Visual Perception in Autism Spectrum Disorder: A Bayesian and Predictive Coding Perspective

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Abstract

Bayesian and predictive coding theories provide controversial explanations for sensory processing abnormalities in individuals with autism spectrum disorder (ASD). By focusing on non-social visual information, theoretical nuances can be outlined and empirical evidence summarized across three levels: Bayesian inference, predictive coding process, and predictive coding precision. Hypotheses based on Bayesian inference, such as weak priors and precise likelihood, offer only descriptive-level accounts for visual processing abnormalities in ASD. Hypotheses or perspectives focusing on the predictive coding process further refine the characterization of visual processing specificity in ASD, yet still lack explanatory power. Hypotheses centered on predictive coding precision provide theoretical explanations, but require further refinement of theoretical details and more fine-grained empirical research for validation. Future research should adopt a refine-then-integrate approach to characterize the specificity of predictive processing in ASD, test theoretical content from the subjective experience perspective of individuals with ASD, and examine developmental changes in predictive function across the lifespan of individuals with ASD.

Full Text

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Abstract: Bayesian and predictive coding theories have provided controversial explanations for sensory processing abnormalities in individuals with autism spectrum disorder (ASD). By focusing on non-social visual information, this paper outlines theoretical differences and summarizes empirical evidence across three levels: Bayesian inference, predictive coding processes, and predictive coding precision. The weak priors and sharper likelihood hypotheses derived from Bayesian reasoning offer only descriptive accounts of visual processing anomalies in ASD. Hypotheses focusing on predictive coding processes further refine the specificity of visual processing characteristics in ASD but remain functionally incomplete. Hypotheses centered on predictive coding precision provide theoretical explanations but require further refinement of theoretical details and more sophisticated empirical research for validation. Future research should adopt a path of first refining and then integrating to characterize the specificity of predictive processing in ASD, test theoretical content from the subjective experience perspective of individuals with ASD, and examine developmental changes in predictive functioning across the lifespan.

Keywords: autism spectrum disorder, visual perception, non-social information, Bayesian, predictive coding

Autism spectrum disorder (ASD) is a heterogeneous neurodevelopmental condition of unknown etiology that affects sensory processing (Robertson & Baron-Cohen, 2017), motor behavior (Zampella et al., 2021), and social functioning (黄钰杰等, 2023). While social alteration theories posit that social deficits constitute the core impairment in ASD, the "sensory-first" account proposes that abnormal sensory processing represents a critical factor in ASD development (Falck-Ytter & Bussu, 2023). These abnormalities emerge during infancy (Chen et al., 2022; Piccardi et al., 2021; Falck-Ytter et al., 2018), even before behavioral symptoms become apparent. Such theories, perspectives, and empirical findings challenge social-centric models of ASD, suggesting that differences manifest across broader sensory processing domains rather than being confined to social realms. Since nearly all empirical brain development depends fundamentally on sensory perception, researchers have proposed that sensory processing abnormalities lead young children with ASD to avoid unpredictable social environments, thereby preventing them from learning social interaction and verbal communication skills (Falck-Ytter & Bussu, 2023).

Focusing on sensory processing abnormalities, researchers have attempted to develop theories explaining atypical sensory experiences in ASD. Bayesian theory posits that the brain does not passively represent sensory information but rather infers its meaning through hierarchical generative models (Clark, 2013). Perception thus arises from the constructive integration of prior information and sensory input. Building on this framework, Pellicano and Burr (2012) first proposed that individuals with ASD cannot use prior information to predict incoming sensory signals, causing them to perceive a more "veridical" sensory world. Following this hypothesis, numerous theories rapidly emerged to explain atypical sensory processing in ASD from a Bayesian perspective (Brock, 2012; Lawson et al., 2014; Palmer et al., 2017; Sinha et al., 2014; Van de Cruys et al., 2014), though these theories differ in their explanatory details.

Understanding the mechanisms underlying sensory processing abnormalities in ASD could positively impact early screening, diagnosis, and targeted intervention strategies (柴浩等, 2022). Therefore, integrating theoretical explanations of atypical sensory processing in ASD is essential. Some researchers have attempted to overlook theoretical differences and synthesize empirical evidence at a broader level of abstraction. Specifically, they consider only whether individuals with ASD differ from typically developing (TD) individuals in their use of priors for perception, without specifying the nature of these differences, labeling this approach the "imbalance hypothesis" (Chrysaitis & Seriès, 2023). Unfortunately, this theoretical compromise has not yielded clear conclusions. Despite extensive research using diverse methodologies, results supporting and refuting the imbalance hypothesis are roughly equal in number and often contradictory. Based on this situation, Chrysaitis and Seriès (2023) argue that unifying the vast body of empirical evidence into a coherent theoretical framework is nearly impossible.

Consequently, we propose an alternative approach that distinguishes theoretical details and delimits types of empirical evidence, contrary to Chrysaitis and Seriès (2023). This can be achieved through three specific strategies. First, clarifying theoretical differences to identify contradictions or integrative possibilities, then combining empirical evidence to test theoretical details. Second, focusing on the visual modality to reduce confounding variables. Empirical studies examining ASD perception from a Bayesian perspective span different sensory channels, yet predictive coding processes across modalities cannot be explained by a single cognitive mechanism (Schubert et al., 2023). Restricting focus to the visual channel reduces potential sources of confusion and variability. Moreover, neuroimaging studies of infants and elderly individuals with ASD have identified the visual cortex as a potential hotspot for persistent alterations throughout development (Martínez et al., 2020; Gandal et al., 2022; Jassim et al., 2021; Girault et al., 2022). Third, focusing exclusively on non-social visual information. Social visual information refers to stimuli directly related to social interaction, such as faces, expressions, eye gaze, or body language. Since the Bayesian perspective was originally introduced to explain sensory processing abnormalities in ASD, distinguishing between social and non-social information is important (陈晓雯等, 2020) to determine whether problems exist in broader sensory processing rather than being specific to social domains.

