

# Autism Spectrum Disorder as a Disorder of Prediction in Sensorimotor Processing

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**Abstract.** Autism Spectrum Disorder (ASD) is a neurodevelopmental disorder characterized by persistent social interactive and communicative difficulties and repetitive, restricted behavioral patterns. Previous theories suggested impairments in two distinct sets of core abilities as an explanation for ASD. One is the delayed ability to reflect on others' mental content, and the other is the lack of the tendency to integrate details to create meanings in contexts. In the current field, there is an emergent explanation to consider ASD as a disorder of prediction. Under this notion, two competing views proposed different accounts for the specific deficits in ASD predictive system. The Bayesian view believes that ASD individuals experience reduced priors and are less reliant on top-down information when making predictions. Alternatively, the predictive error view believes that ASD impairments result from a failure to ignore accidental prediction errors caused by environmental noise, leading to overly frequent updates and less generalizable predictions. Though both views seem credible, no previous studies have comprehensively examined their reliability in empirical evidence. Therefore, the present paper fills in the gap by reviewing the two views and their relevant psychological and neuroscientific evidence with a specific focus on sensorimotor prediction. The major conclusion is that most empirical evidence was consistent with the reduced prior proposal but not the prediction error weighing proposal. Specifically, the ASD population is resistant to reliable contextual priors even though their associative learning may remain unimpaired. In keeping with the reduced prior proposal, the ASD population showed atypical connectivity between brain areas, suggesting insufficient communication of top-down information. Additionally, subjective anxiety during the Bayesian inferential process probably hinders the prediction performance. One possible limitation of the present review is the generalizability of conclusions to the domain of social impairments. Future studies should dedicate to exploring the restrictive conditions on the reduced Bayesian prior and E/I ratio imbalance and the role of anxiety in moderating the predictive process. One practical implication is to promote context-dependent imitations in sensorimotor learning in ASD. This review can provide some insights to future intervention studies and practices for children with ASD.

**Keywords:** Autism Spectrum Disorder; Sensorimotor processing; Bayesian brain; Predictive coding.

## 1. Introduction

Autism spectrum disorder (ASD) is a neurodevelopmental disorder characterized by persistent difficulties in social interactions and sensory symptoms, such as repetitive behaviors and hyper- or hypo- reactivity to stimulus [1]. In the early literature, the conceptualization of this disorder has been incoherent. According to an early review paper, two of the most influential views conceptualized ASD as either a delay of Theory of Mind (ToM) or a weak central coherence (WCC) [2]. The former view believed that the ToM ability was severely delayed in autism. It was supported by evidence where ASD individuals were unable to reflect on the mental contents (e.g., beliefs, thoughts, emotions, knowledge) based on the voice tone or eye gazes of others. Alternatively, the latter view believed that ASD individuals lack the ability of central coherence, i.e., a spontaneous tendency to integrate details to create meanings. Evidence supporting this view comes from studies where ASD individuals failed to make use of word contexts in sentence disambiguation or keep a logically coherent context in self-narrated stories. Nevertheless, even though evidence is consistent with both views, they argued for two distinct sets of abilities as the core to ASD impairments while reducing the other ability as secondary, resulting in asymmetric pictures of this disorder in many earlier studies.

Recently, there has been a growing consensus in the field to think of ASD as a disorder of prediction. Living in a noisy and stochastic world, humans are constantly anticipating what is coming next and adaptively preparing for potential threats in the environment [3]. However, for ASD individuals, some deficits are believed to present in their predictive system, preventing them from correctly predicting the world. As a result, they are constantly bombarded by uncertainties and experience a world different from typical developing individuals. Under this notion, two proposals are put forward to account for the specific deficits in autism predictive systems. The Bayesian view argues that deficits in the predictive system in autism is a result of reduced Bayesian prior [4]. According to this view, the brain unconsciously infers about the world based on the Bayes rule: The posterior possibility of a prediction given the sensory data is evaluated based on the likelihood of the sensory data given the prediction and the Bayesian prior. Bayesian prior is conceptually defined as a probabilistic distribution of the expectation of the environment being in a certain state before any observation [4]. Colloquially, it reflects the subjective confidence in the environment being in a certain state based on all of one's previous knowledge and experiences. Priors play an important role in helping individuals to decide the correct prediction, especially when sensory data is depleted. However, in cases like autism, the influence of previous knowledge is believed to be attenuated, resulting in predictions heavily based on sensory data.

