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Perceptual category learning in autism spectrum disorder: Truth and consequences

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Abstract

The ability to categorize is fundamental to cognitive development. Some categories emerge effortlessly and rapidly while others can take years of experience to acquire. Children with autism spectrum disorder (ASD) are often able to name and sort objects, suggesting that their categorization abilities are largely intact. However, recent experimental work shows that the categories formed by individuals with ASD may diverge substantially from those that most people learn. This review considers how atypical perceptual category learning can affect cognitive development in children with ASD and how atypical categorization may contribute to many of the socially problematic symptoms associated with this disorder. Theoretical approaches to understanding perceptual processing and category learning at both the behavioral and neural levels are assessed in relation to known alterations in perceptual category learning associated with ASD. Mismatches between the ways in which children learn to organize perceived events relative to their peers and adults can accumulate over time, leading to difficulties in communication, social interactions, academic performance, and behavioral flexibility.

Keywords

generalization; learning deficits; developmental disorder; individual differences; neurodiversity

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Autism spectrum disorder (ASD) is a developmental disorder in which cognitive development differs from the norm. The most salient symptoms associated with ASD—restricted/repetitive behaviors and social impairments—mainly are evident in the way that children behave. Possible differences in learning mechanisms or cognitive processing are not

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noted in the diagnostic criteria for ASD (American Psychiatric Association, 2013). Neither are known differences in perceptual processing by children with ASD, which are difficult to detect without specialized tests (Hadad & Schwartz, 2019; Robertson & Baron-Cohen, 2017). Researchers have become increasingly aware that basic perceptual processes (Dakin & Frith, 2005; Haigh, 2018; Mottron & Burack, 2006), and motor control mechanisms (Glazebrook, Elliott, & Szatmari, 2008; Gowen & Hamilton, 2013; Torres & Whyatt, 2018), are often altered in individuals with ASD, but the origins of such differences remain obscure. The possibility that atypical performance in individuals with ASD might be a consequence of atypical category learning mechanisms, first proposed by Klinger and Dawson (1995), has generally been discounted as a less important factor than structural differences in cortical connections (Just, Keller, Malave, Kana, & Varma, 2012; Rosenberg, Patterson, & Angelaki, 2015), or genetic vulnerabilities that may lead to abnormal cortical function (Mottron, Belleville, Rouleau, & Collignon, 2014; Mullins, Fishell, & Tsien, 2016). However, differences in perceptual classification are difficult to detect externally, making it hard to identify when they contribute to symptoms of ASD.

Children with ASD face a wide range of personal and educational challenges that can hinder their ability to learn, including a decreased ability to interact effectively with teachers and peers (Fletcher-Watson & Happé, 2019). Attempts to address this issue historically have centered on creating special environments or interventions that increase opportunities for successful learning, including applied behavioral analysis (ABA) therapy for enhancing social skills and specialized schools. An implicit assumption of this classical approach is that learning mechanisms in children with ASD are no different from those in TD children and that one of the main obstacles impeding their ability to succeed academically and socially relates to how and what they are taught (G. Dawson et al., 2010; Leaf et al., 2016; Roane, Fisher, & Carr, 2016; Rogers et al., 2019). Recent evidence suggests, however, that both neural mechanisms of learning and basic learning processes are often atypical in individuals with ASD.

Studies of atypical learning in children with ASD have garnered less attention from scientists than deficits in social skills, communication, or perspective taking (M. Dawson, Mottron, & Gemsbacher, 2008). Difficulties in learning are often less obvious than the hallmark deficits in verbal and non-verbal social communication, as well as delays in or lack of language development that are often used to diagnose the severity of ASD in children (Masi, DeMayo, Glozier, & Guastella, 2017). Atypical acquisition and generalization of associative learning, including both classical and instrumental conditioning, have been reported (Crawley et al., 2019; Klinger, Klinger, & Pohlig, 2007; Lovaas, Koegel, & Schreibman, 1979; Sears, Finn, & Steinmetz, 1994), as have differences in episodic memory (Boucher & Anns, 2018; Boucher, Mayes, & Bigham, 2012), sensorimotor learning (Foster et al., 2020; Hayes et al., 2018; Ornitz, 1974), perceptual learning (Plaisted, O'Riordan, & Baron-Cohen, 1998), and observational learning (Foti et al., 2014; Taylor & DeQuinzio, 2012). Nevertheless, the evidence concerning learning deficits in individuals with ASD remains mixed, with some researchers failing to find between-group differences for some learning tasks (J. Brown, Aczel, Jimenez, Kaufman, & Grant, 2010), and others finding evidence of slower learning (Bott, Brock, Brockdorff, Boucher, & Lamberts, 2006; Soulières, Mottron, Giguère, & Larochelle, 2011), or faster learning rates (Crawley et al., 2019; Sears et al., 1994), without large differences in final performance measures. Based on a broad review of past work, Dawson and colleagues (2008) concluded that learning by individuals with ASD is often unconventional, spontaneous, sometimes exceptional, and not well understood.

Children with ASD perceive the world (including themselves) differently leading them to behave differently. They often attend to idiosyncratic aspects of objects and events (e.g., texture and spatial orientation) that are less salient for typically developing (TD) children (Bolton, Jochaut, Giraud, & Van De Ville, 2018; Riby & Hancock, 2009). Such differences in perceptual processing could lead children with ASD to form categories that differ from the norm. Conversely, differences in category acquisition might alter how perception develops in children with ASD. Behavioral studies comparing categorization by children and adults with or without ASD have produced equivocal results, with only a subset of studies reporting clear differences between groups (Church et al., 2010; Froehlich et al., 2012; Gastgeb, Dundas, Minshew, & Strauss, 2012). The fact that people with ASD often show little difficulty categorizing items has led many researchers and caretakers to assume that children with ASD learn categories in the same way as TD children. However, similar performance in categorization tasks does not imply that the underlying categories that people use to perform those tasks are equivalent. Discrepant but overlapping categorical criteria can lead to similar sorting actions. And some categories, such as those related to social contexts and conversational norms, may be more difficult for a child with ASD to learn than other categories.

The goal of this paper is to assess past and current evidence for atypical category learning in children with ASD, as well as the extent to which idiosyncratic perceptual categories might contribute to the heterogeneous symptoms associated with ASD. Our review is organized into four sections. *Contributions of Categories to Cognitive Development and Perceptual Organization* summarizes how processes of category learning and perceptual organization can interact early in development, potentially driving atypical developmental trajectories. *Behavioral Evidence of Atypical Category Learning in ASD* focuses on experimental research showing that both children and adults learn perceptual categories in ways that differ from TD individuals. *Theoretical Interpretations of Differences in Category Learning* reviews current theories of ASD that offer possible explanations for why individuals might fail to learn or generalize perceptual categories in the way that most people do, highlighting the limited ability of current theories to account for the heterogeneous performances of individuals with ASD. *Possible Consequences of Atypical Perceptual Category Learning on Children's Lives* describes how divergent category learning capacities in children with ASD can potentially lead to the core symptoms used as diagnostic criteria—restricted interests and repetitive behavior, impaired social interactions, and dysfunctional social communication, and may contribute to systematic differences in cognitive processing. We end with a few recommendations for future research.