In summary, after clarifying relevant concepts and theories within the Bayesian framework, this paper outlines theories explaining atypical sensory processing in ASD across three levels—Bayesian inference, predictive coding processes, and predictive coding precision—and synthesizes relevant empirical findings from the non-social visual domain. Based on this synthesis, we examine connections and distinctions between theories and provide recommendations for future research directions. Given the spectrum nature of ASD, autistic traits refer to the extent to which TD individuals exhibit characteristics associated with ASD (Baron-Cohen et al., 2001). Since some studies examine individuals with high autistic traits, we include such research in our review.

2 Clarification of Basic Concepts and Theories

The view of visual perception as Bayesian inference has generated numerous similar conceptual sets while simultaneously developing corresponding theories. We first clarify basic concepts in Bayesian inference, then summarize differences and connections between Bayesian theory and predictive coding theory to better frame subsequent discussion.

Within the Bayesian inference framework, prior, likelihood, and posterior are key terms. The prior refers to existing knowledge or hypotheses before observing a new scene (Sapey-Triomphe, Pattyn, et al., 2023), which can be divided into structural and contextual priors (Seriès & Seitz, 2013; Teufel & Fletcher, 2020). Structural priors reflect innate or overlearned statistical regularities, such as light coming from above or horizontal and vertical lines being more common in daily life (Girshick et al., 2011). Contextual priors derive from regularities in specific contexts, such as predicting which objects might appear based on a scene. While contextual priors have limited applicability, they can be learned quickly and flexibly through experience (Van de Cruys et al., 2018). Priors enable individuals to generate expectations, which are psychological mechanisms operating based on regularities (Summerfield & Egner, 2009). Likelihood, closely linked to sensory input, refers to the probability of a specific phenomenon given objective input—for example, the probability of observing a particular shade of green in a tree based on a learned model of tree appearance. Through integrating priors and likelihood, a posterior distribution is formed, generating perception (Sapey-Triomphe et al., 2021). Thus, likelihood, prior, and posterior are terms used in Bayesian computational frameworks, whereas sensory input, expectation, and perception describe the processes underlying conscious experience. In this framework, the integration of sensory input (likelihood) and expectation (prior) creates perception (posterior).

Another conceptual set applies to predictive coding theory (Friston, 2005; Summerfield & Egner, 2016), which posits that perception results from predictive coding. Prediction refers to perceiving the external world based on priors, emphasizing the perceptual process. For instance, we predict that household items will remain where they were when we left for work. Prediction errors arise from comparing predictions with sensory input and can be used to update priors or ignored as noise when uninformative (Friston, 2005). For example, if upon entering a room you find the sofa slightly moved, the prediction error is small; but if the sofa has completely changed orientation, the prediction error is large, prompting you to notice the change and update your knowledge. Thus, prediction errors drive learning and update priors, with current prediction errors influencing subsequent predictions. Another key concept is precision, which refers to how precise or strict the brain' s predictions are (Feldman & Friston, 2010). High precision means your brain expects to see exactly what it predicted, whereas low precision means greater tolerance if the external world does not perfectly match predictions. If your brain has high precision for its room prediction, even minor changes like a slightly moved chair will register as a significant surprise. With low precision, a new object might go unnoticed. When precision is high, stimuli matching predictions also elicit stronger neural activity (Bowman et al., 2023).

The primary difference between Bayesian theory and predictive coding theory lies in their explanations of brain function. Bayesian theory holds that the brain performs Bayesian inference based on current sensory input and expectations to generate perception of the world, accumulating evidence probabilistically over time to update its internal models. Predictive coding theory proposes that the brain continuously generates predictions about incoming sensory information based on its internal models, compares them with actual sensory input, computes prediction errors, and updates internal models accordingly. In the predictive coding framework, the brain is hierarchically organized, with higher levels generating predictions and lower levels computing prediction errors. Information flows in two directions: top-down predictions and bottom-up prediction errors. Predictive coding emphasizes continuous interactions between top-down and bottom-up signals across cortical levels. While both are grounded in Bayesian principles, predictive coding provides a more detailed mechanistic framework focusing on predictions and prediction errors in hierarchical brain networks, whereas Bayesian theory is more abstract, concerned only with perceptual inference itself. Thus, predictive coding can be considered the neural implementation of Bayesian inference in the brain.

3 Theoretical Controversies and Empirical Evidence

Within Bayesian or predictive coding frameworks, numerous theories attribute atypical sensory experiences in ASD to fundamental differences arising from predictive impairments. However, these theories differ substantially in their specifics. This section interprets existing theories and synthesizes empirical evidence across three levels: Bayesian inference assessing the relative weighting of priors and likelihood (Pellicano & Burr, 2012; Brock, 2012), predictive coding processes focusing on prediction construction and updating (Sinha et al., 2014), and precision focusing on sensory input and prediction errors (Lawson et al., 2014; Palmer et al., 2017; Van de Cruys et al., 2014). Through introducing and comparing theories across these three levels, we map current theoretical convergences and divergences in explaining ASD.

3.1.1 Weak Priors Hypothesis and Sharper Likelihood Hypothesis

Pellicano and Burr (2012) explained sensory anomalies in ASD using hypo-priors, proposing the weak priors hypothesis. Hypo-priors are attenuated and broader priors that reduce constraints on internal sensory information in ASD, leading to greater reliance on sensory information and experience of a more “real” world (Pellicano & Burr, 2012; Pellicano, 2013). Weak priors place individuals with ASD in a state of being overwhelmed by sensory information, providing an explanation for stereotyped behaviors and preference for regularity.

