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Sensory Perception in Autism: What Can We Learn?

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Abstract

Autism is a neurodevelopmental disorder of unknown etiology. Recently, there has been a growing interest in sensory processing in autism as a core phenotype. However, basic questions remain unanswered. Here, we review the major findings and models of perception in autism and point to methodological issues that have led to conflicting results. We show that popular models of perception in autism, such as the reduced prior hypothesis, cannot explain the many and varied findings. To resolve these issues, we point to the benefits of using rigorous psychophysical methods to study perception in autism. We advocate for perceptual models that provide a detailed explanation of behavior while also taking into account factors such as context, learning, and attention. Furthermore, we demonstrate the importance of tracking changes over the course of development to reveal the causal pathways and compensatory mechanisms. We finally propose a developmental perceptual narrowing account of the condition.

1. INTRODUCTION

Estimates of the prevalence of autism spectrum disorder (ASD) have soared in recent decades, with current reports estimating that 1 in 54 children in the United States and 1 in 89 children in European countries has autism. There is a growing understanding that atypical sensory perception is a fundamental characteristic of the autistic mind and is a core phenotypic marker of the condition (Robertson & Baron-Cohen 2017). This understanding has been promoted by the international diagnostic criteria for autism, which includes sensory sensitivities as a core diagnostic feature [*Diagnostic and Statistical Manual of Mental Disorders* (DSM-5); APA 2013]. Accordingly, research on perception and sensory processing in ASD has grown exponentially in the past few decades (**Figure 1**), revealing key differences in the way individuals with ASD perceive the world. However, critical questions about the nature of these alterations and how they relate to higher social cognition and central symptoms remain unanswered.

First, it is unclear how perception in autism differs from that in typical development (TD), as the investigation of ASD perceptual characteristics has yielded mixed and sometimes inconsistent results. This discrepancy may be attributed somewhat to heterogeneity within the ASD population, but it arises mainly as a result of methodological weaknesses. Systematic investigations of alterations in sensory processing may reveal key phenotypic markers of the condition. These may also have important clinical implications (e.g., creating an environment that is ASD friendly and using sensory alterations as early markers).

Second, in the TD population, sensory perception in general and vision in particular are relatively well understood, and neural computational models of perception are conserved between humans and other animals. Thus, understanding perception in ASD and its underlying neural computation has the potential to provide insights into the underlying neurobiological mechanisms of the condition. However, suggested computational models have failed to account for the various perceptual findings, and it is unclear whether a single model can account for perception in ASD.

Last, many of the investigations of autism assume static expressions of the underlying mechanism. However, symptoms may change as new ones emerge with age, and compensatory strategies may be developed. Tracking changes over the years to depict the developmental trajectory of perception and its interplay with cognitive and social development may shed light on the developmental mechanisms of the condition and predict later emerging symptoms.

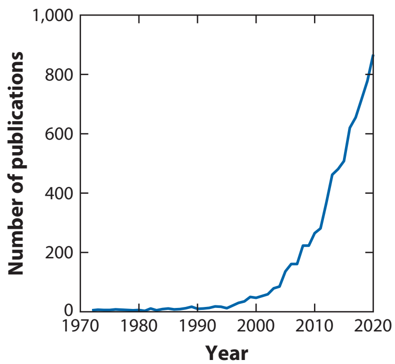


Figure 1

Number of publications with the words "autism" and "sensory" or "perception" in the title or abstract per year (data from **https://app.dimensions.ai/discover/publication**).

This review covers the recent findings and proposed models of perception in ASD. It focuses on research on clinical populations of high-functioning adults and children diagnosed with ASD, with less emphasis on investigations of nonclinical populations using measures of autistic qualities (e.g., the autism-spectrum quotient test). In Section 2, we discuss the major findings regarding atypical perception in autism and point to some of the main gaps in the literature. We show that the inconsistency in the literature is often due to inadequate measurements of perception and sensory processing. We advocate for the use of psychophysical methods to study perception among special populations and in ASD in particular. In Section 3, we review the main competing views. We focus on dominant Bayesian accounts of perception in autism and show the reduced prior hypothesis cannot explain the many and varied findings. In Section 4, we discuss the importance of perceptual models that consider the developmental changes during the first years of life when autism initially emerges.

2. ATYPICAL PERCEPTION IN AUTISM: PROGRESS, CHALLENGES, AND OPPORTUNITIES

Although the notion of atypical perception in autism is widely accepted, the nature of the alterations is debated, and an attempt to cohere the vast findings reported over the years may lead to a complicated and somewhat noisy picture. In this section, we review the main and well-established findings along with some of the conflicting results. We then point to central methodological and conceptual challenges and propose a direction we believe can lead to a coherent understanding of perception in ASD.

However, before discussing the alterations, it is important to note that some basic perceptual functions in ASD are typical. These include visual acuity (Kéïta et al. 2010, Tavassoli et al. 2011), contrast discrimination (De Jonge et al. 2007, Koh et al. 2010), and flicker detection (Bertone et al. 2005, Pellicano et al. 2005). These findings suggest that, at least in vision, early sensory input is intact and alterations may emerge at later stages of perceptual processing.

2.1. Perceptual Superiority and Inferiority

Findings of alterations in detection and discrimination thresholds in ASD are mixed. On the one hand, there is evidence for hypersensitivity and superiority. Findings show visual search superiority, indicated by faster target detection of single features embedded in cluttered visual displays (e.g., Gonzalez et al. 2013, O'Riordan et al. 2001, Plaisted et al. 1998; but see Marciano et al. 2022), and it has been suggested as an early marker in infancy (Gliga et al. 2015). Enhanced low-level processing has been demonstrated across different modalities, including pitch discrimination for simple tones (e.g., Bonnel et al. 2010), detection thresholds for local motion and speed discrimination (Chen et al. 2012, Manning et al. 2015), and tactile discrimination of vibrotactile stimulation (Blakemore et al. 2006, Cascio et al. 2008). On the other hand, there is also evidence of hyposensitivity. Individuals with autism exhibit reduced sensitivity in multisensory integration (Cascio et al. 2012, Paton et al. 2012), olfactory discrimination (Galle et al. 2013), coherent motion (Milne et al. 2002), and temporal interval judgments (Falter et al. 2012).

In some cases, evidence of perceptual superiority and inferiority in ASD varies with stimulus complexity. Concurrent enhanced and impaired performance has been demonstrated for the same visuospatial task: Superior performance has been found for identifying the orientation of simple, luminance-defined gratings, but inferior performance has been demonstrated for complex, texture-defined gratings (Bertone et al. 2005). The complexity of the mechanism underlying these sensory alterations is also implied in the nontrivial associations found between sensory sensitivity and higher-level related processes. For example, enhanced rather than impaired pitch discrimination is linked to language delays, suggesting a mechanism by which hyperacuity to pitch contributes to overly detailed representations of phonological information, thereby delaying the development of phonological categories and subsequent word learning (Eigsti & Fein 2013). These findings suggest that modulations in autistic perception do not simply reflect a general sensory hypersensitivity or hyposensitivity but may point to alterations in somewhat more complex processes.

2.2. The Challenge of Comparing Typical and Atypical Populations: The Case of Visual Perceptual Illusions

The challenge of comparing perception between typical and atypical populations is demonstrated in the study of visual illusions in ASD. Reduced susceptibility to a variety of perceptual illusions in autism has been extensively used to support claims such as local processing style and resilience to top-down effects. However, investigations of visual illusions in ASD are inconclusive. Happé (1996) demonstrated reduced sensitivity to six geometrical illusions in children with autism: the Ebbinghaus, Ponzo, Müller-Lyer, Poggendorff, Hering, and illusory contours (Kanizsa triangle). Hoy et al. (2004) and Bölte et al. (2007) employed the same six illusions but reached different conclusions. Ropar & Mitchell (1999, 2001) tested the Ebbinghaus, Ponzo, Müller-Lyer, and vertical–horizontal illusions, but unlike Happé and Hoy et al., they found similar illusory effects for the two groups. Mitchell et al. (2010) demonstrated weaker effects of the Shepard illusion in ASD, and Chouinard et al. (2013) and Walter et al. (2009) found that reduced susceptibility to illusions was associated with high autistic traits in the nonclinical general population. We argue that these conflicting results may be due to the way these studies measured and compared perceptual processes within and between individuals.

2.2.1. Subjective measurements. The inconsistent findings for visual illusions are based mainly on group differences in speed and accuracy of responses in conditions where an illusory percept arises, contrasted with control conditions in which contextual elements triggering the illusions are eliminated. In many cases, subjects are explicitly required to report the difference in phenomenology induced by the two displays; thus, conclusions about group differences in the susceptibility to perceptual illusions rely solely on direct introspection of the observers, which can be subject to interpretations of task settings and instructions.

