one might be innately specified (Geisler & Kersten, 2002; Scholl, 2006) or rapidly learned in response to experience with the environment (Aslin, 2011). In either case, they can be altered within the order of 5-10 minutes of learning (e.g., Adams et al., 2004) suggesting that they are constantly recalibrated in response to changes in environmental conditions.

Priors improve the efficiency of perceptual systems, even in cases where stimuli are not so ambiguous, by optimizing the trade-off between the precision (or reliability of an estimate) and accuracy (the degree of bias). Jazayeri and Shadlen (2010) demonstrated this using a time reproduction ("Ready, Set, Go!") experiment in which participants had to estimate the duration of the interval between two flashes of light ("Ready" and "Set") and reproduce that duration between "Set" and "Go!" Importantly, the authors manipulated the temporal context such that participants were exposed to trials derived from a particular range (e.g., short, intermediate or long durations) within experimental blocks. Participants' judgments were not accurate reflections of the interval duration or "veridical" in nature. Instead, they were biased towards the mean of the temporal context to which they were exposed and this regression towards the mean was most pronounced for more error-prone, lengthy durations. In other words, (prior) knowledge of the distributions of the temporal context aided performance, particularly under conditions of uncertainty. These findings suggest that we rapidly and implicitly code the reliability of our estimates and use this (albeit "inaccurate") information to reduce uncertainty.

Autistic perception within a Bayesian framework

Bayesian models have been applied successfully to a variety of perceptual problems. We suggest that this powerful computational approach can be applied to the study of sensory symptoms in autism (Pellicano & Burr, 2012). Specifically, we propose that attenuated Bayesian priors might account for the unique phenomenological experience of autistic people. Notably, priors are not absent altogether but are attenuated by degree (that is, have lower precision). Such differences might occur through problems in (implicit) learning and generating of priors or during the integration with sensory information, or both.

This model generates several predictions. First, it predicts that autistic people should show more accurate perception as a consequence of weak priors. Since appropriate Bayesian priors compromise accuracy for improved precision and overall error-reduction, weak priors should cause one to see the world as it "really is", albeit with lower precision. Evidence for this idea is drawn from studies demonstrating less susceptibility to visual illusions (Happé, 1996; Mitchell et al., 2010) and better reproductions of "impossible figures" (Mottron et al., 1999). In another study, Ropar and Mitchell (2002) asked participants to reproduce a slanted circle (i.e., an ellipse), which they were told was a circle, either in the presence or absence of perspective cues. Only autistic individuals' reproductions were far less exaggerated (and thus, much more accurate) when perspective cues were unavailable.

Second, it predicts that attenuated priors should be disadvantageous in those situations where priors help resolve ambiguity. When an object casts its shadow on a background surface, for example, the shadow helps to make objects more recognizable for typical individuals. Instead, cast shadows *impede* recognition for children with autism, suggesting that they make less use of prior information (about shadows) to guide interpretation of the stimulus (Becchio et al., 2010).

Explaining the sensory and other non-social symptoms. According to our theory, common reports of hyper- or hypo-sensitivity are not due to fundamental differences in sensory processing *per se* but, rather, reflect atypicalities in the way that incoming information is *interpreted* by sensory systems. Attenuated priors in autism should cause a greater reliance on bottom-up, incoming sensory signals, which could in turn result in enhancement of sensory stimuli. Such enhanced sensations are consistent with the often-reported experiences of hypersensitivity to sensory information, like Temple Grandin (n.d.) who reports, "My hearing is like having a hearing aid with the volume control stuck on 'super loud'".

Attenuated priors might also explain why autistic individuals can take longer to adapt to particular stimuli or environments. Some children, for example, find the school bell especially distressing and take an unduly long time to get used to the sound. Without a robust template (e.g., of the bell sounding daily around 3pm) against which to match observed sensory evidence, the individual is less able to use this template to predict forthcoming sensory signals. Fewer internal constraints could also lead to the often-reported sense of being overwhelmed by incoming information, or feelings of sensory overload.

Furthermore, if prior constraints reflect the statistical regularities of the environment, then priors should be subject to the specific type of input one has experienced. The idiosyncratic pattern of hyper-sensitivity to stimuli (e.g., aversion to babies crying) and sensory seeking (e.g., fascination with washing machines) should therefore be related to the degree of exposure to particular stimuli in the autistic individual's environment. And such fascinations as well as repetitive behaviors (like spinning the wheels of a toy car) – behaviors over which the individual has full control – might be a means of reducing the uncertainty in the environment.

Attenuated priors might also explain some of the non-social features of autism, including why autistic people can be "insistent on sameness". Children with autism often respond well to daily schedules or "visual timetables", which help order their day and transition smoothly between activities. Weak priors should make it difficult for autistic individuals to use knowledge derived from the past to make predictions about the occurrence of new sensory events. On our account, the often-extreme "resistant to change" in autism is not a problem with "change" per se, but as an inherent difficulty driving expectations about incoming sensory information. Structured schedules often work with autistic pupils because they clearly show what is happening next, thus overcoming the potentially disadvantageous effects of attenuated priors.

Conclusion

There is current consensus (APA, 2012) that sensory atypicalities should be considered one of the hallmarks of autism. Our new account of these features builds on previous suggestions of "more veridical perception" (Mottron et al., 2009) and "reduced top-down control" (Happe & Frith, 2006), critically moving the focus beyond differences in local-global processing. It uniquely situates autistic sensation and perception within a formal Bayesian framework, which has been highly successful in modeling human perception, and provides a parsimonious explanation for both reduced top-down modulation and more precise percepts, and for the sensory and other non-social symptoms.

Although existing experimental data fit well with our account (see Pellicano & Burr, 2012), future empirical work and computational modeling will determine its usefulness as a model. The challenge will be to understand precisely what is altered in autism (e.g., the weighting or updating of priors etc.), to determine its neural instantiation (see in particular, Friston, Lawson & Frith, 2013) and, critically, to situate this account within a developmental context. Our suggestion nevertheless offers a new structure for studying autistic sensation and perception, allowing for more nuanced investigations at the computational level and potentially leading to the necessary empirical base from which to develop effective interventions.

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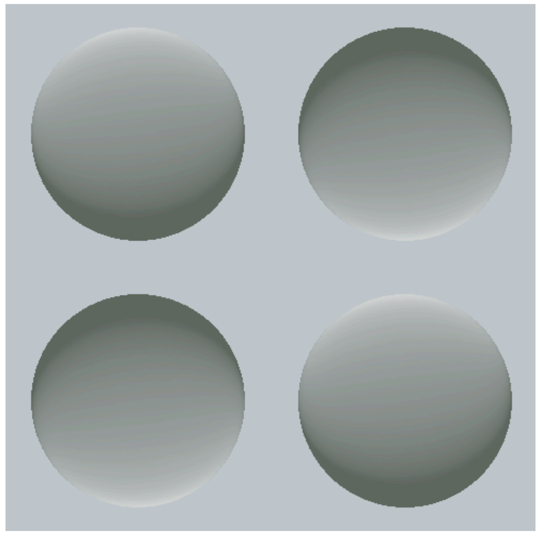

Figure 1. Do these images look like bumps or dents? It depends on where you think the light is coming from. When faced with ambiguous visual input, adults rely on prior knowledge or assumptions to make sense of their surroundings. One such assumption is that light comes from above our heads. In the absence of light-source information, we therefore interpret these images as bumps, if the upper surface is light (top left and bottom right), and as dents, if the upper surface is dark (top right and bottom left).