Contributions of Categories to Cognitive Development and Perceptual Organization

The ability to sort experienced events into categories is fundamental to cognitive development (Gopnik & Meltzoff, 1987). Children under the age of two appear to form novel categories dynamically based on perceptually salient attributes (Rakison & Butterworth, 1998; T. B. Ward, Becker, Hass, & Vela, 1991). Numerous studies show that infants exposed to unfamiliar objects can rapidly learn to categorize those objects based on perceptual similarities (Poulin-Dubois & Pauen, 2017). Infants spontaneously categorize objects based on their perceptual features at 9 months (Bhatt & Quinn, 2011; Starkey, 1981; Sugarman, 1983), learn to recognize complex categories such as stuffed animals by the age of 10 months (Cohen & Strauss, 1979), and begin actively sorting objects into categories starting at around 18 months. Categorization of speech sounds strongly affects children's abilities to learn different languages (Goudbeek, Smits, Swingley, & Cutler, 2017; Kuhl, Williams, Lacerda, Stevens, & Lindblom, 1992), and predicts later reading capacities (T. P. Hogan, Catts, & Little, 2005). Categorization abilities also contribute to general cognitive development, providing the foundation for object permanence, problem-solving abilities, causal understanding, object naming, and linguistic development (Mareschal & Quinn, 2001; Poulin-Dubois & Pauen, 2017).

While some categories emerge in young children rapidly and effortlessly (for example, faces versus not faces), others (such as "food") can take years of experience to acquire. By the age of seven, a child will typically have learned hundreds of thousands of categories: kinds of cookies, games, animals, emotions, rooms, etc. Some of those learned categories will be verbalizable while others (e.g., categories formed by infants) will be purely perceptual. For unfamiliar objects and events, new categories can rapidly be learned. For example, imaginary Pokémon can be classified by species, abilities, and characteristic actions. In laboratory experiments, participants learn to sort abstract shapes as being *mogs*, *bliks*, *greebles*, or *ziggerins* (Richler & Palmeri, 2014). Many categories that children learn are defined by perceptual similarities, similarities that researchers often assume are stable and comparable within and across individuals. Some developmental theories of perceptual organization suggest, however, that many perceptual comparisons that are salient to young children are a direct function of their sensory experiences (Hebb, 1949; Piaget, 1929; Quartz & Sejnowski, 1997). From this perspective, children progressively and implicitly learn how to represent and organize perceptual information and gradually adjust both their judgments of perceptual similarity (e.g., Holt & Lotto, 2010; Kuhl, 1994), and their neural representations of perceptual features, (e.g., Benasich, Choudhury, Realpe-Bonilla, & Roesler, 2014), throughout their lives.

Pattern perception and organization lie at the core of category learning (Jones & Smith, 1993; Rakison & Butterworth, 1998; Rakison & Yermolayeva, 2010). Traditionally, perceptual organization and categorization have been viewed as separate and sequential cognitive processes, with unimodal features being detected and grouped into perceptual wholes (e.g., object representations) before these experiential representations are compared to a trove of stored representations that capture what is known about categories within which percepts can be grouped (Goldstone & Barsalou, 1998; Palmeri & Cottrell, 2010; Palmeri & Gauthier, 2004). More recent models of perceptual organization, however, propose that the formation of perceptual units is more dynamic, with experience-dependent feature construction shaping the kinds of percepts one forms, and existing categorical representations shaping how features are grouped (Goldstone & Hendrickson, 2010; Goldstone, Lippa, & Shiffrin, 2001; Harnad, 1987; Hochstein & Ahissar, 2002; Wagemans, 2018). From this perspective, how one perceives the world is warped by the categories one has learned, with properties relevant for categorization emphasized (Goldstone et al., 2001), and with learned expectations about how the world is organized affecting processing of sensory patterns at every level (Wagemans et al., 2012). Gestalts shape the percepts that are categorized, and categories partly determine the Gestalts involved in constructing percepts (e.g., some appear to be learned, Bhatt & Quinn, 2011). The relationship is bidirectional and mutually supporting, with specific domains of perceptual expertise emerging from more domain-general learning mechanisms (Goldstone et al., 2001). Perceptual systems strongly constrain how sensory patterns are processed, but also adapt to what one extracts from perceptual experiences (Figure 1).

Learning during early development plays a key role in shaping cognitive processes and social competencies because of downstream effects. Perceptual attributes that adults easily isolate, are often fused for young children (Kemler & Smith, 1978; Smith, 1989). Differentiation of fused attributes and unitization of correlated features create perceptual primitives (Bhatt & Quinn, 2011; Goldstone, Son, & Byrge, 2011). In infants, perceptual similarity is dynamic as attention to different cues shifts across contexts and as new categories are formed (Smith & Heise, 1992). The strongest evidence of such effects comes from studies of categorical perception (Goldstone & Hendrickson, 2010). For instance, extended experience with categorizing specific speech sounds affects both discrimination and segmentation. Infants sensitive to speech differences at two months, become less sensitive to those differences over the following eight months (Werker & Tees, 1984). A child’s ability to discriminate within-category differences may also be influenced by the distribution of items experienced (Gureckis & Goldstone, 2008; Junge, van Rooijen, & Raijmakers, 2018). Similarly, experience with objects interacts with object segmentation processes when infants perceptually process complex visual scenes (Bertenthal, 1996). How infants perceptually segment objects, words, and limbs determines how they view the world and enables them to communicate effectively (Bhatt & Quinn, 2011). Familiar configurations of features apprehended during category learning can become part of the perceptual primitives that an infant subsequently uses to parse scenes and recognize objects (Bhatt & Quinn, 2011; Hebb, 1949; Needham, Dueker, & Lockhead, 2005; Quinn, Schyns, & Goldstone, 2006; Schyns, Goldstone, & Thibaut, 1998), blurring the dividing line between perceptual organization and categorization. From an early age both lower and higher levels of perceptual processing can guide and be guided by the output of category learning processes that produce perceptual organization (Bhatt & Quinn, 2011; Quinn & Schyns, 2003; Yoshida, Pons, Maye, & Werker, 2010).

Perceptual category learning during early development depends at least in part on brain plasticity, the capacity of neural networks to adjust processing based on repeated experiences. Genetic and neuroscientific studies of ASD suggest that the neural circuits of children with this disorder may be modified by past experiences in atypical ways (Kim, Gibboni, Kirkhart, & Bao, 2013; LeBlanc & Fabiolini, 2011; Mottron et al., 2014; Oberman, Rotenberg, & Pascual-Leone, 2015; Rubenstein & Merzenich, 2003). For example, connections may change faster or slower than normal or in ways that are less reliably linked to learning. Such differences could lead to abnormal category learning with cumulative consequences throughout the lifespan. Many of the genes linked to ASD are known to affect synaptic transmission in ways that are likely to influence synaptic plasticity mechanisms (Mottron et al., 2014; Mullins et al., 2016). Imbalances in neural inhibition versus excitation within neural networks can also affect the way that experiences reorganize cortical circuits (Nelson & Valakh, 2015; Rubenstein & Merzenich, 2003), as can atypical connectivity patterns within networks (Dovgopoly & Mercado, 2013). Given that cortical development and brain plasticity are almost certainly divergent in children with ASD (Mottron et al., 2014), it is important to consider how atypical learning mechanisms might either contribute to (or compensate for) the symptoms associated with ASD. Perceptual category learning enables young children to build the mental representations from which conceptual understanding emerges. Consequently, when category learning is disrupted or atypical, it can potentially have profound impacts on cognitive development. The following section focuses mainly on findings from experiments in which participants learn novel visual categories based on feature similarity (family resemblance), rather than categories based on meaning, use, or formal taxonomy. The same basic processes underlying visual perceptual category learning may extend to other domains.