2.2.2. Comparing means. A major portion of the research on autistic perception has focused on significance testing, asking whether performance in two main conditions (experimental versus control) differs significantly. This work aggregates data within and across participants and makes statistical inferences mainly on the basis of the overall mean difference between the sampled populations. Specifically, these studies focus on group differences in response time or accuracy, often measured with single signal strength. Such measurements frequently show large variability among participants and are therefore more susceptible to sample size. Moreover, using single stimulus strength, these measures often confound group differences due to overall performance levels and capacities, such as sustained attention, understanding of the instructions, and processing time.

2.3. The Advantages of Using Psychophysical Measurements

The contrasting findings have led to various suggestions for reforming experimental and data analysis practices. A prominent suggestion is the use of much larger samples, supported by power calculations. We argue, however, that rather than using statistical inference on large samples, more robust and meaningful data can be obtained with psychophysical testing.

2.3.1. Replicability. Psychophysical methods in which a small number of participants perform a large number of experimental trials enable an investigation of the full range of the relationships between stimulus intensity and experience at the individual level. Such methods increase measurement precision by minimizing within-condition and within-participant variance, such that the individual rather than the group becomes the replication unit (Smith & Little 2018). These methods involve models that typically predict performance across a range of stimuli and performance levels simultaneously—that is, across the entire psychometric function (Lu & Dosher 1999). They define a relationship between the response of a perceptual mechanism to a given stimulus and the participant's psychophysical judgment, with the result expressed variously as a threshold or a sensitivity index (Graham 1989). With these strong quantitative models, the research focus gradually changes from overall mean difference testing to model fitting.

2.3.2. Objective assessment of subjective experience. By measuring performance for a range of signal strengths at the individual participant level, psychometric functions provide two important and possibly independent measurements of perception (**Figure 2**). Sensitivity indicates the individual's ability to detect differences between varying stimuli (usually defined as the inverse of perceptual thresholds). It is often reported as the standard deviation of distribution or the slope of the psychometric function. Subjective representation of perception is measured in terms of the distance from the true physical value. It is indicated by the point of subjective equality (PSE) of the fitted function, representing the perceived value of the physical stimulus. Disentangling possible differences in sensitivity versus subjective perception between TD and ASD may shed useful light on the nature of perceptual modulations in ASD.

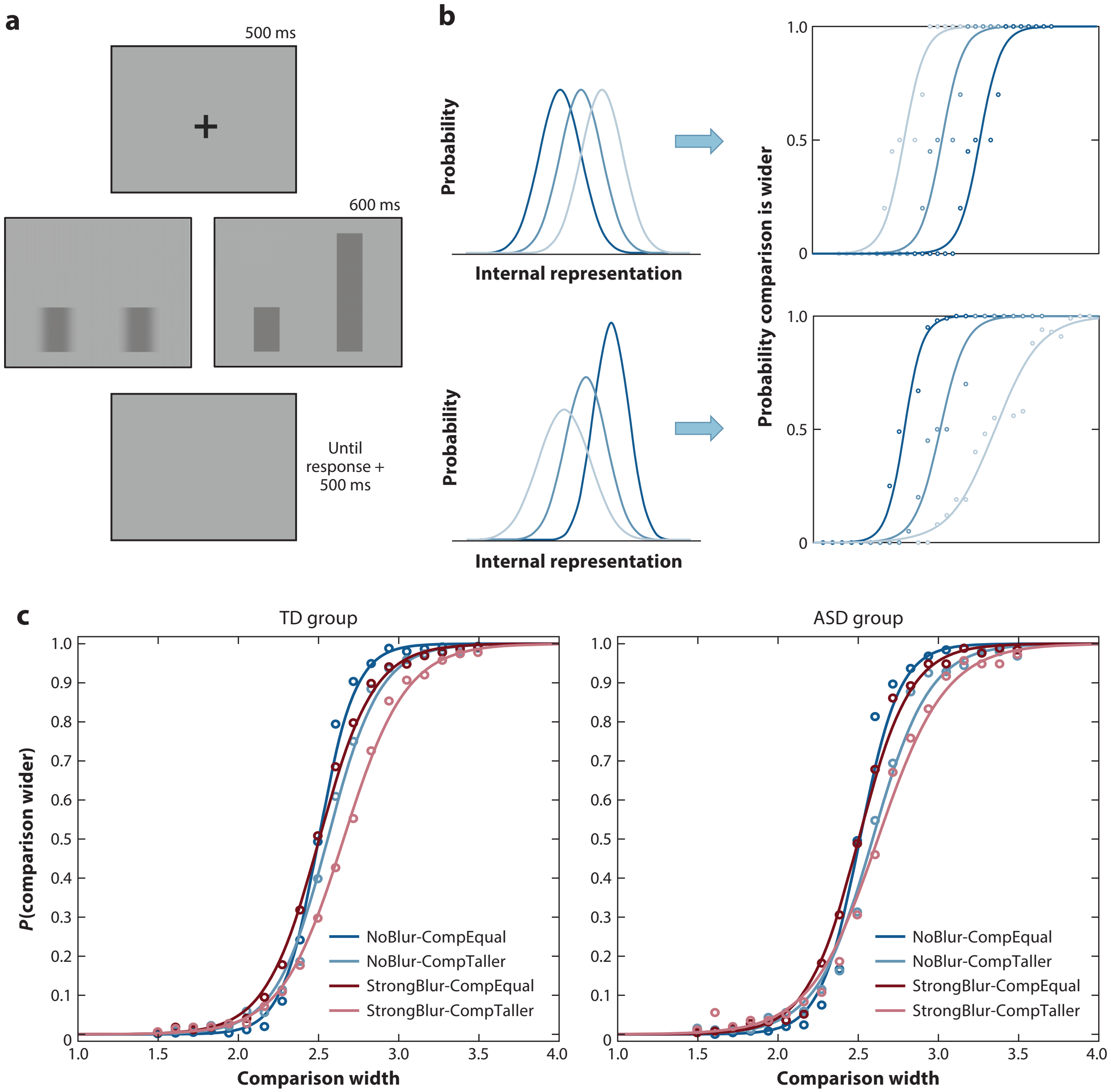
2.3.3. Coherent picture of visual illusions. In the case of perceptual illusions, psychophysical measurements allow researchers to determine whether modulations in susceptibility to perceptual illusions (measured in terms of differences in PSEs), or rather differences in overall performance and perceptual sensitivity (measured in terms of thresholds), underlie modulated responses to illusory displays. **Figure 2** illustrates these possible independent relations between the two measures of perception: As the figure shows, individuals with ASD exhibit noisier width judgments, with poorer resolutions, than controls do (indicated by the elevated thresholds). Yet there are no differences between the groups in the overall magnitude of the illusion, measured in terms of the differences in PSEs of the fitted functions (see also **Figure 3**).

Employing psychophysical methods has yielded consistent results. Manning et al. (2017) found typical susceptibility to Ebbinghaus and Müller-Lyer illusions in children diagnosed with autism when they employed both a two-alternative forced-choice (2-AFC) task and methods of adjustment. Similarly, Milne & Scope (2008) used a forced-choice judgment of the dimensions of a shape defined by illusory contours and—contrary to Happé's study that used the same displays—found no differences between those with and without autism. Hadad and colleagues (Avraam et al. 2019, Binur et al. 2022, Hadad & Schwartz 2019) used 2-AFC tasks and found typical susceptibility to the width–height illusion and the weight–brightness illusion, both of which involve integration across dimensions, with the latter also involving integration across sensory modalities. The findings thus converge across these psychophysical studies to suggest typical effects of perceptual illusions in autism.

2.3.4. Qualitative differences by quantitative measurements. Testing across various signal strengths also allows qualitative differences to be identified, and this may reveal important principles in the underlying mechanisms. For example, consider the case of the flash–beep illusion, in which multiple light flashes are perceived when a single flash is accompanied by multiple beep sounds. When the illusion is tested with a single light–sound stimulus onset asynchrony (SOA), a similar illusion can be obtained in children with autism and controls (Foss-Feig et al.

2010). However, when tested with a range of SOAs, the illusion in ASD extends over a larger range of SOAs, revealing altered multisensory temporal functioning in children on the spectrum.