Building on the weak priors hypothesis, Pellicano and Burr (2012) predicted specific atypical perceptions and behaviors in ASD. Due to weak priors, individuals with ASD sometimes form more accurate perceptions than TD individuals. For example, illusions are considered statistically optimal solutions to reality derived from prior involvement (Weiss et al., 2002), and individuals with ASD, having weaker prior constraints, are less susceptible to visual illusions and biases (Rozenkrantz et al., 2021). However, when facing high-noise sensory input, lacking prior assistance impairs their task performance. The weak priors hypothesis also makes predictions about visual holistic perception in ASD. The ability to extract effective visual information from entire scenes is crucial for forming and maintaining priors (Pellicano & Burr, 2012). As statistical representations, priors can be extracted from experience and simultaneously from scene statistics, summarizing features of local elements (Whitney & Yamanashi, 2017). The weak priors hypothesis predicts that individuals with ASD may have relatively weaker ability to extract statistical information from visual scenes (Pellicano & Burr, 2012).

While the weak priors hypothesis identifies weaker priors as the key to sensory anomalies in ASD, Brock (2012) noted an alternative possibility from Bayesian theory. Based on Bayesian models, the sensory overwhelm experienced by individuals with ASD could arise through two pathways: either decreasing prior concentration (increasing prior variance, i.e., broader weak priors) or increasing sensory information concentration (decreasing likelihood variance, i.e., less sensory noise). Corresponding to the weak priors hypothesis, the latter can be termed the sharper likelihood hypothesis (Brock, 2012). For instance, research on the rubber hand illusion found that adults with ASD estimated sensory information with higher precision compared to TD adults (Paton et al., 2012). The sharper likelihood hypothesis provides a bottom-up explanatory pathway for sensory processing abnormalities in ASD.

The sharper likelihood hypothesis was not proposed to compete with the top-down weak priors hypothesis but rather to emphasize the importance of objectively and equally discussing both explanatory pathways within Bayesian theory. Both hypotheses can account for current deviations in sensory experiences observed in ASD. Therefore, separating the influences of these two hypotheses on outcomes is crucial.

3.1.2 Empirical Evidence from a Bayesian Perspective

Most evidence supporting the weak priors hypothesis is based on illusion phenomena. Studies have found that when using sound-induced flash illusions, children with ASD perceive fewer flash illusions compared to TD children (Stevenson et al., 2014). Researchers have also employed line discrimination tasks with horizontal lines superimposed on black-and-white dot backgrounds that induce the Ponzo illusion in some trials. Although neither ASD nor TD adult groups consciously perceived the Ponzo illusion, the ASD group was significantly less affected by it (Carther-Krone et al., 2016). Nayar et al. (2017) used eye-tracking to compare gaze patterns of ASD and TD children when viewing Kanizsa illusion contours, finding that children with ASD fixated less on the center of illusory contours, indicating reduced holistic perception. Another fMRI study using randomly generated Kanizsa illusion figures found that compared to TD children, children with ASD showed weakened automatic contour integration in lateral occipital regions (Knight et al., 2023).

Evidence supporting the weak priors hypothesis also spans different research contents and experimental paradigms. Using Mooney images as stimuli, researchers compared visual processing patterns of degraded images before and after presenting original images. TD adolescents showed top-down optimization in eye movements when viewing degraded images for the second time, with reduced fixation counts and shorter saccade distances, whereas this optimization was significantly reduced in adolescents with ASD (Król & Król, 2019). Weak priors phenomena have also been found in individuals with high autistic traits; for example, high-trait adults are less influenced by directional cues and rely more on sensory information for veridical perception (Lawson et al., 2018). Research on dynamic visual stimuli found that when visual cues provided probabilistic information about ball drop locations, ASD adults' visual motion patterns were less influenced by cues compared to TD adults (Arthur et al., 2023). Additionally, studies have found that compared to TD adults, ASD adults show impaired ability to extract color statistics from rapidly presented visual scenes but superior discrimination of individual colors (Maule et al., 2017). Neural evidence has also been obtained. Using magnetoencephalography to examine context modulation in visual processing of simple gratings through connectivity between visual areas V1 and V4, researchers found that while feedforward V1-to-V4 connections mediated by gamma were intact in ASD adults, feedback V4-to-V1 connections mediated by alpha were significantly reduced (Seymour et al., 2019).

Conversely, numerous studies do not support the weak priors hypothesis. Using Mooney images, researchers required participants to identify degraded images before and after presenting original images. They found that both high-trait and ASD adolescents showed improved accuracy after seeing originals, indicating that the ASD group formed specific priors and could use them completely in the task (Van de Cruys et al., 2018). Another study using a task to judge whether ambiguous stimuli were left- or right-biased, with cues preceding ambiguous stimuli to induce biases, found that both ASD and TD adolescents were influenced by cues and showed response biases without between-group differences, suggesting that ASD adolescents are similarly affected by priors in low-level visual perception (Bosch et al., 2022). At the neural level, an fMRI study using Kanizsa illusion materials found that both TD and ASD adolescents showed simultaneous up- and down-regulation patterns in visual area V1, indicating that illusory shape processing in primary visual cortex also exists in ASD (Utzerath et al., 2019). Most of these studies used the same or similar paradigms as those supporting the weak priors hypothesis. While they cannot fully falsify the hypothesis, they demonstrate that weak priors in ASD are unstable to some degree.