Behavioral Evidence of Atypical Category Learning in ASD

Individuals with ASD often report perceptual experiences that diverge from the norm (Bogdashina, 2016; Grandin, 1995, 2009). Such self-reports provide a unique perspective into what living with ASD is like. Donna Williams, a popular author with ASD, describes her experiences of chairs as follows: “Chair was not a picture, it was a felt shape, slappable, which didn’t bounce back, with one kind of acoustic for molded plastic, another for vinyl, another for cloth, another for wood. It had a certain movement when rocked which ball, cup, door don’t have” (D. Williams, 2003, p. 78). Williams contrasts her subjective experiences with those reported by Temple Grandin, who describes her mental impressions as similar to a cascade of photo-realistic pictures: “If you say the word ‘butterfly’, the first picture I see is butterflies in my childhood backyard. The next image is metal decorative butterflies that people decorate the outside of their houses with and the third image is some butterflies I painted on a piece of plywood when I was in graduate school. Then my mind gets off the subject and I see a butterfly cut of chicken that was served at a fancy restaurant approximately 3 days ago.” (Grandin, 2009, p. 1437). Grandin further suggests that she even answers abstract questions by “putting photo-realistic pictures into categories,” which she describes as thinking in pictures. Such reports strongly suggest that at least some individuals with ASD categorize percepts and events in atypical ways (see also Bouvet et al., 2014). The origins of such divergent subjective experiences remain unclear, however, because atypical sensory, perceptual, and/or conceptual processing could potentially drive these kinds of differences (Minshew, Meyer, & Goldstein, 2002).

Starting in the 1990s, researchers began systematically exploring whether category learning by children with ASD might differ from learning by TD children (Klinger & Dawson, 1995, 2001; Minshew et al., 2002), noting that impaired category learning could explain several of the difficulties faced by these children. Subsequent studies of category learning have generated a confusing mix of findings, suggesting that category learning is unaffected for a subset of children and adults with ASD for some category learning tasks (Bott et al., 2006; Molesworth, Bowler, & Hampton, 2005, 2008). Most laboratory studies of category learning have participants learn to label abstract images such as cartoons or two-dimensional patterns, but a few have also examined how people with ASD learn to categorize more socially-relevant stimuli such as faces, speech, and event schemas (Loth, Gomez, & Happe, 2008, 2011). Table 1 summarizes the results of experiments on category learning by individuals with ASD conducted to date.

Classifying Naturalistic, Socially-Relevant Stimuli

Numerous studies have examined atypical processing of faces and facial expressions by children and adults with ASD (Adolphs, Sears, & Piven, 2001; Behrmann et al., 2006; Boucher & Lewis, 1992; G. Dawson, Webb, & McPartland, 2005; Dwyer, Xu, & Tanaka, 2019; Gastgeb, Rump, Best, Minshew, & Strauss, 2009; Humphreys, Hasson, Avidan, Minshew, & Behrmann, 2008; Joseph & Tanaka, 2003; Kleinhans, Richards, Greenson, Dawson, & Aylward, 2016; Scherf, Behrmann, Minshew, & Luna, 2008; Tanaka et al., 2012; Wolf et al., 2008). Individuals with ASD seem to be less sensitive to global motion and have difficulty integrating multiple perceptual inputs, such as a variety of information from different sensory categories or different details of the whole picture, especially when, as noted above, those details must be integrated across multiple modalities (Evers, Van der Hallen, Noens, & Wagemans, 2018). The deficits in face processing seen in individuals with ASD are often described as resulting from a tendency to emphasize local details, such as isolated facial features, rather than more global/holistic properties (M. Dawson et al., 2008). Such “tunnel vision” can in turn be related to stimulus over-selectivity, in which individuals with ASD are responding to partial or irrelevant environmental cues instead of more abstract properties (S. M. Brown & Bebko, 2012; Ploog, 2010).

Studies of high-functioning (HF) adults and children with ASD (without intellectual disability) that tested their ability to learn about face categories from either schematic drawings (Gastgeb et al., 2009), or photos of faces (Gastgeb, Wilkinson, Minshew, & Strauss, 2011), showed differences in what individuals with ASD learned about novel faces relative to matched TD controls. Although not all individuals with ASD learned to categorize novel faces in ways that differed from the norm, many did (Gastgeb et al., 2011). Importantly, differences in the formation of face categories were not attributable to differences in how long participants viewed faces, as measured through eye-tracking. Comparisons of face categorization by different age groups suggest that although individuals with ASD often do improve at categorizing faces as they develop, they may continue to perform atypically even as adults (Newell, Best, Gastgeb, Rump, & Strauss, 2010; Rump, Giovannelli, Minshew, & Strauss, 2009). Early delays in facial categorization abilities, in particular, may lead to atypical trajectories of social learning by individuals with ASD across the lifespan (Webb, Neuhaus, & Faja, 2017).

The ability to form face-related categories throughout development is vital in grounding many decision-making processes employed during social interactions. TD children gradually acquire a sophisticated perceptual "face space" that enables them to rapidly and effortlessly interpret a wide variety of social scenarios (Valentin, Cholet, Nestrud, & Abdi, 2016). Interpretation of faces and facial expressions clearly depends on categories related to age, gender, race, emotional state, species, and so on. However, few studies have linked differences in processing of facial cues to category learning mechanisms.

Facial expressions are not the only social stimuli that individuals with ASD categorize atypically. They also show differences in how they categorize speech (DePape, Hall, Tillmann, & Trainor, 2012; Haesen, Boets, & Wagemans, 2011; Stewart, Petrou, & Ota, 2018). Past studies of speech have focused more on how individuals process familiar speech than on how they learn speech-related categories, making it difficult to know whether the reported differences reflect atypical sensory processing, atypical auditory learning and plasticity, or both. As with face processing, not all individuals with ASD show noticeable differences in how they categorize speech sounds (Chiodo, Mottron, & Majerus, 2019), which has led some researchers to conclude that categorical processing of speech and similarly complex sounds is intact in individuals with ASD.

The complexity of naturalistic perceptual categories such as facial expressions or speech sounds makes it difficult to evaluate when they are being learned differently or how those differences might affect cognition and behavior. Studies of simpler perceptual categories provide a way to tease apart the specific factors that may lead individuals with ASD to learn categories in atypical ways and the potential consequences of atypical perceptual category learning.

Artificial Perceptual Categories

Studies of category learning typically have adults or children learn to classify static visual images of recognizable objects or visual patterns (see Table 1). Learning a new perceptual category involves judging similarities and differences between members of the categories, as well as learning to associate qualities of category members to specific sorting responses—category labels, spatial placement, identifying functional properties, and so on. Early studies of categorization in individuals with ASD focused more on performance with familiar objects than on acquisition (Tager-Flusberg, 1985a, 1985b; Ungerer & Sigman, 1987). These studies found that performance in simple sorting tasks was not impaired in individuals with ASD. Subsequent research in which individuals with ASD learned to sort images into two pre-designated categories challenged this conclusion (Klinger & Dawson, 1995, 2001), suggesting that formation of categories based on prototypical qualities of images was specifically impaired. Further experiments, however, countered the suggestion that ASD had any effect on category learning, by demonstrating that individuals with ASD were able to learn perceptual categories (Bott et al., 2006; Molesworth et al., 2005; Soulières et al., 2011; Soulières, Mottron, Saumier, & Larochelle, 2007). For example, Soulières and colleagues (2011) reported that perceptual category learning was not severely impaired in individuals with ASD, but simply progressed more slowly than in TD participants. Overall, these studies provided equivocal evidence regarding whether individuals with ASD learned categories differently.

Early debates about when and if category learning is affected by ASD were driven, in part, by preconceptions about the nature of the disorder and concerns about the adequacy of experimental methodologies. In particular, deficits in category learning or categorization abilities observed in individuals with ASD frequently were attributed to problems not specific to ASD (e.g., low verbal IQ). To increase experimental control of such potentially confounding factors, several researchers began using perceptual classification tasks that had been extensively vetted by cognitive psychologists studying categorization for half a century, such as Posner’s (1970) random dot pattern classification task (Church et al., 2010; Froehlich et al., 2012; Gastgeb et al., 2012; Kana et al., 2013; Schipul & Just, 2016; Vladusich, Olu-Lafe, Kim, Tager-Flusberg, & Grossberg, 2010). Efforts were also made to ensure that all participants were comparable in their general cognitive capacities and in their ability to follow instructions.