Investigations of orientation perception using a limited range of orientations have yielded mixed results. Whereas some reported enhanced sensitivity (e.g., Bertone et al. 2005), others failed to show a difference (e.g., Brock et al. 2011). When an extended range of orientations were measured, including both cardinal and oblique orientations, hypersensitivity (lower thresholds) to oblique orientations was associated with higher levels of autistic traits (Dickinson et al. 2014). Poor orientation sensitivity, specifically along the vertical axis, was found in children diagnosed with autism, whereas the ability to discriminate line orientation along the oblique axis remained



(Caption appears on following page)

Figure 2 (*Figure appears on preceding page*)

Demonstration of typical susceptibility in ASD to the width–height illusion (where a taller rectangle is typically perceived as thinner than a shorter rectangle). (*a*) Participants were asked to judge which of two simultaneously presented rectangles (a standard and comparison) is wider. Rectangles were of either same height (*middle*, *left*) or different height (*middle*, *right*). In some trials, the vertical edges of the rectangles were blurred at varying degrees by a Gaussian filter (*middle*, *left*). (*b*) Illustrations depicting relations between Bayesian parameters and psychometric function. (*Top*) Strength of the illusion affects the position of distribution of judgments and results in shifted psychometric functions (shifts in PSEs). (*Bottom*) Reduced sensitivity results in changes in slope (JNDs) and position (PSEs) of the psychometric functions, as increasing effects of the illusion are expected for noisier measurements. (*c*) Psychometric functions plot the proportion of trials in which the participants reported the comparison as wider as a function of the width of the comparisons. Magnitude of the illusion is similar in TD and ASD, indicated by a comparable shift in the PSEs of the psychometric functions of different-height (CompTaller) and same-height (CompEqual) trials. ASDs show reduced sensitivity (indicated by the shallower slopes) and nonadaptive scaling of the bias to the sensory noise (similar shift in PSEs across the different degrees of blur; denoted NoBlur and StrongBlur). Abbreviations: ASD, autism spectrum disorder; JND, just noticeable difference; PSE, point of subjective equality; TD, typical development. Panels *a* and *c* adapted from Binur et al. (2022). Panel *b* adapted with permission from Stocker & Simoncelli (2006).

unaffected (Sysoeva et al. 2016). This finding implies qualitative modulations in the way the autistic visual system becomes sensitive to features that are more prevalent in the natural world (e.g., cardinal orientations), presumably exhibiting reduced learning of the environment statistics. Although further research is needed, these findings imply important qualitative differences in how perceptual specialization develops in ASD.

2.4. Summary and Future Directions

Perception in ASD is still not entirely understood, and many questions regarding perceptual experiences and behavior remain unanswered. Inconsistent results and mixed findings may reflect various methodological problems and wrong theoretical assumptions, such as homogeneity within the clinical and nonclinical populations. One way to tackle this issue is to use a large sample size that accounts for between-subject variability and within-group differences (e.g., clustering). However, gathering a large sample size can be challenging when measuring perceptual performance, which requires conditions that permit complete control over stimulus presentation and reliable measurement of behavior. Moreover, alteration in sensory perception can be complicated and expressed only when a full range of stimulus intensity is tested.

Here, we advocate for a different approach, which uses rigorous psychophysical methods and focuses on better characterizing perception and performance at the individual level within a population. Applying such methods enables objective measurement of perception and an investigation of the full range of the relationships between stimulus intensity and experience and can reveal qualitative differences between individuals. Such explorations can also serve as pilot research for subsequent large-scale studies, as they can help focus the range of explorations. Finally, psychophysics measurements are closely related to neurocomputational models of perception. Thus, using such measurement may help link autistic behavior and symptoms with neurobiological mechanisms. In Section 3, we focus on some of the popular models of perception in ASD.

3. MODELS OF AUTISTIC PERCEPTION

3.1. Domain General Accounts

Classic accounts of superior and impaired perceptual processing in autism converge with the claim that autistic perception by default is more locally oriented. However, this claim was held by two competing hypotheses: (*a*) weak central coherence (WCC) and (*b*) enhanced perceptual functioning (EPF). The WCC hypothesis suggests atypical perception in autism arises from alterations in domain general mechanisms affecting perceptual style. A processing bias favoring

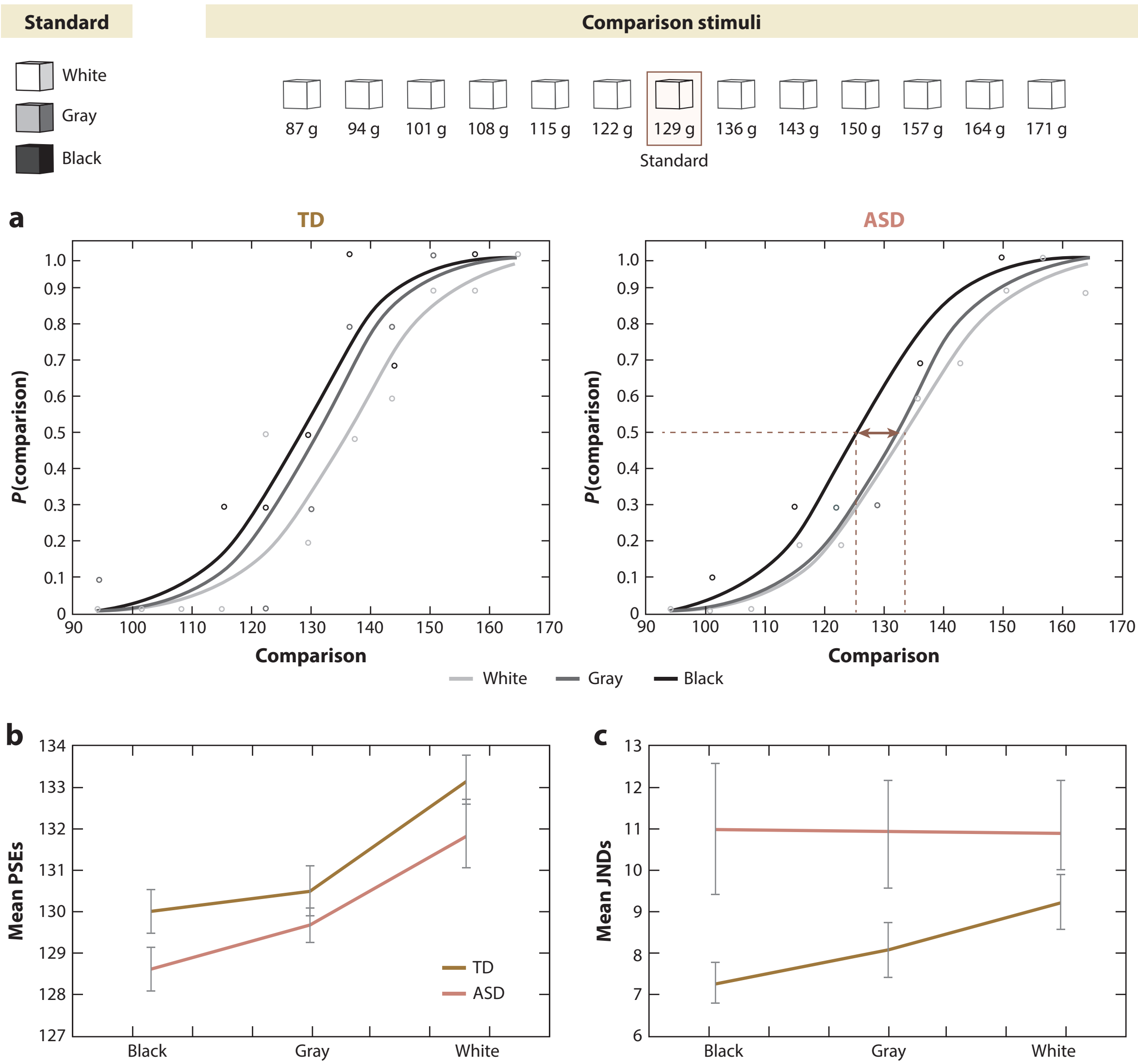


Figure 3

Violation of Weber's law in ASD for illusively perceived weights of objects of varying brightness levels. In this illusion, darker objects, when observed, are judged heavier than brighter objects but otherwise are identical objects. However, when lifted and observed, the opposite pattern of brighter objects judged heavier is obtained. (*a*) The psychometric functions plot the proportion of trials for which participants reported the comparison as heavier, as a function of the brightness of the standards. PSEs of the functions are indicated by the dashed lines, and the bias magnitude is reflected in the shift of the PSEs. (*b*) Both groups exhibited larger PSEs for the white standard and smaller PSEs for the black standard compared with the gray, control standard. (*c*) However, only the group with TD demonstrated scaling of the JNDs to the perceived weight, in adherence to Weber's law. Individuals with ASD demonstrated constant JNDs across the perceived weights. Abbreviations: ASD, autism spectrum disorder; JND, just noticeable difference; PSE, point of subjective equality; TD, typical development. Figure adapted from Hadad & Schwartz (2019).

local over global levels of information results in a relative failure to extract the gist or to see the bigger picture in everyday life (Happé & Frith 2006). Evidence supporting this view comes from studies showing reduced sensitivity to global motion discrimination (Robertson et al. 2012), greater reliance on feature-based processing of faces (e.g., Sasson 2006), reduced dominance of the global configuration of hierarchical stimuli (e.g., Behrmann et al. 2006), and reduced contextual effects in illusory displays (e.g., Happé 1996).