Even results supporting the weak priors hypothesis cannot exclude explanations from the sharper likelihood hypothesis. Researchers have begun attempting to separate the effects of priors and likelihood on visual perception using technical methods. Some have argued that the key to inconsistent results is the lack of computational models that can determine whether behavioral differences stem from weaker priors or stronger likelihood (Karvelis et al., 2018). Karvelis et al. (2018) used a statistical learning task with visual motion perception, where participants estimated the direction of coherent dot motion. Previous research showed that TD individuals rapidly and implicitly develop expectations for the most frequent motion direction, biasing their perception of dot motion direction in low-contrast trials (Chalk et al., 2010). Using Bayesian computational models to quantitatively assess changes in likelihood and priors, results showed that ASD adults did not have weaker priors but rather formed more precise sensory representations. Another EEG study examined how prior information influenced visual detection tasks (gray checkerboards) by providing probabilistic information about target locations. Using signal detection theory and drift diffusion models to reveal decision parameters underlying visual perception formation, results showed that ASD adults assigned higher weight to sensory information in visual decision-making (Tarasi et al., 2023). These findings explicitly support Brock' s (2012) sharper likelihood hypothesis.

3.2.1 Predictive Coding Impairment Hypothesis

While Bayesian-based hypotheses provide entry points for understanding perceptual anomalies in ASD, they do not clarify how priors become weaker or likelihood becomes sharper. Therefore, researchers propose explaining perceptual anomalies in ASD within the more specific predictive coding framework (van Boxtel & Lu, 2013). Surrounding predictive coding processes, multiple hypotheses or perspectives have emerged focusing on prediction specificity in ASD. Based on their focus on different stages of predictive coding, these hypotheses can be divided into prediction construction impairment and prediction updating impairment, collectively termed the predictive coding impairment hypothesis.

The prediction construction impairment stage focuses on abnormalities in the dimension of prediction conformity. Although not strictly based on predictive coding theory, Sinha et al. (2014) proposed that ASD relates to abnormal prediction of events (inaccurate estimation of conditional probabilities), naming it the predictive impairment in autism (PIA) hypothesis. When relationships between successive events are weak or separated by large temporal gaps, individuals with ASD show reduced sensitivity to these relationships, meaning they cannot establish effective predictions. This temporal dimension of impaired prediction ability disrupts planning and judgment of subsequent actions. For example, observations of early feeding videos showed that infants with ASD failed to effectively anticipate and open their mouths in response to approaching spoons (Brisson et al., 2012). Inability to establish effective predictions makes it difficult for individuals with ASD to adapt to sensory environments, living in a seemingly "magical" world where events occur unexpectedly and without cause. An important consequence of reduced prediction ability is increased perceived novelty of environmental stimuli. Therefore, at the neural level, Sinha et al. (2014) hypothesized that individuals with ASD would show hyperactivation, manifesting as reduced adaptation to prediction-congruent information (Wasifa et al., 2021).

The prediction updating impairment stage focuses on abnormalities in the dimension of prediction violation. Strictly speaking, no explicit theory or hypothesis has been proposed in this area; rather, conclusions derive from a relatively consistent body of empirical findings. Therefore, this section provides a general summary of these results, with more detailed introduction of research content in the empirical evidence section. Within the predictive coding framework, generating prediction errors in response to prediction-violating information is key to learning. Imagine if prediction errors cannot be generated under violation conditions; perception would continue according to the original predictive pattern, missing opportunities to update information and establish more accurate new predictions. Individuals with ASD show different perception patterns from TD individuals under prediction-violation conditions, primarily manifesting as continued information processing according to the original predictive pattern and inability to flexibly update predictions (Greene et al., 2019; Sapey-Triomphe et al., 2022; Treves et al., 2023).

Overall, prediction construction impairment and updating impairment are based on different stages of predictive coding processes and therefore do not conflict. Moreover, these two stages of impairment may reflect abnormalities in the same predictive mechanism. Compared to TD individuals, individuals with ASD have greater difficulty establishing predictive internal models; once predictions are formed, they also struggle to update these models when external environments change.

3.2.2 Empirical Evidence for Predictive Coding Impairment

Prediction construction impairment in ASD has received empirical support. By presenting visual stimuli dynamically that moved toward one of two target locations, with targets divided into prediction-congruent (high probability) and prediction-violating (low probability) conditions, researchers examined participants' predictive eye movement trajectories. Results showed that ASD children, adolescents, and adults required more trials to accurately establish predictions about target locations, whereas age-matched TD groups formed stable predictions about target locations in early trials (Ganglmayer et al., 2020; Schuwerk et al., 2016; Tan et al., 2023). These findings explicitly support the PIA theory.

However, some empirical studies have found that individuals with ASD can effectively establish predictions. For example, ASD children showed no difference from TD children in predicting locations and timing of moving visual stimuli (Tewolde et al., 2018). Another study divided stimulus locations into regular and random patterns, finding that ASD adults performed equivalently to TD adults, with no between-group differences in learning dynamics (Pesthy et al., 2023). These studies suggest that visual dynamic prediction or statistical learning abilities for visual static stimuli may be intact in ASD, challenging the view of universal predictive coding impairment. Researchers propose that further studies are needed to assess the specific contexts in which predictive coding is impaired in ASD, or that atypical predictive processing does not necessarily imply behavioral deficits (Pesthy et al., 2023; Tewolde et al., 2018).