Unfortunately, neither use of simpler stimulus sets nor limiting participants to more cognitively homogenous samples has reduced the heterogeneity of category learning and generalization performance shown by individuals with ASD. Even within single studies, some children with ASD learned and generalized abstract shape categories in ways that were behaviorally indistinguishable from TD children, while other children with ASD showed large deficits when acquiring the exact same categories (Dovgopoly & Mercado, 2013; Mercado et al., 2015; Voorspoels, Rutten, Bartlema, Tuerlinckx, & Vanpaemel, 2018). Nevertheless, there is now clear experimental evidence that even HF individuals with ASD sometimes show profound deficits in their capacity to learn new categories that TD children have no problem learning and that do not depend on social competence or interpretation of social stimuli.

Limitations of Past Behavioral Studies

An underlying assumption of most past studies of category learning and categorization by individuals with ASD is that if the disorder affects a person’s ability to learn a certain type of category, then learning deficits should be readily apparent in between-group comparisons of performance on any categorization task of that type. A related assumption is that if categorization performance is similar between TD and ASD groups after training, then both groups have learned functionally equivalent categories in comparable ways during training. Both assumptions ignore the heterogenous performance profiles that are typical of individuals diagnosed with ASD, as well as the fact that nominally identical tasks can be learned in various ways that are not functionally equivalent (e.g., sorting objects based on their appearance versus their names). When only a subset of individuals with ASD show clear deficits in category acquisition, researchers often conclude that category learning and categorization are unaffected by ASD. However, the fact that some individuals with ASD can successfully sort some images and sounds does not imply that they are acquiring categories comparable to those formed by TD individuals. The assumption that if ASD affects category learning, then groups of individuals with ASD should show universal performance deficits in categorization tasks, has proven to be problematic given that most experimental studies based on this assumption have generated contradictory findings.

Furthermore, the types of category learning and generalization typically tested in laboratories are often not representative of the complex situations faced by children younger than five, in which categories must be spontaneously acquired over periods of years, with minimal explicit feedback regarding whether the latent categorical distinctions being learned by young children are adequate or aberrant. Because the categories learned by children, especially non-verbal categories, are hidden from view, it is exceedingly difficult to identify when category formation is following an atypical trajectory, much less to predict how atypical categories formed early on might affect the acquisition of later categories that ground complex cognitive, communicative, and social skills. Relatedly, it is difficult to identify what specific mechanisms are leading to category learning deficits. Current theoretical views about the factors that may disrupt or enhance category learning focus heavily on systematic biases in how individuals with ASD process incoming sensory signals. From this perspective, problems arise not from how children with ASD learn, but from how they encode the events that they learn about.

Theoretical Interpretations of ASD-Related Differences in Category Learning

Current views on category learning in ASD often point to abnormalities in sensory processing, perceptual organization, verbal ability, or executive control as the source of any difficulties in categorization (e.g., Boucher & Anns, 2018). These information-processing-based explanations all assume that when children with ASD categorize items differently, it is because they perceive information about those items differently. By analogy, a child who is colorblind might run into problems learning to separate green from red apples, but this learning deficit is because of differences in the inputs she is learning about, not because of anything atypical about how she learns categories. Similarly, atypical perceptual category learning in children with ASD might, in principle, arise from differences in how they sense, perceive, or interpret the world.

Dysfunctional Cognitive Control

Individuals with ASD can integrate information across modalities but are often impaired at multisensory integration of sensory signals during divided attention tasks, possibly due to narrow allocation of attentional resources (Magnee, de Gelder, van Engeland, & Kemner, 2011). Problems may also arise when integration of complex information is required (Minshew & Goldstein, 1998; Vivanti & Hamilton, 2014). Deficits of this sort are often attributed to ineffective cognitive control (Griffith, Pennington, Wehner, & Rogers, 1999; C. Hughes, Russell, & Robbins, 1994; Just et al., 2012; Yerys, Hepburn, Pennington, & Rogers, 2007), resulting from reduced involvement of frontal regions and/or reduced cortical connectivity (J. R. Hughes, 2007; Just et al., 2012). Deficits in cognitive control are not predictive of category learning deficits in adults with ASD (Soulières et al., 2011), however, weakening this interpretation.

Bayesian models of ASD similarly argue that “top-down” processing distorts how individuals with ASD integrate sensory information (Pellicano & Burr, 2012). For example, Pellicano and Burr (2012) proposed that individuals with ASD make less use of prior knowledge, so that they see things as they are rather than as how they expect them to be. Similarly, inflexibility in predictive processes (e.g., predictive coding) are said to disrupt perceptual inferences required to recognize objects and events (Sinha et al., 2014; van Boxtel & Lu, 2013; Van de Cruys et al., 2014), possibly by giving greater weight to sensations than to contextual cues and learned interpretations (Karvelis, Seitz, Lawrie, & Series, 2018; Lawson, Rees, & Friston, 2014; Palmer, Lawson, & Hohwy, 2017). Bayesian models would seem to predict that children with ASD should show advantages at learning new perceptual categories, especially when no feedback is available, and that learning abstract categories should be more difficult. In contrast, HF children with ASD who show no apparent deficits in academic coursework sometimes show profound deficits in learning to categorize novel, abstract shapes (Church et al., 2010; Church et al., 2015). Additionally, theories that suggest children with ASD rely less on learned Bayesian priors (top-down processing) than TD children provide no clear explanation for inter- or intra-individual heterogeneity in perceptual category learning by children with ASD.

Atypical Sensitivities to Subsets of Sensations

Hypersensitivity to specific sensory features is common in children with ASD, with greater sensitivity predicting more severe symptoms (Baranek, Boyd, Poe, David, & Watson, 2007; Bryant, Woynaroski, Wallace, & Cascio, 2019; J. Ward, 2019). Sensory hypersensitivity (and hyposensitivity) can lead to difficulties in shifting cognitive focus to maximize the analysis of sensory information, suggesting a potential “bottom-up” explanation for atypical category learning. In selective attention tasks with varying perceptual loads, hypersensitive individuals with ASD may require increased effort to disregard irrelevant distractors (Baruth, Casanova, Sears, & Sokhadze, 2010), or may display extreme focus to certain features due to sensory hypersensitivity (Bogdashina, 2016; Remington, Swettenham, Campbell, & Coleman, 2009). For example, although providing visual feedback in a pointing task leads to more accurate gestures toward a target in TD individuals, it may be an irrelevant distractor for ASD individuals who perform better when relying solely on proprioceptive information (Glazebrook, Gonzalez, Hansen, & Elliott, 2009). On the other hand, extreme attention to particular features may underlie enhanced detection and localization of vibrotactile stimuli seen in ASD individuals (Blakemore et al., 2006; O’Riordan & Passetti, 2006).

Monotropism, which relates to the limited distribution of attention during information processing by individuals with ASD (Goldstein, Johnson, & Minshew, 2001), may be driven in part by atypical sensory processing, including hypersensitivities. Evidence for inflexible attention to certain sensory stimuli can also be seen when children with ASD only respond to a single component of a stimulus, described as stimulus overselectivity (Lovaas & Schreibman, 1971; Lovaas, Schreibman, Koegel, & Rehm, 1971). Restriction of attentional resources to specific sensory domains is also thought to contribute to restricted domains of interests (Greenaway & Plaisted, 2005), inflexibility in interest levels (Murray, Lesser, &

Lawson, 2005), and atypical motor control (Glazebrook, Elliott, & Lyons, 2006; Gowen & Hamilton, 2013; Hayes et al., 2018; Nazarali, Glazebrook, & Elliott, 2009).