Alternatively, the EPF model does not claim deficits in the processing of global aspects (Wang et al. 2007) but a superiority per se of low-level perceptual operations (Mottron et al. 2006). The model is supported by findings of superior performance in the embedded figure task (e.g., Jarrold et al. 2005) and by findings demonstrating that global aspects can be typically processed when participants are explicitly instructed to do so (Koldewyn et al. 2013).

Research has failed to conclusively support either hypothesis, and conceptual differences between WCC and EPF have decreased considerably since they first originated. Both accounts now agree that, rather than demonstrating the all-or-nothing ability of global processing, differences between TD and ASD reflect tendencies or inclinations (Hadad & Ziv 2015, Hadad et al. 2019a, Koldewyn et al. 2013) that are manifested in differences in the temporal pattern of the global–local processing and, specifically, in slower global processing in ASD (Van der Hallen et al. 2015).

Before research findings can be integrated, however, several pitfalls and methodological challenges must be addressed. As empirical evidence for global–local processing relies mostly on group differences in reaction times, a real opportunity for an integrated account lies in systematic psychophysical testing of autistic perception.

The classic accounts of perception in ASD, such as the processing style accounts (e.g., the WCC hypothesis), aimed to explain perception in ASD with a single fundamental domain general mechanism. Recently, however, the focus has shifted toward accounts that rely on alterations in canonical microcircuitry, which refer to basic computation carried by components of neural circuitry throughout the brain. In this section, we review the two main canonical processes suggested to be involved in ASD: divisive normalization (Heeger et al. 2017, Rosenberg et al. 2015) and Bayesian inference (Friston et al. 2013b, Pellicano & Burr 2012). We discuss the contribution of these models to our understanding of autistic perception and note their limitations.

3.2. Divisive Normalization

There is genetic and molecular evidence of an increased ratio of cortical excitation to inhibition in ASD (Collins et al. 2006, Sanders et al. 2011, Yizhar et al. 2011). On the basis of this evidence, neurobiological investigations have hypothesized that neuronal excitation-to-inhibition (E/I) imbalance in autism may account for functional characteristics across sensory, cognitive, and social domains (Jamain et al. 2008, Markram et al. 2007, Rubenstein & Merzenich 2003). Computational studies have attempted to link the E/I imbalance hypothesis to ASD behavior via a neural computational model known as divisive normalization—a nonlinear, canonical neuronal microcircuitry process that occurs throughout the brain. According to the model, an individual neuron response is the outcome of the ratio of the neural excitation to the pooled excitation of the population of neurons in which it is embedded (Heeger et al. 2017, Rosenberg et al. 2015). E/I imbalance is inherent to the divisive normalization process, which maximizes sensitivity by facilitating discrimination among representations of different stimuli and reducing redundancy.

Using computational simulation, Rosenberg et al. (2015) argued that reduction in the amount of inhibition that occurs through the divisive normalization process can account for a variety of alterations in sensory processing, attention, and decision-making. For example, reduced inhibition in divisive normalization may account for psychophysical findings showing a reduced spatial suppression effect in motion perception in ASD (Foss-Feig et al 2013), and it may also account for weaker neural suppression within the human middle temporal complex (hMT+), a visual motion-selective region in the lateral occipital lobe (Schallmo et al. 2020). However, additional investigation of spatial suppression in typical observers, as reported in Heeger et al. (2017), revealed that divisive normalization cannot account for all spatial suppression characteristics,

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Perception in autism does not adhere to Weber's law, one of the most basic principles of typical perception (Hadad & Schwartz 2019). According to Weber, the ratio of the just noticeable difference (JND) to the reference stimulus intensity is constant ($\Delta I/I = C$, where ΔI is the increase in stimulus intensity to a stimulus of intensity I that is required to produce a detectable change in intensity). The minimum intensity required to detect a change thus increases with stimulus magnitude. Individuals with autism spectrum disorder (ASD) do not show this typical proportional increase in thresholds (JNDs) with stimulus intensity. This has been demonstrated across different modalities and for illusively perceived intensities (**Figure 3**). These findings have theoretical implications both for understanding perceptual atypicalities and for clinical use.

First, the proportional increase in JNDs with stimulus intensity demonstrates a low-level calibration mechanism that typically disregards minor and insignificant changes in the input while amplifying sensitivity to significant information. The disproportionate responsivity to changing incoming stimulation in autism may lead to alterations in sensory processing (possibly affecting the likelihood function; see Section 3). This may result in differences in thresholds between groups varying with stimulus magnitudes, and thus may account for the seemingly inconsistent findings of differences in perceptual sensitivity among individuals with ASD and TD. Individuals with ASD may show elevated thresholds for low intensities but demonstrate performance comparable to (and even higher than) that of neurotypical individuals at higher intensities.

Second, violation of Weber's law may account for the different subtypes of sensory abnormalities shown along intensities within the same individual (e.g., hyposensitivity to some intensities but hypersensitivity to others along the same dimension of stimulation). Measuring Weber's fraction can thus identify different subtypes of sensory abnormalities (e.g., hypo- or hypersensory responders). As research on sensory symptoms has been primarily clinically focused and limited to subjective descriptions, this psychophysics, measuring individual thresholds and Weber fractions, may offer strong objective measures of sensory symptomatology in autism.

suggesting that other processes may be involved in this phenomenon, and that spatial suppression differences between TD and ASD due to an E/I imbalance are unlikely in divisive normalization.

Divisive normalization may also explain some recent psychophysical findings for ASD. For example, the disturbances in the contextualization of neural responses to their surroundings in ASD, as suggested by the E/I imbalance in divisive normalization, are consistent with the violation of Weber's law (Hadad & Schwartz 2019) (see the sidebar titled Altered Basic Psychophysics and Sensory Symptoms in Autism). However, further study is required to determine whether and how divisive normalization plays a role in Weber's law.

Although divisive normalization has the potential to link genetics and molecular findings with alteration in perception, thus far there is no behavioral support for this view. Further research combining psychophysical protocols with neurocomputational modeling is required to test this hypothesis. In particular, research on ASD should test psychophysics protocols designed to demonstrate divisive normalization, such as surround suppression and cross-orientation suppression (Heeger et al. 2017).

3.3. Bayesian Perceptual Inference in Autism Spectrum Disorder

Perception has long been described as a process of unconscious inference, in which individuals rely on the available sensory information and an internal model of the world to make automatic best guesses about their environment (Helmholtz 1962, Petzschner et al. 2015). For example, consider the task of finding your own socks in a pile of laundry. You rely on sensory information like the colors and shapes of the items in the pile, but you also rely on prior knowledge ("they should be

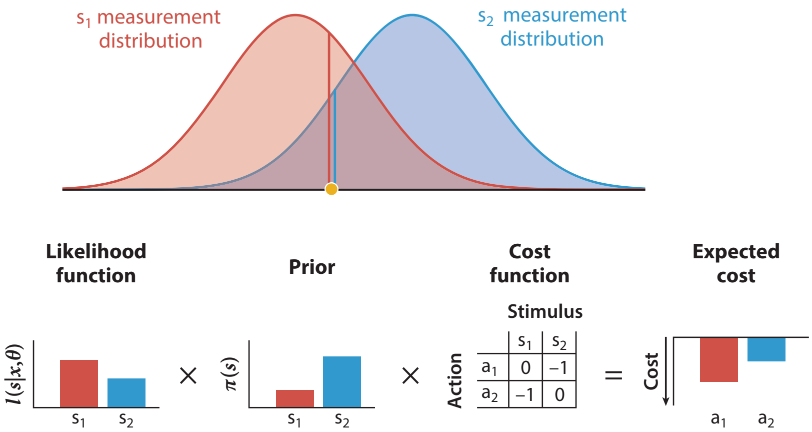

Figure 4

Graphical depiction of Bayesian inference in a perceptual categorization task. s_1 and s_2 are the distributions of the noisy signal of each stimulus category. The yellow circle depicts the internal signal in one trial. The likelihood function is equal to the height of each of the two measurement densities at the value of the observed internal response. The action a_1 corresponds to choosing stimulus s_1. The expected cost of each action is obtained by multiplying the likelihood, prior, and cost corresponding to each stimulus and then summing the costs associated with the two possible stimuli. The optimal decision rule is to choose the action with the lower cost (the bar with fewer negative values). In this example, the prior is biased toward s_2, making a_2 the optimal choice even though s_1 is slightly more likely. Figure adapted with permission from Rahnev & Denison (2018).

dark"), and you can also update your prior knowledge (e.g., if you find one dark blue sock, then the next dark blue item is likely to be the matching sock).