At the neural level, the PIA hypothesis assumes that individuals with ASD show low adaptation to prediction-congruent sensory information (Sinha et al., 2014), which has received empirical support. Wasifa et al. (2021) used electroencephalography (EEG) to examine whether individuals with ASD exhibit repetition suppression—reduced neural activity to repeated stimuli—for repeated visual stimuli. They found that TD children showed significantly reduced P1 components to repeated stimuli, demonstrating repetition suppression, whereas children with ASD showed enhanced P1 trends. This result supports the PIA hypothesis. However, another fMRI study found inconsistent results. D' Mello et al. (2023) also used a repetition suppression paradigm and found that ASD adults, like TD adults, showed neural repetition suppression effects for object stimuli in bilateral lateral occipital cortex and for word stimuli in left fusiform gyrus. The researchers concluded that this indicates intact brain function for establishing predictions in ASD.

Notably, whether the repetition suppression paradigm effectively manipulates predictions remains controversial. Feuerriegel et al. (2021) pointed out that repetition suppression paradigms confound physical and psychological adaptation. In short, repeated stimulus presentation causes physical adaptation, but determining whether psychological adaptation occurs requires separating physical stimulus properties. The visual statistical learning paradigm can effectively separate physical stimulus properties. In this paradigm, cues and targets are presented sequentially, with cues predicting target appearance probabilities (high probability = prediction-congruent, low probability = prediction-violating). By balancing relationships between different cues and targets, this paradigm can maintain consistent target appearance frequencies within blocks, thereby controlling physical stimulus properties. One fMRI study based on this paradigm manipulated repetitiveness by setting whether cues and targets were identical stimuli, creating four conditions: prediction-congruent repetition and non-repetition, and prediction-violating repetition and non-repetition. Results showed that ASD adolescents exhibited reduced neural activity to repeated stimuli in lateral occipital cortex, demonstrating repetition suppression, but enhanced neural activity to prediction-congruent stimuli (Utzerath et al., 2018). This indicates intact physical adaptation but impaired psychological adaptation to prediction-congruent stimuli in ASD.

Studies have also found that individuals with ASD cannot effectively update predictions under prediction-violation conditions. Using an associative learning task that probabilistically linked tones to rotation directions of dot pairs, participants reported rotation directions. Results showed that both TD and ASD adults formed predictions based on probabilities, but the ASD group updated predictions less when predictions were violated (Sapey-Triomphe et al., 2022). Another study used eye-tracking to examine gaze patterns during visual learning in ASD and TD adolescents. Simple visual stimuli served as cues providing predictive information about subsequent stimulus locations. Results showed that in prediction-violation trials, ASD adolescents fixated less on locations corresponding to learned priors, failing to update cue-outcome associations and thus generating ineffective prediction errors (Greene et al., 2019). Treves et al. (2023) manipulated target location predictability, with a green star appearing in one of four locations. In predictive blocks, stimulus locations repeated in a fixed sequence, whereas in non-predictive blocks, locations were random. Results showed that when stimuli switched from repeating sequences to random locations early in the experiment, ASD adults made fewer errors. This simultaneously indicated that the ASD group lost opportunities to learn new strategies from errors.

3.3.1 Aberrant Precision Hypothesis and HIPPEA Theory

As the originator of predictive coding theory, Friston et al. (2013) argued that atypical sensory processing in ASD results from reduced predictive precision, preventing individuals from instantiating predictions during perceptual integration. In this framework, predictive precision controls the degree of trust placed in predictions versus sensory information. In the brain’ s hierarchical processing, different levels exhibit differential estimates of predictive precision. This estimation is essentially a form of metacognition; therefore, Friston et al. (2013) proposed that ASD should fundamentally be considered a metacognitive disorder. Building on the perspective of impaired predictive precision in ASD, Lawson et al. (2014) proposed the aberrant precision hypothesis, whose core tenet is the imbalance between predictive precision and sensory precision. Specifically, individuals with ASD generate relatively low predictive precision at higher neural levels but relatively high sensory precision at lower neural levels, with this imbalance primarily resulting from inability to reduce sensory precision at lower levels. Compared to top-down predictive processing, the aberrant precision hypothesis 主张 that atypical bottom-up sensory information processing constitutes the core source of ASD symptoms.

Like the aberrant precision hypothesis, the high and inflexible precision of prediction errors in autism (HIPPEA) theory also centers on precision estimation. However, HIPPEA theory proposes that high and inflexible precision estimates of prediction errors cause the range of atypical sensory symptoms in ASD (Van de Cruys et al., 2014). The precision of prediction errors is the ratio of sensory precision to predictive precision. Moreover, Van de Cruys et al. (2014) argued that to fully explain ASD, it is necessary to account for changes or dynamic adjustment mechanisms of precision over longer timescales. Estimation of prediction error precision exists constantly in predictive coding and flexibly adjusts according to environmental input and organism state, depending on prior learning and judgments of current environmental uncertainty. Environmental cues provide two types of uncertainty: irreducible and reducible. The former arises from inherent randomness in the world and noise in our perception, while the latter requires internalized learning for prediction correction. When reducible uncertainty exists in the environment, TD individuals increase precision to enhance perception of prediction errors and initiate learning of new regularities. For individuals with ASD, while they can generate prediction errors, their precision estimates for these errors remain consistently high and inflexible. This means individuals with ASD constantly overestimate environmental variability and remain in a continuous state of learning new environmental regularities.

From the predictive coding precision perspective, humans must minimize uncertainty to avoid being overwhelmed by numerous stimuli in complex, changing environments. The absence of this ability causes individuals with ASD to experience a chaotic and disordered world, perpetually in a state of overlearning. Overlearning leads to formation of narrower priors, causing ASD predictions to deviate substantially from reality, with these errors not being dismissed as negligible noise. This effectively means that generalization ability in ASD is nearly zero.