Neurocomputational models of atypical processing in sensory cortices (e.g., Gustafsson, 1997; Gustafsson & Paplinski, 2004; Noriega, 2007) further suggest that atypical sensory inputs might affect category learning. In particular, divisive normalization—modulation of the activity of individual neurons by the activity of surrounding populations of neurons—may be affected by imbalances in the excitatory versus inhibitory (E/I) interactions within cortical networks (Rosenberg et al., 2015). This interpretation is consistent with earlier proposals that atypical cortical connectivity contributes to ASD (Belmonte et al., 2004; Davis & Plaisted-Grant, 2015; Minshew & Williams, 2007), but provides more precise predictions about how differences in low-level processing should affect perceptual sorting in ASD (Van de Cruys, Vanmarcke, Steyaert, & Wagemans, 2018). As with other models of ASD, evidence for divisive normalization-related effects on perceptual processing is mixed (Palmer, Lawson, Clifford, & Rees, 2019; Van de Cruys et al., 2018). Simulations suggest that E/I imbalances can affect perceptual category learning (Dovgopoly & Mercado, 2013), but not in the ways that have been observed experimentally. Genetic predispositions for ASD are associated with synaptic mechanisms that can affect both neural interactions and plasticity (Mottron et al., 2014; Mullins et al., 2016), and there is evidence of atypical plasticity in visual cortex during category learning (Schipul & Just, 2016; Schipul, Williams, Keller, Minshew, & Just, 2012). Whether such differences influence either the development of perceptual processing or the learning of new perceptual categories is unknown.

Highly selective responsiveness to (or suppression of) sensory stimulation can clearly influence what children with ASD learn, including the kinds of categories that they form (Mottron et al., 2013; Mottron & Burack, 2006; Soulières et al., 2007). Undoubtedly, selective sensory learning happens in children with ASD and could explain why they might learn more rapidly (or slowly) than TD children, as is seen in classical conditioning (Sears et al., 1994), and habituation studies (Guiraud et al., 2011). However, atypical sensitivities to sensory patterns seem unlikely to lead to the heterogeneous category learning capacities or domain-specific strengths associated with ASD (Mottron, 2019). Additionally, it is unclear why atypical sensory sensitivities would adversely affect learning categories of shapes or random dot patterns, especially when atypical learning is only observed for subsets of these patterns (Mercado et al., 2015; Vladusich et al., 2010). To explain such phenomena, some researchers have proposed that individuals with ASD organize percepts in ways that deviate from the norm (Bogdashina, 2016; Grossberg & Seidman, 2006; Markram & Markram, 2010; Mottron et al., 2014).

Biased Local versus Global Perceptual Organization

Atypical perceptual processing accounts of ASD propose that the cognitive difficulties faced by individuals with ASD relate more to how sensations are organized into a meaningful whole than to dysfunctional bottom-up or top-down processing (Fletcher-Watson & Happé, 2019; Newell et al., 2010). For instance, weak central coherence theory attributes atypical performance to a reduced capacity for globally combining details of stimuli (Booth & Happe, 2018; D’Souza, Booth, Connolly, Happe, & Karmiloff-Smith, 2016; Happe & Frith, 2006; Shah & Frith, 1993; Van der Hallen, Evers, Brewaeys, Van den Noortgate, & Wagemans, 2015). Relatedly, Mottron and colleague's (Mottron, Dawson, Soulieres, Hubert, & Burack, 2006) enhanced perceptual function model suggests that local processing of sensory inputs dominates perceptual organization in individuals with ASD. In the visual domain, enhanced processing of local details may facilitate visual discrimination (O'Riordan & Plaisted, 2001; Plaisted et al., 1998), visual search (Shirama, Kato, & Kashino, 2017), and mental image mapping (Mottron, Dawson, & Soulieres, 2009; Soulieres, Zeffiro, Girard, & Mottron, 2011). Enhanced processing of details has also been linked to a preference in ASD individuals for using proprioceptive feedback during sensorimotor learning and adaptation instead of visual feedback (Guerra, Spoto, Parma, Straulino, & Castiello, 2017; Haswell, Izawa, Dowell, Mostofsky, & Shadmehr, 2009; Hayes et al., 2018; Izawa et al., 2012). Enhanced discrimination between sensory events may in turn decrease generalization of learning to similar stimuli (Riley, 1968; Soulières et al., 2011), which could, in principle, reduce an individual's ability to acquire categories that are defined by common features (Plaisted, 2001). In other words, selective attention to unique details of perceptual experiences might affect how percepts are organized and how categories are learned. Behavioral evidence for decreased dependence on global processing of percepts remains mixed, however (Evers et al., 2018), and questions persist about what types of perceptual processing qualify as either local or global (Ahissar & Hochstein, 1997; D'Souza et al., 2016; Evers et al., 2018).

Neurocognitive theories link apparent imbalances between local and global processing in individuals with ASD to atypical interactions between cortical regions (Just et al., 2012; Mottron et al., 2013; Mottron et al., 2009; Schipul & Just, 2016). For instance, work examining aberrant scalp topography in response to emotional facial stimuli found that individuals with ASD processed information more slowly, suggesting a failure of cortical specialization or atypical cortical area recruitment (Wong, Fung, Chua, & McAlonan, 2008). Several lines of evidence confirm that cortical processing in individuals with ASD is atypical in ways that could lead to imbalances between local and global processing (Poulin-Lord et al., 2014). In addition, studies of the neural correlates of category learning suggest that multiple brain regions change in parallel as learning progresses (Bao, 2015; Bathellier, Ushakova, & Rumpel, 2012; Deneux, Kempf, Daret, Ponsot, & Bathellier, 2016; Gluck, Poldrack, & Keri, 2008; Keri, 2003; Miller, Freedman, & Wallis, 2002; Ohl, 2015; Ohl, Scheich, & Freeman, 2001; Sigala & Logothetis, 2002), including regions that show atypical activation and organization in individuals with ASD.

A recently proposed alternative explanation for atypical perceptual category learning by children with ASD is that rather than being systematically biased to focus on details, children with ASD may diverge from TD children and from each other in terms of the perceptual representations that they extract from sensory patterns. According to the idiosyncratic perceptual transformation hypothesis (Mercado & Church, 2016), children with ASD may learn categories differently because they process sensory patterns in ways that are more strongly shaped by their unique, experience-dependent developmental histories (see also Mottron et al., 2014). In essence, the hypothesis is that children with ASD integrate sensory inputs in idiosyncratic ways (e.g., focusing on a subset of features that most people would not notice) that can interfere with their ability to form typical perceptual categories.

Atypically formed categories may contribute to the domain-specific strengths and weaknesses associated with ASD and could also be partly driven by them. This hypothesis not only accounts for the mixed findings from past studies of category learning by individuals with ASD, but also can account for intra-individual variations in visual category learning across tasks and stimuli (Mercado & Church, 2016; Mercado et al., 2015). Recent findings of idiosyncratic perceptual processing (Bolton et al., 2018; Lin, Shirama, Kato, & Kashino, 2017), cortical connections (Hahamy, Behrmann, & Malach, 2015; Nunes, Peatfield, Vakorin, & Doesburg, 2019), and cortical activity associated with interpreting social scenes (Bolton et al., 2018; Byrge, Dubois, Tyszka, Adolphs, & Kennedy, 2015), in individuals with ASD are consistent with, and were predicted by, the idiosyncratic perceptual transformation hypothesis.

Most theories of atypical perception in ASD, both behavioral and neurocomputational, predict that children with ASD should have no problems learning perceptual categories Predictive coding models (e.g., Van de Cruys et al., 2014) can potentially explain why some children with ASD might experience problems forming perceptual categories, because these models specifically assume that learning mechanisms can be disrupted by inadequate weighting of past experiences in processing new inputs. However, predictive coding models neither predict which category learning tasks will be problematic, nor explain why abstract category learning seems to be less affected or why children with ASD would develop divergent codes. Theories that link alterations in experience-dependent plasticity to atypical cognitive development and perceptual expertise (e.g., Mottron et al., 2014) are perhaps best suited to capturing the complex ways in which idiosyncratic learning trajectories might lead to the diverse symptoms associated with ASD.