This notion has been formally framed as Bayesian statistical decision theory, a principled method of reasoning under uncertainty that describes how to combine three components of information optimally: (*a*) likelihood, the noisy (not completely reliable) internal response to an external stimulus; (*b*) prior, the initial belief about the probability of each possible stimulus; and (*c*) cost function, the expected reward for each possible action for each possible stimulus (Petzschner et al. 2015, Rahnev & Denison 2018). When the task requires a categorical decision or action (e.g., Is this my sock or not?), the Bayesian framework includes a decision rule, which indicates under what combination of the three information quantities an observer should perform one action or another (**Figure 4**).

Along with the growing popularity of Bayesian models of perception, the debate over perception in ASD has shifted toward whether an attenuated prior (Pellicano & Burr 2012) or enhanced likelihoods (Brock 2012, Karvelis et al. 2018, Lawson et al. 2014) account for the perceptual alterations in the condition. Moreover, this approach has been extended, within the predictive coding framework, to metacognition of perception and the view that the underuse of perceptual priors in autism is due to attenuation of higher-level prior beliefs (hyperpriors) on sensory prior parameter distributions (Friston et al. 2013b). In either case, a critical hypothesis of the Bayesian view is that individuals with ASD overweigh likelihood over prior perception (Brock 2012, Friston et al. 2013b, Karvelis et al. 2018, Lawson et al. 2014, Pellicano & Burr 2012).

The strength of the reduced prior hypothesis comes from its ability to potentially explain alternations in top-down and context effects at both perceptual and cognitive levels of processing. For example, in cognitive decision-making, the hypothesis has the potential to explain reduced context bias and increased rationality in ASD (Rozenkrantz et al. 2021). In perception, the hypothesis is taken to explain the contingency of ASD's perceptual sensitivity on context (Pellicano 2013). Moreover, because some visual illusions are considered to reflect perceptual priors, the hypothesis can explain reports of reduced susceptibility to visual illusions (Mitchell & Ropar 2004, Happé 1996) (see also Section 2.2 on perceptual illusions in ASD). Finally, because Bayesian priors reduce signal noise and variability, the reduced prior hypothesis can explain studies showing heightened sensitivity to stimulus noise. For example, stimulus noise leads to a larger increase in thresholds in individuals with ASD than in individuals with TD (Park et al. 2017, Zaidel et al. 2015).

However, support for the Bayesian inference view relies mostly on post hoc interpretations and inferred Bayesian processes, without quantitative assessment of alternative explanations. Only recently have studies used prior manipulation and analytical approaches to test for Bayesian inferences in ASD. In the next section, we review some of their main findings.

3.3.1. Is perceptual prior attenuated in autism spectrum disorder? The effect of prior knowledge on perception can be demonstrated most dramatically in the perception of ambiguous images. For example, the natural prior that light is often projected from above determines whether an ambiguous shaded form will be perceived as concave or convex. In such a task, individuals with ASD performed similarly to individuals with TD (Croydon et al. 2017). Other studies showed that the natural priors of brightness and size in a weight judgment task were intact in ASD (Buckingham et al. 2016, Hadad & Schwartz 2019). Moreover, a study testing recognition of black-and-white ambiguous images (Mooney images) found that exposure to the natural source image substantially affected image recognition. These findings indicate that, similar to individuals with TD, individuals with ASD can gather sensory information over time to generate predictions on the natural environment.

However, it is unclear whether this is the case for all types of priors and stimuli. For example, the reduced oblique effect in children with ASD (Sysoeva et al. 2016) indicates reduced adaptation to the natural statistics (e.g., Dragoi et al. 2001). It is also unknown whether and how the development of natural priors and the learning of environmental statistics are altered in ASD.

In discrimination or estimation tasks of quantitative features (e.g., duration, orientation, and size), observers utilize the statistics of stimulus history as prior knowledge. When stimulus distribution is uniform, prior is demonstrated by a response bias to the mean of previously presented features (Petzschner et al. 2015). Using this approach, several studies have shown that, similar to individuals with TD, individuals with ASD demonstrate regression to the mean in various features, tasks, and modalities. For example, regression to the mean was found in a visual judgment of size task (Corbett et al. 2016, Sapey-Triomphe et al. 2021a), a duration judgment (Karaminis et al. 2016), and an auditory judgment of pitch (Lieder et al. 2019), as well as an estimation task of duration (Karaminis et al. 2016). These findings suggest that individuals with ASD can learn the statistics of the environment and implement them as prior knowledge. In the case of duration bias, however, using a computational model, Karaminis et al. (2016) argued that given the higher variability (broader likelihood function) in ASD than in TD, we should expect higher regression to the mean in ASD than in TD. But the model assumes the same Weber's law across the two groups, an assumption that was recently challenged (Hadad & Schwartz 2019).

In summary, studies thus far do not provide strong evidence of an attenuated perceptual prior in ASD. In fact, in a simple perceptual task, individuals with ASD utilize both natural priors and learned task-related priors in a manner similar to that of individuals with TD. However, as we go on to explain, priors are complex and depend on context and other capacities, including metacognition, attention, and learning. Thus, to assess perceptual inference in ASD, one must investigate the dynamic of prior forming and its relations to all other Bayesian components.

3.3.2. Decision rule in autism spectrum disorder. According to the Bayesian model, the optimal decision rule integrates prior, likelihood, and cost to calculate a decision criterion that minimizes expected cost (Körding & Wolpert 2006, Maloney & Mamassian 2009). In perceptual discrimination tasks, the most straightforward method of testing the Bayesian inference model with its components is to use the framework of signal detection theory, which postulates that perception is a process of discriminating signal from noise. Surprisingly, however, only a few studies have adopted this approach.

An effective approach to prior manipulation in categorical tasks is to vary the base rate (i.e., the rate of one category over another). In a categorical task with two categories, each with the same probability (same base rate), in which all incorrect responses are equally punished and all correct responses are equally rewarded, an optimal observer has a uniform prior function and a minimum expected cost that minimizes error rates. Skewes & Gebauer (2016) tested the effect of priors in a categorical decision by manipulating categories' base rates (i.e., the same occurrence frequency within long blocks of trials). Observers had to categorize a sound as coming from the left or the right distributions of locations, and the base rate of one location category was three times more likely than that of the other. Both TD and ASD groups shifted their decision criterion in favor of the category with the higher prior probability, but to a lesser degree than an optimal observer. Notably, the criterion shift of the ASD group was more conservative (i.e., a minor shift) and hence even less optimal than that of the TD group. However, without controlling for all other factors that can affect the criterion, it is unclear whether the attenuated prior accounts for these findings.

One alternative explanation is that, when there is uncertainty about the base rate, observers initially assume an unbiased base rate (uniform prior) (Rahnev & Denison 2018). Without controlling for this, it is unclear whether group differences in the initial assumption account for the differences in criterion adjustment.

Another possibility is that individuals with ASD have an inflexible decision rule. Indeed, investigations of drift-diffusion models have shown that individuals with ASD are more cautious when making a speeded perceptual discrimination response and adopt a more conservative criterion in general (Pirrone et al. 2017, 2018)—a finding that cannot be attributed to a reduced prior. Moreover, a recent study showed that in a localization task, individuals with ASD have an enhanced consistency bias and tend to make the same decisions over trials (Feigin et al. 2021). Thus, an inflexible decision rule rather than attenuated prior may explain the reduced base rate effect in individuals with ASD.

3.3.3. Effect of context on prior beliefs. The natural and task-related priors demonstrate an intact use of perceptual expectation and prior belief in ASD. Nevertheless, in real-life situations, priors and expectation effects depend on environmental context and the ability to dynamically adjust to context changes. For example, your expectation of finding socks in different places around your apartment may change depending on whether you have recently adopted a puppy. In other words, adjustment of prior belief to context depends on our ability to learn the environmental statistics, assess the volatility of the environment, and adjust behavior accordingly.

Consistent with the notion of reduced flexibility in ASD, a recent study found participants with ASD could learn and use prior in a two-interval forced-choice (2-IFC) task on size judgments by showing regression to the mean of previously presented sizes. However, participants were less flexible in adjusting the prior according to the distribution of the environment (i.e., the variability of the previously presented sizes) (Sapey-Triomphe et al. 2021a).