3.3.2 Empirical Evidence Related to Predictive Precision

Because the mechanisms tested are more specific, experimental paradigms examining predictive coding precision hypotheses are generally more complex in design. One study used the width-height illusion (tall rectangles appear narrower than short rectangles), blurring vertical edges of rectangles to increase sensory noise. Results showed that blurring enhanced the width-height illusion in TD adults but produced no difference in ASD adults. That is, while individuals with ASD could experience the width-height illusion based on predictions, they did not increase the weighting of predictions in perception when sensory input became more ambiguous. Researchers concluded that this indicates inflexible, non-adaptive predictive precision in ASD (Binur et al., 2022).

Another study examined the precision hypothesis using the time-order effect in stimulus perception. When repeatedly perceiving object sizes, visual perception biases toward the average. When comparing sizes of two sequentially presented objects, the first stimulus, which must be maintained in memory, has greater noise and thus lower sensory precision, making it more susceptible to prior influence and causing perception to bias toward the average—the time-order effect. In the experiment, participants compared sizes of two sequentially presented black circles, with the first circle' s prior range set as either narrow or broad. The narrow condition generated more accurate priors, while the broad condition generated inaccurate priors. Researchers reasoned that the weak priors hypothesis would predict no time-order effect under either condition; the sharper likelihood hypothesis would similarly predict no time-order effect but better task performance in ASD; HIPPEA theory would predict time-order effects under both conditions but no difference in effect magnitude between conditions for ASD. Results supported HIPPEA theory: TD adults showed larger time-order effects when the first circle's prior range was narrow, whereas ASD adults showed equivalent time-order effects across both conditions, indicating inflexible weighting of precision in ASD (Sapey-Triomphe et al., 2021).

Another study used a visual search task where a salient but task-irrelevant distractor appeared with higher probability on one side (prediction-congruent) and lower probability on the other side (prediction-violating). Results showed that, like TD adults, ASD adults learned to avoid attention capture by distractors in prediction-congruent locations. However, when distractors appeared in prediction-violating locations, the ASD group could not avoid attention capture as effectively as the TD group, resulting in impaired task performance. Researchers interpreted this as supporting HIPPEA theory (Fredrik et al., 2021). Specifically, HIPPEA theory proposes that individuals with ASD are overly sensitive to small prediction errors, causing "every slight violation of regularity to trigger new learning" (Van de Cruys et al., 2014). When a distractor suddenly appears in an unpredictable location, violating established regularities, the resulting prediction error triggers a new learning process that captures attention in ASD, whereas TD individuals better suppress this capture due to lower sensitivity to small prediction errors.

At the neural level, HIPPEA theory has also received empirical support. Using fMRI with auditory cues providing predictions about rotation direction of dot pairs, an inverted visual perceptual inference model characterized neural correlates of predictions and prediction errors at different hierarchical levels in ASD. Results showed that at the behavioral level, predictive abilities were intact in ASD adults. At the neural level, predictions were hierarchically encoded in both groups, and prediction errors activated shared regions. However, group differences emerged in anterior cingulate cortex and putamen, where ASD adults showed stronger encoding of prediction errors at intermediate and high-level predictions (Sapey-Triomphe, Pattyn, et al., 2023). Researchers concluded that this supports HIPPEA theory, suggesting that excessively high precision of prediction errors may underlie predictive difficulties in ASD.

However, some studies do not support predictive coding precision hypotheses. Ward et al. (2022) argued that since precision is a fundamental component of perception and learning, differences should be detectable before full clinical symptom manifestation. They studied 3-year-olds with high and low likelihood of ASD using an implicit learning paradigm to examine how sensory noise affects prediction formation. To learn a sequence, participants had to select which visual information to attend to while ignoring small prediction errors caused by sensory noise. Results showed that compared to low-likelihood children, high-likelihood children showed no signs of heightened sensitivity to prediction errors when sensory noise was added, whether in reaction time or location decisions. The researchers concluded that this challenges high-precision theories of ASD (Ward et al., 2022). However, given the specific participant population and reliance on behavioral measures alone, this conclusion requires more empirical testing and is insufficient to refute HIPPEA theory.

3.4 Connections and Distinctions Between Theories

Pellicano and Burr (2012) pioneered the Bayesian perspective to explain atypical sensory processing in ASD, proposing the weak priors hypothesis. Brock (2012) subsequently proposed the sharper likelihood hypothesis, suggesting that overly precise sensory representations make it difficult for individuals with ASD to integrate with top-down priors. Both hypotheses can account to some extent for symptoms such as attraction to sensory details, difficulty establishing holistic representations, and sensory overwhelm. However, current empirical evidence is divided. Studies finding and failing to find weak priors are roughly equal in number. Critically, when analytical methods separate sensory information encoding strength from prior use ability, results show that individuals with ASD primarily exhibit enhanced sensory information encoding (Karvelis et al., 2018; Tarasi et al., 2023). This finding appears to better support the sharper likelihood hypothesis.

Within the predictive coding framework, explanations for sensory anomalies in ASD can be further distinguished into two levels: predictive coding processes and precision. Predictive coding processes focus on prediction construction and updating impairments, providing deeper explanatory pathways for the weak priors hypothesis within the Bayesian framework. The core reason individuals with ASD struggle to use priors is impaired dynamic encoding processes of prediction and updating—difficulty forming stable predictive representations and adjusting prediction models based on prediction errors. Precision-focused theories align with the sharper likelihood hypothesis, attributing atypical perception in ASD to problems with sensory input (Van de Cruys et al., 2014), but they further specify and clarify predictive coding mechanisms. Unlike the sharper likelihood hypothesis, which focuses on high-intensity sensory information encoding itself, the aberrant precision hypothesis and HIPPEA theory further elucidate the mechanisms underlying excessive attentional and cognitive resource allocation to sensory information in ASD, providing more microscopic analysis of weight distribution disorders in predictive coding. Meanwhile, predictive coding theories also emphasize the importance of dynamic predictive coding processes.