Possible Consequences of Atypical Perceptual Category Learning on Children’s Lives

One major challenge for researchers attempting to understand ASD has been to identify mechanisms that can potentially explain the constellation of symptoms associated with this disorder. Several theorists have attempted to construct a unified, mechanistic account of associated deficits with varying success (Grossberg & Seidman, 2006; Happe, Ronald, & Plomin, 2006; Just et al., 2012; Mullins et al., 2016; Van de Cruys et al., 2014). Other researchers describe the heterogenous collection of strengths and limitations associated with ASD as resulting from multiple parallel factors; for example, a “fractionable triad” of components that can lead to repetitive and restricted behaviors and interests, social interaction deficits, and communication problems (Fletcher-Watson & Happé, 2019; Happe et al., 2006). Most past models assume that category learning is essentially unaffected in individuals with ASD, and thus do not directly address possible effects of atypical category learning or categorization on symptoms. This consensus view might seem to suggest that atypical category learning is an unlikely candidate mechanism for explaining any of the symptoms associated with ASD. However, because perceptual categorization provides the foundation for many other cognitive processes, atypical categories can significantly affect *all* processing, not just of shapes and faces, but also of social situations and other complex events.

All of the major symptoms that are diagnostic of ASD can potentially be related to atypical perceptual category learning contributing to divergent developmental trajectories. If it is further assumed that the formation of perceptual categories in children with ASD is highly dependent on initial conditions and specific sequences of experiences unique to each child (as proposed by the idiosyncratic perceptual transformation hypothesis), then atypical category learning mechanisms can also account for the heterogeneity of symptoms and severity observed across the autism spectrum, for large intra-individual variations in category learning capacities (Mercado & Church, 2016), for the prevalence of mixed results across studies of cognitive processing by individuals with ASD, and for the domain specific strengths and weaknesses associated with ASD.

Restricted Interests

Consider, for instance, the narrowing of attention in early development of children with ASD that is associated with monotropism (Murray et al., 2005), the tendency to "hyper-systematize" (Baron-Cohen, 2008), and restricted interests in specific domains. These tendencies are often attributed to hyper-attention to a subset of objects, topics, or activities, and with an obsessive allocation of time directed towards the favored domain. This kind of selective attention arises from learning processes. By definition, restricted interests involve an atypical preoccupation with a subset of stimuli or events that TD individuals collectively view as undeserving of the time and interest that children with ASD give them. In other words, a person with restricted interests learns to classify certain items or events in ways that diverge from the norm. Individuals with restricted interests have learned to categorize (and value) a subset of objects or events differently from most humans. Similarly, spatially arranging and sorting objects by size, color, or smell beyond a typical developmental stage can be viewed as instances of atypical categorization or category-related construction. It is not restricted interests themselves that are symptomatic of ASD, because most developing children show preferences for a subset of activities and objects (Harrop et al., 2018; Harrop et al., 2014). Rather, it is the more pervasive and persistent role that those categories play in directing a child's activities that raise caretakers' concerns, particularly when fixations on activities or objects interfere with social interactions or lead to emotional dysregulation (Honey, Leekam, Turner, & McConachie, 2007). Children with ASD who have been able to successfully turn their focused interests into careers provide support for the possibility that atypical category learning abilities can also potentially lead to positive outcomes.

Social Interactions

The relationship between restricted interests and social interactions is unclear. In principle, a child with ASD might show signs of being fixated on socially interacting with particular individuals, classes of individuals (e.g., babies or pets), or social activities (e.g., playing a particular game); such symptoms would presumably provoke less concern than social avoidance or less culturally appropriate social interactions. Most social interactions depend on dynamic classification of social cues, communicative signals, social contexts, socio-cultural norms, facial and vocal expressions of emotions, and identification of intentions and goals, thus requiring sophisticated multisensory categorization abilities. Failure to learn to correctly classify such sequences can potentially lead to frustration or anxiety when attempts to engage with others result in unexpected or unfavorable consequences.

Classifying the actions of others relies in part, on generating an accurate internal model of an agent's intent and consequences. In fact, motor learning studies have found correlations between impaired social communication and impaired imitation and performance of gestures (Izawa et al., 2012). One possible explanation for such correlations is that generating accurate internal action models, typically associated with initiating movements, is also necessary for generating appropriate responses in social situations. Without the ability to construct such models, one may also fail to recognize the social outcomes of an action for oneself and others (Rizzolatti, Fogassi, & Gallese, 2001). Thus, learning to recognize and classify socially-relevant information is crucial for navigating novel and dynamic social situations and for learning social skills. Categorization of environmental contexts, actions, emotions, people, and social situations all play a key role in perspective taking and successful selection of social scripts, such that deficits in the categorical processing of such stimuli may profoundly disrupt social interactions.

Repetitive Actions

Repetitive, stereotyped actions are another prominent diagnostic symptom of ASD that may arise from atypical category learning in less obvious ways. Unlike restricted interests, stereotyped movements intuitively seem to indicate lack of inhibitory motor control or perhaps some mode of self-stimulation. Another possibility, however, is that repetitive movements serve to maintain cross-modally coordinated proprioceptive, tactile, and visual inputs that may ground multisensory categories used to separate the self from the environment and others (Brincker & Torres, 2013; Van de Cruys et al., 2014). For instance, hand flapping generates both kinesthetic and visual sensorimotor feedback that is salient and resistant to external sensory interference (Ornitz, 1974). If children with ASD have difficulties learning to categorize the perceptual cues that TD children commonly use to establish self-representations and to generalize from past experiences (e.g., how it feels to move one's arms while wearing different coats), then repetitive movements may facilitate self-discrimination and the development of a reliably identifiable self-representation (i.e., a perceptual category of familiar visuo-kinesthetic sensations that a child learns to label as "me"; James, 1890).

Communication

All children with ASD show some impairment in social communication such as failure to make eye contact, respond to questions, or maintain conversations in social situations. Evidence consistent with atypical communicative classification by individuals with ASD comes from studies of the McGurk effect—an illusion caused when video of speech production mismatches a playback of speech (Bebko, Schroeder, & Weiss, 2014), and conversational speech (Eigsti, Bennetto, & Dadlani, 2007). Language learning is fundamentally dependent on linking multimodal categories of speech sounds to perceptual categories of experienced events as well as to semantic categories, abstract concepts, and so on. Impairments in grammar, syntax, prosody, and pragmatics have been attributed to delays in language learning (Eigsti et al., 2007; Rapin & Dunn, 2003; Rapin, Dunn, Allen, Stevens, & Fein, 2009). Interest in how language mediates social communication has distracted researchers and clinicians from considering more basic mechanisms. For example, the association of ASD with children's use of idiosyncratic meanings for words can be viewed as a byproduct of anomalous category formation from enhanced sensitivities to subtle differences in similar items in conjunction with impaired generalization (Boucher & Anns, 2018; Pellicano & Burr, 2012; Plaisted et al., 1998). Effectively, children with ASD may be constructing definitions that diverge from typical meanings in ways that are not always apparent.

Cognitive Processing

Atypical cognitive processes have figured prominently in theoretical explanations of ASD, despite the fact that cognitive deficits are not considered to be diagnostic (Fletcher-Watson & Happé, 2019; J. E. A. Hughes et al., 2018; J. H. Williams, Whiten, & Singh, 2004). These explanations include both domain-general cognitive processes (like executive functions, C. Hughes et al., 1994; Pennington & Ozonoff, 1996), and more specialized abilities (like theory of mind, Baron-Cohen, 2001) that may contribute to observable symptoms. Acquired cognitive and perceptual skills have received less attention, despite showing signs that they may be particularly affected by atypical learning mechanisms (Mottron et al., 2014; Mottron et al., 2009). Perceptual category learning, in particular, both drives and constrains the development of most other cognitive abilities, including language and socio-communicative skills (Baum, Stevenson, & Wallace, 2015). As such, any deviations in the process of category learning could potentially have far reaching effects. The following sections briefly discuss how atypical category learning could potentially contribute to savant abilities, multisensory integration, and atypical observational learning in children with ASD.