Prior adjustment also depends on assessing how much the environment tends to change (i.e., volatility). Investigations of ASD assessment of the volatility of the environment have yielded mixed results. On the one hand, a study that found a reduced effect of cue predictiveness on reaction time and pupillometry response in a visual categorization task (face or house) used a hierarchical predictive coding model that attributed the results to an increased volatility assessment in ASD (Lawson et al. 2017). On the other hand, an investigation of reward learning showed no differences in response to changes in reward volatility for children with ASD and children with TD (Manning et al. 2017). One possible explanation for this discrepancy is that overestimation of volatility develops later in ASD. We discuss the important role of development studies of ASD in Section 4.

3.3.4. Prior updating. As suggested by Lawson et al. (2017), one prediction of the overestimation of the volatility hypothesis is that individuals with ASD assign heavier weights to recent experiences rather than to long-term past experiences. This prediction, however, is inconsistent with several recent findings. Lieder et al. (2019) showed that although regression to the mean in a pitch discrimination task in individuals with ASD was similar to that in individuals with TD, bias toward recently presented features (i.e., one to four trials back) was smaller in individuals with ASD than in individuals with TD. In a following study with a synchronization task in which observers synchronized their finger tapping tempo to that of a metronome beat, individuals with ASD showed reduced error corrections across consecutive beats, suggesting slower update of internal intervals (Vishne et al. 2021). In addition, individuals with ASD demonstrated slower updating of prior in an associative learning task between an auditory stimulus (a beep) and a visual stimulus (orientation). Namely, compared with a control group, the ASD group showed a reduced prediction effect when the association was changed (Sapey-Triomphe et al. 2021b).

These findings imply that although individuals with ASD can form prior beliefs and integrate them with sensory information in a manner similar to that of individuals with TD, they tend to rely less on recent experience and are less flexible when adjusting their beliefs. This slower updating and learning can explain the reduced effect of prior and expectation when observers learn prior over trials, such as in the reduced effect of cue predictiveness on reaction time reported by Lawson et al. (2017) and the reduced effect of base rate on decision criterion in Skewes & Gebauer (2016). Inflexible perceptual prior is consistent with key characteristics of ASD, such as cognitive inflexibility and atypical learning.

However, it is still unclear whether slow updating of bias in 2-IFC tasks reflects inflexible perceptual prior or perhaps other levels of representations, such as working memory, and whether slow updating is inherent to ASD or contingent on task difficulty or stimulus type. For example, Hartston et al. (2022) found that performance in a facial recognition task in ASD relies more on recent experience, demonstrating fast updating of priors in ASD. Thus, further studies using various stimulus types with a control for task difficulty are needed to determine prior flexibility in ASD.

3.3.5. Perceptual learning. In perception, flexibility and learning are demonstrated in the training-induced improvement in basic perceptual tasks (perceptual learning). Although the mechanism of perceptual learning is unclear—it may reflect changes at early signals (Yotsumoto et al. 2008) and feature representation (e.g., Yashar & Denison 2017) or later decision rule (Zhang et al. 2010)—its long-lasting improvement suggests that perceptual learning reflects cortical plasticity. Investigations of perceptual learning in individuals with ASD showed atypical learning compared with individuals with TD (reviewed by Church et al. 2015). In a recent study, individuals with ASD were slower to improve over training days in a texture segmentation task (Harris et al. 2015). Moreover, when training in one stimulus location was tested in a new stimulus location, individuals with ASD showed reduced transfer of learning. These findings point to alterations in mechanisms responsible for cortical plasticity in early visual areas. However, further study is required to explain these differences in perceptual learning within the Bayesian framework and whether and how these differences relate to cortical plasticity during development.

3.4. Future Directions

Atypical statistical and perceptual learning may reflect alterations in different mechanisms. For simplicity, we distinguish between two categories of mechanisms. The first category is alterations in the information needed for learning and perceptual decisions (e.g., prior updating). One such mechanism is visual attention, which modulates various aspects of sensory processing and learning, including perceptual learning and its transfer (Donovan et al. 2015, Szpiro & Carrasco 2015), and statistical learning (Baker et al. 2004). Reduced focused and sustained attention may also reduce the sensory information necessary for prior updating. Thus, while perceptual decision in ASD may be similar to that in TD, atypical attention may alter the information necessary for perceptual decisions and slow down learning and information updating. Evidence for atypical attention in ASD comes from investigations of eye movements and pupillometry (e.g., Granovetter et al. 2020, Wang et al. 2015) and from investigations showing symptoms of attention deficit hyperactivity disorder (ADHD) and ASD often co-occur (Leitner 2014). Thus, to better understand the role of attention in perception in ASD, future studies should assess attentional functioning such as eye movements during prior learning and directly compare ADHD and ASD.

The second category is alterations in the decision rule. In this case, the available information is similar to that in TD, but an inflexible decision rule, such as consistency bias (Feigin et al. 2021), leads to reduced bias by recent trials (Lieder et al. 2019). Because perceptual learning may reflect the adjustment of decision rules (Zhang et al. 2010), inflexible decision rules may also lead to atypical perceptual learning. Inflexible decision rules can also explain the reduced adjustment of perceptual bias and performance to the variability of prior and sensory information (Binur et al. 2022, Hadad & Schwartz 2019).

The inflexible decision rule may involve suboptimal decision processes in ASD, which cannot be explained by a single-level Bayesian model. Perhaps hierarchical models, which consider metacognitive factors such as confidence and consistency versus volatility assessment (Friston et al. 2013a), would be necessary to explain perceptual decision in general and in ASD in particular. Note, however, that perception in TD is not always optimal and that recent studies advocate for perceptual models that focus on detailed explanations of behavior rather than attempting to preserve a static ideal of an optimal Bayesian model (e.g., Rahnev & Denison 2018).

In summary, psychophysical studies and computational modeling have advanced our knowledge of perception in ASD, but we are far from fully understanding the alterations in sensory processing in ASD and how they relate to central symptoms. Our aim should be to fully characterize perception in ASD and to build computational models that can describe these behavioral measurements and relate them to neurobiological findings. We argue that the synergy between rigorous psychophysical measurements and neurocomputational models of perceptual decisions can lead the way to achieve this. The endeavor should consider the neurodevelopmental nature of ASD and its interplay with perceptual development. In the next section, we focus on this critical aspect and propose research directions within the developmental context.

4. DEVELOPMENTAL PERSPECTIVE OF PERCEPTUAL ALTERATIONS IN AUTISM

Models of autistic perception have been developed mainly within frameworks based on the typical, mature perceptual system. Given the neurodevelopmental nature of autism and the nonlinear and dynamic nature of brain development, the way forward is to build a developmental model longitudinally, assessing changes as they occur. As different abilities show varying trajectories of development, this is critical for revealing the causal pathways and identifying the critical primary deficits.

In ASD, some perceptual skills begin as seriously impaired but, over time, may restore behavioral performance to the typical range presumably by employing compensatory mechanisms. For example, in the McGurk effect, visual speech stimuli and auditory speech sounds are perceptually fused into speech that is different from either the visual or the auditory signal. Children with autism are delayed in showing this effect but appear to catch up with their typically developing peers at older ages (Taylor & Seltzer 2010). This finding indicates that some abnormalities in the developmental trajectory of audiovisual integration diminish with age. Other deficits, such as assessment and adjustment of perception to the volatility in the environment, may not appear at younger ages (Manning et al. 2017) but become evident over the course of development (Lawson et al. 2017). Thus, in a coping system continuously adapting and developing compensatory mechanisms, explaining the cognitive and perceptual profiles is best achieved by tracing the processes through which associated symptoms emerge over the course of development.

In this section, we discuss ways to extend existing models into developmental frameworks following major principles in the mechanisms driving changes in perceptual functioning. To promote a computational developmental model of autistic perception, we ask the following questions: (*a*) Which elements of the perceptual models undergo substantial development, and (*b*) how are those elements changed across age and exposure, considering both linear and nonlinear trajectories of development? We evaluate the theoretical and testable predictions arising from this framework and suggest how they may address a key question regarding autistic perception: Is it simply a typical but delayed development that, because of sensitive periods, renders processing in adulthood significantly altered, or rather, are there substantial modulations in the developmental trajectory of perception in autism?