Overall, the three levels of theories connect and build upon each other progressively (Figure 1 [Figure 1: see original paper]). The Bayesian framework lays the foundation for predictive coding theory, which provides more systematic development and understanding of Bayesian concepts. Simultaneously, these three levels differ in their focus. The Bayesian framework primarily offers descriptive-level theoretical hypotheses, predictive coding process theories focus more on abnormal aspects of coding dynamics, and precision theories directly analyze biases in weight allocation of sensory information in predictive coding. Together, they construct a multi-level, systematic theoretical architecture that helps us comprehensively 描绘 the unique "profile" of visual processing in ASD. The core of these hypotheses and theories is emphasizing separable components of predictive processing that need not be mutually exclusive within a single hierarchical framework.

However, this does not mean all these theories can explain visual processing abnormalities in ASD. These hypotheses can be viewed as a continuum of precision—from relatively broad, descriptive theories to increasingly refined, explanatory theories. At the broadest level, the weak priors and sharper likelihood hypotheses within the Bayesian perspective focus on the process of priors and likelihood constructing perception but do not consider how priors and likelihood themselves become problematic. This level provides a low-precision ruler that cannot consistently measure predictive processing patterns in research. Theories focusing on predictive coding processes provide more precise rulers that better describe different phenomena and accommodate interactions between components rather than locating dysfunction in isolated components. The most precise rulers are precision-based theories, which emphasize that imbalanced precision weighting of predictions, prediction errors, or their integration is the key issue, offering stronger explanatory power. Notably, in empirical studies focusing on precision testing, theoretical explanations can be exclusive—for example, supporting HIPPEA while simultaneously not supporting weak priors or other hypotheses (Sapey-Triomphe et al., 2021).

The main contradiction between these theories lies between prediction updating impairment (Greene et al., 2019; Sapey-Triomphe et al., 2022; Treves et al., 2023) and HIPPEA theory. The former suggests low sensitivity to prediction errors, while the latter proposes excessively high and inflexible precision of prediction errors (Van de Cruys et al., 2014). Although these hypotheses have not formed a unified theoretical view, given the multiple heterogeneous manifestations of ASD symptoms across individuals, such diversity may be possible or even necessary. Individuals with ASD simultaneously exhibit hyper- or hypo-responsiveness to sensory experiences—for example, overlooking novel visual stimuli while being abnormally sensitive to minor visual changes (Baranek et al., 2006; Baranek et al., 2013; Foss-Feig et al., 2012; Robertson & Baron-Cohen, 2017). Whether prediction updating impairment and HIPPEA theory separately explain hypo- and hyper-responsiveness or should be integrated into a single framework requires further exploration. Notably, HIPPEA theory emphasizes not only excessively high precision of prediction errors but also their inflexibility. Whether prediction updating impairment can be integrated into the assumption of inflexible prediction error precision is key to further refining HIPPEA theory.

[Figure 1: see original paper] Theories and hypotheses explaining atypical sensory processing in ASD from Bayesian and predictive coding perspectives

Predictive coding theory, derived from Bayesian inference, is considered one of the most influential theories in cognitive science (Bowman et al., 2023), offering hope for understanding sensory processing and other behavioral abnormalities in ASD. However, as theoretical perspectives deepen and research content expands, theoretical consensus has become increasingly distant. Given this situation, this paper attempts to approach non-social visual information and stratify theories according to their focus, synthesizing corresponding empirical evidence. On this basis, various theories and empirical results are not irreconcilable. Given the complex landscape of understanding atypical sensory processing in ASD from a predictive coding perspective, we propose three future research directions.

4.1 A Practice Path of Domain-Specific Refinement Followed by Integration

Similar to explaining ASD etiology, researchers have sought a specific predictive coding characteristic to explain sensory processing anomalies in ASD. However, deeper research suggests that attempts to find a single theory may ignore real-world complexity. Indeed, we should not underestimate the complexity of the brain and ASD phenotypes, particularly given highly constrained experimental tasks and models (Noel et al., 2020). Just as researchers finally abandoned the search for a single genetic or cognitive cause for different ASD symptoms after years of exploration (Happé et al., 2006), we should also break free from the conceptual constraint of seeking a simple, clear, single theory for sensory processing abnormalities in ASD. Guided by this thinking, future work can proceed in two directions:

On one hand, consistent with this paper, research domains should be subdivided to examine disagreements and integrative possibilities within each domain—for example, focusing on predictive processing of auditory, tactile, or social visual information. One study found that when gratings changed in spatial frequency, individuals with ASD showed higher detection and response thresholds, but when gratings changed in contrast, thresholds did not differ from TD individuals (Sapey-Triomphe, Dierckx, et al., 2023). Such research further subdivides non-social visual information into fine-grained categories like spatial frequency and contrast, revealing differential processing of these visual attributes in ASD. Examining theoretical controversies from more specific domains is more likely to achieve some degree of consistency within narrow scopes. Additionally, empirical studies reveal that research design depends on the question being tested, which directly leads to large differences in experimental paradigms used to test different theories, with few studies able to directly distinguish between theories. Therefore, while focusing on domain specificity, attention must also be paid to application and innovation of experimental paradigms.