Savantism.—Atypically advanced skills in specialized domains such as language, mathematics, or music (often referred to as savantism) appear to be more prevalent within the ASD population compared to the general population of children with intellectual impairments (Meilleur, Jelenic, & Mottron, 2015; Treffert, 2009). It remains unclear whether savantism is an effect of pre-existing differences in neural connections that affect information processing or a consequence of atypical learning mechanisms that drive divergent trajectories in experience-dependent changes in cortical connections during early development (Heaton & Wallace, 2004; LeBlanc & Fabiolini, 2011). Some have described savantism as an instance of hyper-learning (M. Dawson et al., 2008; O'Connor, 1989), associated with hyperplasticity that leads to differences in how the brains of children with ASD are wired (Mottron et al., 2014; Mottron et al., 2013), and ultimately causing them to process information in atypical ways (J. E. A. Hughes, Simner, Baron-Cohen, Treffert, & Ward, 2017).

Restricted interests have been noted as a possible contributing factor in savantism (Baron-Cohen, Ashwin, Ashwin, Tavassoli, & Chakrabarti, 2009). In fact, most of the cognitive skills associated with savantism (and systematizing) involve learning to recognize and label abstract similarities across patterns (Bouvet et al., 2014; Mottron et al., 2014; Mottron et al., 2013), a canonical instance of category learning and generalization. For example, some children with ASD show hyperlexia, or accelerated and precocious reading and comprehension of words, despite what initially appears to be delayed language learning (Mottron et al., 2013; Silverberg & Silverberg, 1967). Neurological evidence that points to greater visual perceptual processing of word forms relative to semantic processing may account for the ability of hyperlexics to fluently read words that they do not understand (Ostrolenk, Forgeot d'Arc, Jelenic, Samson, & Mottron, 2017). This phenomenon suggests that language acquisition by some children with ASD might utilize different processes and operate on a different timescale compared to what occurs in TD children (M. Dawson et al., 2008). As noted above, children with restricted interests learn to classify a subset of objects or events differently. Extended atypical categorization of language-relevant percepts (e.g., evoked by printed text) is highly likely to lead to divergent learning trajectories, even when learning mechanisms are fully intact. The presence of potentially interfering processes (i.e., altered neural noise or abnormal synaptic plasticity processes) may further amplify learning-related differences in the acquisition of domain-specific perceptual and cognitive skills associated with savantism.

Multisensory Integration.—The possibility that savantism is a phenomenon that arises from altered learning processes is suggested by correlations with synesthesia and altered multisensory integration (Baron-Cohen et al., 2013; J. E. A. Hughes et al., 2017). For example, fixation on mapping sounds to pitch names may enhance the detectability of reoccurring patterns and relationships between pitches, which may in turn manifest as a savant-like ability to immediately and accurately transpose melodies or improvise compositions (Boso et al., 2013). A case study of FC, an ASD savant, revealed that synesthetic abilities such as associating pitches to days of the week, or specific months and numbers to personalities, likely arose from a combination of certain associations with past experiences and cross-modal idiosyncratic associations (Bouvet et al., 2014). Idiosyncratic but stable associations are what qualify a percept as synesthetic. For ASD savants, synesthetic percepts may provide a personalized and reliable method for organizing perceptual information that facilitates advanced mnemonic and computational abilities (Bor, Billington, & Baron-Cohen, 2007; Bouvet et al., 2014; Rothen, Meier, & Ward, 2012).

Developmentally, multisensory integration arises from extensive interaction with environmental cues in order to establish cross-modal connections (Wallace, Woynaroski, & Stevenson, 2019). Children with ASD show delayed audiovisual integration in exhibiting the McGurk effect relative to TD children (Bebko et al., 2014; Beker, Foxe, & Molholm, 2018; de Gelder, Vroomen, & Van der Heide, 1991), and delayed integration of visual, tactile, and proprioceptive cues (Cascio, Foss-Feig, Burnette, Heacock, & Cosby, 2012). In planning movement, integrating different sensory information about a target stimulus into a coherent whole can be more challenging for individuals with ASD (Glazebrook et al., 2009; C. Hughes, 1996; Mari, Castiello, Marks, Marraffa, & Prior, 2003), despite heightened stimulus responses as a result of hypersensitivity (Gowen & Hamilton, 2013). Fundamental to multisensory integration is the ability to discern which sensory patterns should be integrated or given greater weight relative to others. Failure to selectively organize and integrate multisensory cues can result in impairments in executing skilled motor movements (dyspraxia), a condition often observed in individuals with ASD (Gowen & Hamilton, 2013).

Proposed mechanisms underlying atypical multisensory integration include impaired neuro-oscillatory functions, long-range underconnectivity in the brain, and overconnectivity within local brain regions (Bebko et al., 2014; Koolschijn, Caan, Teeuw, Olabarriaga, & Geurts, 2017; LeBlanc & Fabiolini, 2011), all of which could be a consequence of atypical mechanisms of experience-dependent cortical plasticity (Mottron et al., 2014). Atypical learning mechanisms can affect not only how children with ASD learn about complex, multimodal events (including speech), but also more fundamental cognitive developmental processes that determine how they represent the world, themselves, and others (M. Dawson et al., 2008; Klinger & Dawson, 1995).

Observational Learning.—Much of what children learn early in development comes from their observations of others' actions. Both Kanner (1943) and Asperger (1991) noted atypical observational learning in children with ASD, a symptom that is now often attributed to imitative deficits (Gallese, Rochat, & Berchio, 2013; Rogers, 1999; Taylor & DeQuinzio, 2012; Vivanti & Hamilton, 2014; J. H. Williams et al., 2004). Children with ASD retain the ability to imitate (Foti et al., 2014; Foti et al., 2018; Nadel et al., 2011), and in some cases are more prone to imitating than other children. For instance, ASD is often associated with persistent echolalia and echopraxia, in which heard speech or observed actions are automatically repeated (Gernsbacher, Morson, & Grace, 2016; van Santen, Sproat, & Hill, 2013; Wolfe, Pound, McCammon, Chezan, & Drasgow, 2019). Voluntary imitation of non-meaningful gestures and sequences of complex actions appears to be more difficult for individuals with ASD (Vivanti & Hamilton, 2014), although capacities are highly heterogeneous across individuals.

The idiosyncratic observational learning capacities seen in individuals with ASD may be related to atypical multisensory integration and category formation. Researchers studying abnormalities in sensorimotor learning associated with ASD suggest that atypical visual-motor integration (Heyes, 2011; Mostofsky & Ewen, 2011), or perceptual organization of kinesthetic patterns (Chen et al., 2018; Lloyd, MacDonald, & Lord, 2013), could contribute to differences in motor planning and learning about the body, which may in turn interfere with the development of perception-action representations (Gowen & Hamilton, 2013; Zalla, Labruyere, & Georgieff, 2006). Piaget (1952) proposed that internal action models provide the foundation for later cognitive faculties. If infants and toddlers respond to sensorimotor patterns in idiosyncratic ways, then the unique qualities of their experiences may lead them to develop divergent representations that could influence how they perceive and categorize actions (Bertenthal, 1996; Cook, Blakemore, & Press, 2013; Donnellan, Hill, & Leary, 2012; Gowen & Hamilton, 2013; N. Hogan & Sternad, 2012; Lockman, 2000; Marko et al., 2015; McAuliffe et al., 2019; Sinha et al., 2014). The earliest categories constructed by infants likely relate to the look and feel of self-produced movements. Poorer infant motor skills at six months predict ASD status and expressive language abilities at three years (LeBarton & Landa, 2019), and jerkiness of movement predicts atypical perception of biological motion (Cook et al., 2013), consistent with the possibility that early differences in learning and plasticity processes could potentially have broad cascading effects (Brian, Bryson, & Zwaigenbaum, 2015; Mottron et al., 2014).