4.1. Which Elements of the Perceptual Models Change During Development?

Research on perceptual development has focused on age-related changes in sensitivity and has only recently tested other aspects of perceptual judgments (decision rule, prior, and cost functions). This line of research suggests that although performance in adulthood sometimes deviates from idealized decision models (Rahnev & Denison 2018), deviations from optimality are pervasive during perceptual development (Nardini & Dekker 2018). These studies show that multiple components of the decision model undergo major development during infancy and childhood. Until late into childhood, children use decision rules less efficiently: They underweigh informative cues (e.g., Sweeny et al. 2015), use qualitatively different decision rules (e.g., Jones & Dekker 2018), and are slow to learn and use priors and costs (e.g., Dekker & Nardini 2016).

For example, when different cues can be integrated to reduce uncertainty in perceptual judgments, typically developed adults go beyond the limits of individual sensory systems' resolutions by integrating multiple estimates (Nardini et al. 2010). This ability, however, does not develop until late childhood (Nardini et al. 2008, 2010). Moreover, whereas the adult perceptual system seems generally optimized for reducing sensory uncertainty, the developing system seems more optimized for speed and for detecting sensory conflict—presumably critical for calibrating the developing sensory systems. This suggests age-related changes occur in the optimization of decision rules, not just in perceptual sensitivity.

4.2. How Perceptual Decision Models Change Across Age and Exposure: Linear and Nonlinear Trajectories of Development

The focus of developmental research on perception has been conventionally limited to a linear progressive path through which experience improves and broadens early-emerging abilities as new ones proliferate with development and increasing experience. However, a regressive path may also characterize development through which ecological experience places restrictions on perception so that the initially broadly tuned perceptual representations are gradually refined and specialized through narrowing of certain abilities. Thus, a more complete framework of perceptual development, typical and atypical, must involve the two trajectories of development and their interplay.

4.2.1. Broadening and narrowing of perceptual processes during development. Evidence of specific time windows during which exposure refines perceptual resolutions comes from studies of face recognition, phoneme discrimination, and music perception. Across these different perceptual domains, exposure to predominant, native stimuli during the first year of life leads to improved native discriminations (Quinn et al. 2014). However, experience may also have regressive effects that lead to narrowing of certain forms of perception during early development. For instance, studies of speech perception found that 6-month-old infants could discriminate nonnative consonants but that such discrimination ability gradually declined through the first year of life (Werker & Tees 1999). Narrowing was also demonstrated at the multisensory processing level, gradually reducing the perceptual salience of some multisensory categories of information and thereby narrowing response options to match ecological constraints (Lewkowicz 2014).

4.2.2. Reduced narrowing and perceptual sensitivity in autism. Perception in autism is less constrained by ecological exposure, and narrowing processes seem milder. This is demonstrated in reduced other-race effects in face discrimination: In ASD, discrimination specific to native, own-race faces is weaker, whereas discrimination of other-race faces remains unaffected (Hadad et al. 2019b, Hartston et al. 2022). Reduced narrowing in ASD was also observed for speech perception: Significant differences in performance were found between children with ASD and their typically developing counterparts on discrimination of the native phonemic contrasts. By contrast, no difference was found between the two groups on discrimination of the nonnative phonemic contrasts (Matsui et al. 2022). Reduced effects of experience on perception in autism are also evident for basic perceptual skills involving nonsocial stimuli, such as in integral and separable perception of multidimensional stimuli (Hadad et al. 2017) and orientation discrimination (Sysoeva et al. 2016). Greater sensitivity in TD to gratings with horizontal or vertical (0°/90°; cardinal) orientations than to gratings with other, oblique orientations demonstrates adaption to the natural statistics (Furmanski & Engel 2000), with this oblique effect gradually increasing with age in typically developing infants (e.g., Sokol et al. 1987). Thus, deficits seen in children diagnosed with autism specifically in orientation discrimination along the vertical axis, but not along the oblique axis, demonstrate weaker specialization to these statistics. Disrupted mechanisms of early experience-dependent learning that normally takes place during the critical period for orientation selectivity may underlie these deficits (**Figure 5**).

This hypothesis allows detailed predictions about development in autism: Specific deficits in progressive development co-occurring with reduced narrowing and abnormal trajectory of regressive processes are expected in ASD. This outcome should result in impaired native discriminations but leave nonnative discriminations intact and perhaps enhanced, as claimed by the EPF view and demonstrated for some perceptual domains (e.g., Mottron & Burack 2001).

This experience-dependent learning has a specific critical period during which it plays a role in shaping sensitivity. Refining the sensitivity of the neuronal detectors determining likelihoods entails normal input during specific early times (e.g., Blakemore & Van Sluyters 1975). Evidence of reduced experience-dependent learning in autism, for both social and nonsocial stimuli, implies changes in attentional and perceptual functioning already early in infancy. Environmental regularities are shown to be crucial in supporting the efficient formation of the representations required to adequately describe the external environment. Whatever the underlying causes, we argue that deviations from attaining perceptual specialization may underlie perceptual

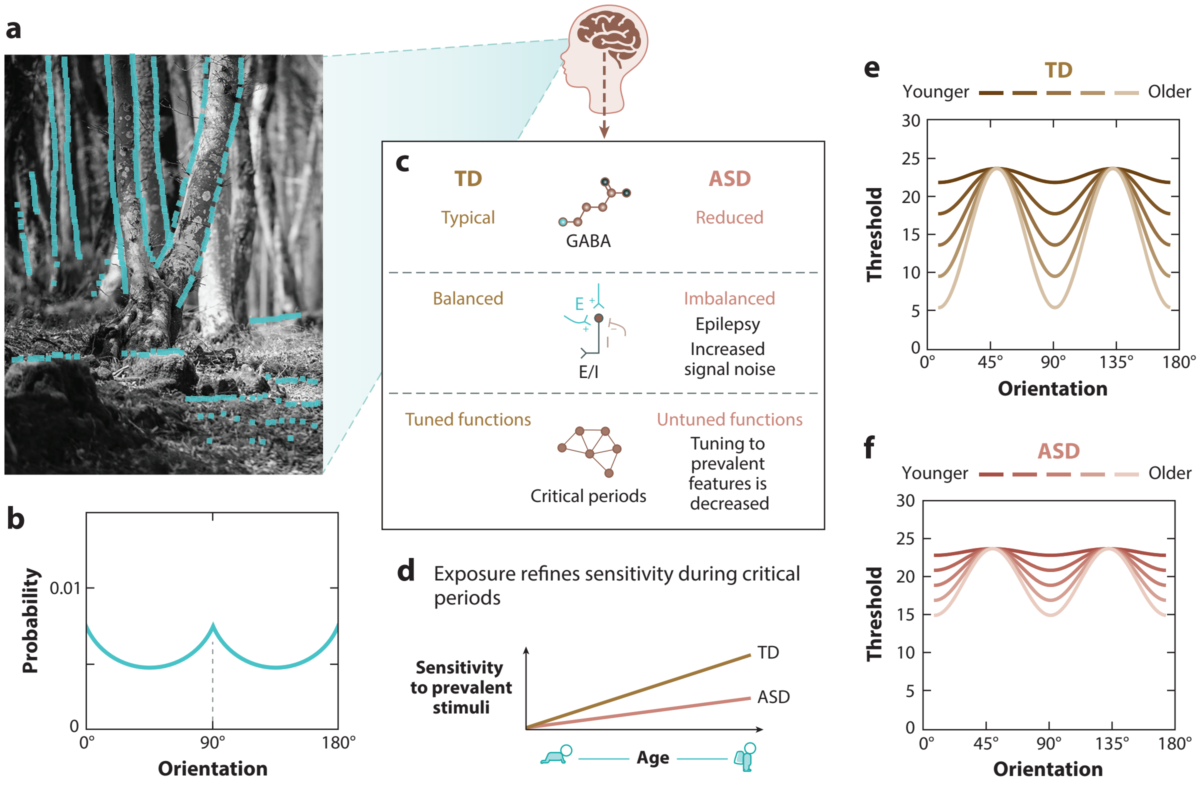

Figure 5

A proposed developmental account of perceptual narrowing in ASD linking modulated GABAergic levels and reduced experience-based learning in autism. (*a*, *b*) An example of prevalent features in the natural environment (taken from Girshick et al. 2011). (*a*) An example of a natural image, with strongly oriented locations marked in teal. (*b*) The orientation distribution in the natural image; there is higher probability to cardinal (horizontal and vertical) orientations than to oblique orientations. (*c*) Reduced GABAergic and E/I imbalances in autism are associated with reduced neural selectivity and untuned functions. (*d*) Disrupted mechanisms of early experience-dependent learning in autism that normally takes place during critical periods may lead to reduced sensitivity to prevalent features. (*e*, *f*) Predicted orientation thresholds during development in TD and ASD. (*e*) In TD, thresholds are relatively low (indicating higher sensitivity) for cardinal orientations (the prevalent feature). (*f*) In ASD, thresholds are atypically higher for cardinal orientations but typical for oblique orientations, indicating less-tuned representations in ASD, specifically for prevalent features. Abbreviations: ASD, autism spectrum disorder; E/I, excitation-to-inhibition; GABA, gamma-aminobutyric acid; TD, typical development. Panel *b* adapted with permission from Girshick et al. (2011).

abnormalities in autism. Thus, less tied experience-dependent learning may result in broadly tuned representations and inefficient perceptual functioning.