On the other hand, further comparison and integration should be conducted based on domain subdivision to clarify commonalities and specificities of predictive coding mechanisms across domains. Regarding the relationship between atypical sensory processing and social information processing in ASD, three views exist: First, some empirical studies may directly generalize results from non-social visual domains to social cognitive domains, considering them interrelated and stemming from common predictive impairment mechanisms (Ganglmayer et al., 2020). Second, a more advanced view suggests that predictive impairments in sensory processing are the antecedent cause of social information predictive impairments (Falck-Ytter & Bussu, 2023). Third, some researchers propose that the two may be separate—for example, intact predictive coding for non-social information but impaired predictive coding for social information (Bosch et al., 2022). Therefore, whether the relationship between atypical sensory processing and social information processing in ASD is correlational, causal, or separate requires more empirical research and theoretical integration for verification and deepening.

Overall, this "refine first, integrate later" research strategy will not only help address current theoretical disagreements but also substantially advance our understanding of abnormal predictive coding mechanisms and developmental trajectories in ASD, gradually refining the theoretical framework for explaining atypical sensory processing in ASD through predictive coding and providing more precise scientific foundations for diagnosis and intervention in ASD populations.

4.2 Focusing on Subjective-Level Visual Experience in ASD

Current research on atypical visual perception in ASD primarily focuses on two aspects: behavioral level (e.g., visual detection or discrimination, mainly reflected in task performance) and neural activity level (i.e., changes in neural activity during perception). Subjective-level visual experience remains neglected. One study found that when using computational models to fit visual predictive coding in ASD, objective behavioral data were well-fitted, but subjective report data were poorly fitted (Karvelis et al., 2018). This reflects a long-standing research challenge in consciousness: subjective report results are difficult to quantify.

The core perspective of understanding ASD from Bayesian or predictive coding viewpoints is that the human brain actively interprets visual information rather than passively perceiving it (Intaitė et al., 2019). Focusing solely on theoretical explanations of ASD may risk putting the cart before the horse. Researchers attempt to build theories to understand sensory processing abnormalities in ASD, yet these theories are rarely validated from the subjective experiences of individuals with ASD themselves. As Todorova et al. (2024) note, this often makes individuals feel they must conform to theoretical definitions rather than theories conforming to their experiences. Todorova et al. (2024) argue that efforts to explain atypical sensory information processing in ASD have neglected the voices of individuals with ASD themselves. Through questionnaires and interviews with ASD adults about HIPPEA, results showed that individuals with ASD believe HIPPEA theory can explain many of their life experiences. They experience a world that is truly nuanced and appears pixelated. However, they question HIPPEA theory's explanations for higher-level cognitive processes such as social interaction, emotional processing, and motivation.

This study stands out among numerous empirical investigations of predictive coding abnormalities in ASD. Combining phenomenological evidence helps determine whether proposed theoretical mechanisms translate into everyday perceptual experiences and decision-making. Therefore, finding appropriate ways to measure subjective experiences across different developmental stages in ASD is particularly important. Creative methods may capture subjective phenomena, such as analyzing drawing content from children with ASD. Transforming subjective phenomena into concrete indicators remains a difficult challenge. Nevertheless, testing theories from a first-person perspective of individuals with ASD is an indispensable key step. Indeed, even neurotypical individuals construct different perceptual representations when facing identical sensory worlds (Tarasi et al., 2023). Predictive coding emphasizes the subjectivity and diversity of perception. For individuals with ASD, they may experience a chaotic and unstable visual world, and this experience requires their own expression.

4.3 Examining Predictive Coding Abnormalities in ASD from a Developmental Perspective

Most empirical studies are conducted with ASD individuals at specific age stages—infants, children, adolescents, or adults—with few studies simultaneously considering predictive coding differences across age stages. This may stem from dual challenges of recruiting participants across ages and designing paradigms appropriate for different developmental abilities. However, examining predictive coding mechanisms from a developmental perspective is also crucial.

One possibility is that predictive coding abnormalities in ASD gradually alleviate with increasing mental age. This hypothesis derives from observations of sensory symptoms in ASD—for example, studies finding that sensory symptoms correlate negatively with mental age in ASD (Baranek et al., 2006). If predictive coding mechanism abnormalities are indeed the primary cause of these sensory symptoms, they may gradually diminish as brain development matures. Research shows that high-functioning individuals with ASD continuously adapt to external environments in their own ways (Ai et al., 2022). Therefore, increasing age may enable individuals with ASD to gradually build more effective internal models, thereby increasing tolerance for prediction errors and reducing excessive sensitivity to minor changes. The critical time point for alleviation of predictive coding abnormalities would then require further longitudinal tracking studies for verification. Additionally, different research result discrepancies may be attributable to different age groups of participants.

A second, opposite possibility is that predictive coding mechanisms are initially immature in both groups, but with age, individuals with ASD cannot effectively establish and optimize predictive coding like TD individuals. This hypothesis derives from some research findings. One study found that compared to TD adults, both ASD and TD children showed imprecise encoding of prior information (Van de Cruys et al., 2021). Lawson et al. (2017) found that adult ASD individuals showed a tendency to overestimate volatility of sensory environments, a tendency not present in ASD children. This raises the possibility that both ASD and TD children have weak establishment of contextual priors, but TD children' s predictive coding abilities gradually develop and mature over time. In contrast, statistical learning development in ASD children is hindered, leading to predictive coding impairments in adulthood. In other words, predictive coding impairment develops gradually over time rather than being massively different from TD children from the start.

Regardless of which developmental trajectory is closer to reality, longitudinal tracking and multimodal empirical research are needed for verification. A developmental perspective is crucial for understanding predictive coding mechanisms in ASD, as it helps clarify not only the time course of symptom changes but also reveals whether symptom origins involve innate deficits in mechanisms themselves, developmental obstacles, or a combination of both. Future work should establish prospective longitudinal tracking studies to identify developmental changes in predictive coding over time in ASD.

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Note: Figure translations are in progress. See original paper for figures.