Conclusions and Directions for Future Research

Despite increasing evidence from genetic and neuroscience research that neural plasticity mechanisms may function differently in individuals with ASD (Mottron et al., 2014; Mullins et al., 2016), few theoretical approaches to understanding ASD have considered the possibility that basic learning mechanisms may contribute to the major symptoms of the disorder. Mismatches between the ways in which children learn to organize perceived events relative to their peers and adults can accumulate over time, leading to a diverse set of difficulties in communication, social interactions, academic performance, and behavioral flexibility. Atypically formed categories can affect not only developmental trajectories, but also the efficacy of interventions in which children attempt to learn novel ways of overcoming behavioral, cognitive, and emotional difficulties.

Past studies of perceptual processing in individuals with ASD have emphasized group comparisons of performance to identify processes that are intact, superior, or dysfunctional. This approach has led to more debates and confusion than to a consensus about how children with ASD perceive themselves and the world (Booth & Happe, 2018; Fletcher-Watson & Happé, 2019). Recent emphases on neurodiversity and the complexity of the ASD phenotype are beginning to encourage researchers to abandon this simplistic approach to identifying underlying mechanisms. Although it may not be possible to identify “the difference that makes a difference” in the cognitive or neural capacities of people with ASD by comparing group-level variations in the brains or behaviors of participants with and without ASD, understanding when and how cognitive difficulties develop is critical to treating and accommodating children with this disorder. Identifying how perceptual representations and categories emerge, diverge, and converge in individual children with and without ASD during development is an important step toward understanding how atypical category learning may affect the lives of people with ASD.

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Figure 1.

An allegorical caricature of how ongoing perceptual experiences can be warped by tuning introduced by past experiences (adapted from Goldstone, 2010; illustrated by Joe Lee)

Table 1.

Experiments on category learning by individuals with ASD. Studies that only included individuals with high functioning (HF) ASD as participants are indicated as such under the "Subjects" heading.

Study	Subjects	Ages	Stimuli	Training Procedure	Results
Klinger & Dawson (2001)	ASD (12) TD (12) Down's (12)	5–21	black and white drawings of imaginary animals	4 trials where 8 category members and 8 non-category members were shown with feedback	ASD and Down's had difficulty with prototype formation
Molesworth, Bowler, & Hampton (2005)	ASD (15) TD (15)	8–14	black and white drawings of imaginary animals	5 s to look at a card, followed by a practice session with corrections. Sort cards into 'insects' and 'monsters'	No impaired or absent prototype recognition memory effect in ASD
Gastgeb, Strauss, & Minshew (2006)	HFASD (28) TD (24) HFASD (28) TD (27)	9–48	color pictures of cats, dogs, couches, and chairs; recordings of spoken category labels	an initial instructional example with no feedback followed by 4 practice trials using birds and tables	HFASD were significantly slower at recognizing atypical category members
Bott, Brock, Borckdorff, Boucher, & Lamberts (2006)	HFASD (12) D (17)	19–62	black rectangles of varying dimensions	250–1000 trials with feedback; completion criterion of 40 consecutive correct trials	HFASD found category structure more difficult to learn
Molesworth, Bowler, & Hampton (2008)	HFASD (18) TD (18)	9–15	black and white drawings of imaginary animals	study 16 cards for 3 min, no feedback; show cards one at a time, sort into 2 categories, with error correction	HFASD had varying categorization performances with theprototype
Gastgeb, Rump, Best, Minshew, & Strauss (2009)	ASD (51) TD (49)	8–53	black and white drawings of faces with varying attributes	familiarized to 14 faces shown individually for 2 s each	ASD chose mean prototype less often
Church *et al.* (2010)	HFASD (20) TD (20)	7–12	random dot pattern shapes with varying levels of distortion	30 trials with feedback	HFASD less likely to recognize prototype at test; IQ not predictive of performance.
Vladusich, OLu-Lafe, Kim, Tager-Flusberg, & Grossberg (2010)	ASD (19) TD (21) ASD (13) TD (18)	15–28	random dot patterns with varying levels of distortion	exposure to 32 training exemplars; practice with eight items; 32–320 trials with feedback; completion criterion of 75% correct trials	ASD required more training and showed less transfer, showed a prototype effect; nonverbal IQ predicted prototype learning
Brown, Azcel, Jimenez, Kaufman, & Grant (2010)	ASD (31) TD (31)	8–14	color photos of Mr. Potato Head toy in varying configurations	214 trials of probabilistic classification learning, with feedback	ASD and TD showed comparable performance
Soulieres, Mottron, Giguère, & Larochelle (2011)	HFASD (16) TD (16)	11–29	color images of imaginary animals	40 trials with feedback, then 16 trials without feedback, followed by 120 trials with feedback	ASD required more training; generalized to novel stimuli
Gastgeb, Wilkinson, Minshew, & Strauss (2011)	HFASD (20) TD (20)	17–42	color photos of morphed faces	exposed to 16 faces, then shown two faces, one being the prototype	HFASD unable to pick the prototype with odds greater than chance; no difference in looking time compared to TD
Froehlich *et al.* (2012)	HFASD (24) TD (25)	18–36	random dot patterns, with varying levels of distortion; photographs of dogs, people, flowers	exposed to 9 photos from 3 categories linked to letters; label familiar and novel photos; then exposed to sets of dot patterns with and without letter labels for 135 trials	HFASD showed intact prototype formation; categorized more highly distorted dot patterns less accurately

Study	Subjects	Ages	Stimuli	Training Procedure	Results
Gastgeb, Dundas, Minshew, & Strauss (2012)	HFASD (20) TD (19)	17–42	random dot patterns with varying levels of distortion	familiarized to 40 high distortion dot patterns.	HFASD showed reduced prototype formation, “fuzzy category boundaries”
Meyer (2014)	HFASD (18) TD (16)	8–14	black and white drawings of imaginary animals	8 familiarization trials where 8 category members were shown and labeled	HFASD showed a prototype effect; verbal ability correlated with prototype learning.
Church *et al.* (2015)	HFASD (43)	7–12	random dot pattern shapes with varying levels of distortion	30 trials with feedback	HFASD showed two generalization patterns: intact and degraded; deficits reduced by training with prototype.
Mercado *et al.* (2015)	HFASD (56), TD (13)	7–13	random dot pattern shapes with varying levels of distortion	30 trials with feedback in 3 tasks and 60 trials with feedback in 1 task; or 30 trials with feedback.	HFASD showed two generalization patterns: intact and degraded, with high intra-individual variability
Schipul & Just (2016)	HFASD (16), TD (16)	16–42	random dot patterns with varying levels of distortion	alternated blocks of familiarization and training trials with feedback; completion criterion of 70% correct	HFASD showed slower learning, atypical cortical changes
Ellawadi, Fein, & Naigles (2017)	ASD (16) TD (22)	5–7	color photos of birds, cats, cars, and chairs	72 trials without feedback	ASD showed less stability across trials; nonverbal IQ predicted category structure
Snape, Krott, & McCleery (2018)	ASD (15) TD (15) ASD (15) TD (15)	3–6	cartoon style color images of everyday objects	20 exposures to 3 cards, labeled by a bear puppet	ASD showed similar performance overall, with some differences in category formation
Hetzroni, Hessler, & Shalahevich (2019)	ASD (24) IDD (24) TD (24)	5–16	cartoon style color images of everyday objects in pairs	26 trials of a matching-to-sample task (relational or perceptual)	ASD showed bias toward selecting perceptual matches