Consistent with this suggestion, functioning in autism seems more effortful for many perceptual domains that operate in an effortless, mandatory manner in neurotypical development. This has been recently shown for global–local perception. The strong claims of global deficits accounting for the local processing style in autism have been replaced by hypotheses of more optional, nonobligatory global processing that demands explicit effort and time (Van der Hallen et al. 2015). This is evident even under conditions when the global aspect is extracted spontaneously, in a mandatory manner in TD. These inefficient integration skills in ASD may often appear as a bias toward local information (Happé & Frith 2006) and sometimes as a superior performance in tasks that benefit from these abilities (e.g., Jarrold et al. 2005). A similar pattern is demonstrated in cue integration tasks. Adults with autism integrate cues when they are congruent but not when they are incongruent (Bedford et al. 2016). This is in clear contrast to the mandatory integration process seen in typically developed adults, occurring irrespective of congruency between the cues. Mandatory, spontaneous, and sometimes effortless processes may govern the efficiency with which the perceptual system interprets incoming input, particularly input matching natural statistics. As such, they may induce errors, such as in the case of integrating conflicting cues. If these processes are indeed more effortful and inefficient in ASD, they may not necessarily be mandatory and thus may be less prone to such errors.

4.2.3. Reduced narrowing and decision rule in autism. In TD, experience shapes priors (Adams et al. 2004), drives learning the consequences of actions (cost), and shapes reasoning and higher decision-making with age. Adults often use cognitive shortcuts, or heuristics, to ease cognitive load. These heuristics allow quick and effortless decision-making, considered to be adaptive as they increase efficiency of processing. Yet they can also lead to biased reasoning, suboptimal decision-making, and cognitive biases (Tversky & Kahneman 1974). Early during TD, children seem less prone to such heuristics in learning and reasoning. This has been attributed to an early period of neural flexibility and plasticity, succeeded by a narrower and more inflexible, though more efficient, set of mental computations (Gopnik et al. 2015).

Similar to perceptual sensitivity, exposure does not affect cognitive decision-making in autism as it does in TD. Adults with ASD frequently display judgments that are more objective and decision-making that is less biased than that of typically developed adults. This has been attributed to reduced susceptibility to factors that typically confound rational thought and behavior, such as overreliance on intuition, overweighing of representative information, and attraction to reward (Rozenkrantz et al. 2021). Although these modulations in perceptual and cognitive processes in autism may under certain conditions confer distinct strengths to individuals with autism, such as overrationality or hypersensitivity, more broadly they reveal the inefficiency and the nonadaptive manner by which incoming input is processed in autism.

4.3. Possible Mechanisms and Future Directions

Weaker experience-based learning in autism may be attributed to overall reduced responsiveness to the environment (Elsabbagh & Johnson 2010). Specific impairments in the interactive relations between perception and attention and their tuning to the regularities of the environment may disrupt the developing specialization of the perceptual system. Looking into this possible mechanism entails testing attention and perception of social and nonsocial stimuli during infancy, with specific focus on responses to the statistical regularities of natural scenes. Early signs of increasing specific tuning to frequently encountered stimuli are typically shown at 9–10 months of age (Quinn et al. 2013); thus, beyond theoretical contribution, identifying signs of reduced tuning in infancy may advance early diagnosis and interventions before sensitive periods are closed and secondary effects accumulate.

Our suggestion of reduced narrowing and specialization of perception in autism is consistent with results from human genetics studies providing strong support for the E/I imbalance hypothesis (Satterstrom et al. 2020). There is evidence for the role of GABAergic inhibitory transmission in regulating the strength of experience-dependent plasticity and in fine-tuning the network excitability. Modulated levels of GABAergic and disrupted E/I imbalance in autism may account for the less-tuned perceptual representations shown specifically for extensively experienced stimuli (i.e., own-race faces, cardinal orientations), whereas sensitivity and tuning of perceptual representations of less experienced stimuli remain unaffected (**Figure 5**). The development of sensory, motor, and cognitive functions is associated with considerable changes in neural selectivity that are thought to depend on the maturation of inhibitory GABAergic interneurons during experience-dependent critical periods (Heeger et al. 2017). Future studies should directly inspect how altered neurocomputational mechanisms, specifically those stemming from E/I imbalances, are related to experience-dependent learning and plasticity early during development.

5. CONCLUDING REMARKS

The proposed mechanism suggests autistic perceptual abilities should be seen not as all-or-nothing capacities but perhaps as an out-of-tune system. Developmental mechanisms by which experience-based learning refines perception are altered in autism, deviating from typical mechanisms of perceptual specialization. Reduced experience-based learning is shown for both social stimuli (e.g., faces, phonemes) and nonsocial stimuli (e.g., orientations), suggesting a broad altered mechanism that may account for sensory alterations and symptoms. Social symptoms may arise directly (e.g., weakened face processing) or as secondary outcomes.

These ideas also suggest the early onset of tuning in TD, already evident at 9–10 months of age, can be used for early diagnosis and for appropriate interventions to reverse modulated perception and behavior.

This review advocates for the use of psychophysical measurement as the first step toward understanding the properties of perception in ASD. The benefits of psychophysics make it suitable for comparing performance between age groups and may help reveal qualitative and quantitative perceptual changes over the course of development. Computational models can then account for these changes and uncover the underlying neurocomputational processes and their developmental path.

SUMMARY POINTS

1. Although sensory perception is a core phenotypic marker of autism, it is still unclear how perception in autism differs from that in typical development.
2. Inconsistent results and mixed findings may be due to methodological problems. In particular, comparing means (e.g., accuracy and reaction time) across groups without considering the full range of stimulus intensity may reflect quantitative differences in performance levels but not qualitative differences in sensory processing.
3. Suggested computational models have failed to account for the many and varied findings. Specifically, recent quantitative studies showing intact perceptual prior in autism are inconsistent with the reduced prior hypothesis.
4. Many of the investigations of autism assume static expressions of the underlying mechanism. However, symptoms may change as new ones emerge with age, and compensatory strategies may be developed.
5. Accumulating evidence suggests inflexible learning, decision-making, and prior updating in autism spectrum disorder (ASD). Individuals with ASD also show reduced learning of prevalent features in the environment (e.g., own-race faces, cardinal orientations).
6. We propose that reduced plasticity and learning during exposure-dependent critical periods may underlie atypical perception in ASD.

FUTURE ISSUES

1. Further study is necessary to determine whether the assumption that autistic traits extend across a spectrum to the nonclinical population is indeed correct. Investigating the relations between autistic traits (as measured, for example, in the autism-spectrum quotient test) in the nonclinical population and perceptual alterations found in the clinical population may help determine whether this assumption is correct.
2. Further investigation employing rigorous psychophysics is required to better understand how altered basic perception is related to sensory abnormalities and to allow an objective characterization of sensory symptoms, a core phenotypic marker of autism. Studies such as those demonstrating modulations in low-level perceptual processes (e.g., adaptation effects, Weber's law) may offer a plausible mechanistic account for sensory symptoms in autism.
3. The relations between low-level sensory sensitivity and higher-level related processes are unknown. Further exploration of low- and high-level computations of perceptual and cognitive functions could inform us about the causal relations between these functions.
4. Placing sensory-perceptual alterations as a core phenotypic marker of autism assumes uniqueness of these alterations to autism. However, suggested models have not always been successful in reporting unique findings, as some of their accounts have been extended for other neurodevelopmental disorders. For example, the reduced prior hypothesis has been claimed to account for behavior and symptoms of other neurodevelopmental and mental disorders, such as schizophrenia and anxiety disorders. These claims indicate that more elaborated models, which also take into account detailed aspects of functioning, are required to define the specific shared and unique perceptual characteristics of the different disorders.
5. Future investigation of perceptual learning in children and adults with ASD may shed light on possible alterations in cortical plasticity in the condition.
6. Future studies should directly inspect how altered neurocomputational mechanisms, specifically those stemming from excitation-to-inhibition imbalances, relate to experience-dependent learning and plasticity early during development.
7. A developmental perspective of sensory-perceptual functioning in autism is essential for diagnosis and for determining the relations between different levels of accounts and functioning.

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