Alternatively, the prediction error weighing view argues that ASD predictive deficits are due to an abnormally high weighing of lower-level prediction errors [3]. The basis of this view is the hierarchical organization of brain areas working simultaneously bi-directionally: lower-level areas send primary sensory data bottom-up and higher-level areas predict incoming sensory data by generating predictions according to the Bayes rule and send them top-down [5]. Nevertheless, because of the uncertainty of the world and the noisiness of the biological processing system, these top-down predictions are never perfect. The mismatch between the top-down prediction and the sensory data is called the prediction error. According to this view, each prediction error is assigned a precision value by the brain. The higher the precision value, the more likely new learnings would be triggered. In optimal cases, only real discrepancies could receive high precision value and drive individuals to learn the environmental regularities that are not yet fully learnt. However, in suboptimal cases like autism, the precision values assigned to prediction errors at the lower-level areas are too high. In consequence, ASD individuals are unable to filter out the prediction errors caused by the external and internal noises and constantly update their predictions until they become hardly generalizable.

Since few attempts had been made to evaluate the accuracy of both seemingly credible views, the present paper aims at filling this gap by reviewing both views in relation to the recently published studies on sensorimotor predictions in ASD. The rest of the paper would unfold by first reviewing the reduced prior proposal argued by the Bayesian view and the inflexible weighing of the prediction error proposal argued by the predictive error view in psychological experiments. Following that, the possible role of anxiety in the Bayesian predictive process that emerged from psychological experimental evidence was identified and discussed. Finally, both views were reviewed in the context of an influential neuroscientific theory that argues for reduced neural inhibition in ASD brains. This review can provide some suggestions to the design of interventions and relevant studies for children with ASD.

## **2. Sensorimotor Processing in ASD in Psychological Experiments**

### **2.1 Reduced Use of Contextual Priors but Intact Associative Learning**

Priors are most frequently operationalized as “previous knowledge” or “previous experience” of some sort because they can be used to disambiguate situations and anticipate the correct upcoming stimulus. However, it is worth clarifying that contexts also count as one subtype of Bayesian priors because they can be used for the same function. For example, a professor sees a student raising his hand in the middle of the class. Even though many meanings could be associated with a hand raise (e.g., asking for a ride), the context of a classroom confines the range of possible meanings to a

question or an answer. Yet, because ASD individuals are believed to experience the reduced influence of the priors, they are unable to disambiguate situations like this and correctly infer other's meanings. In studies where, sensorimotor predictions in autism are explored, priors are typically operationalized as the knowledge that a behavioural outcome can be reliably predicted by a piece of contextual cue. In studies reviewed in the present paper, the behavioural outcome of an action is associated with a part of the background where the action takes place. Participants are instructed to learn the association through a short familiarization session, following which they would be asked to predict the correct behavioural outcome given the contextual cue associated with that outcome. According to the reduced prior proposal, the ASD group would be less reliant on the contextual cue than the control group when predicting the outcome.

Consistent with the reduced prior proposal, the ASD population showed failures in predicting the corresponding behavioural outcome when the contextual cue is the most reliable. The ASD population seems to be extremely reluctant to draw on reliable contextual priors. Evidence from ASD children showed no difference between group performances when the contextual cues were 10%, 40% and 60% predictive of the behavioural outcome. However, only when the contextual cues were 90% predictive of the behavioural outcome, the ASD group was less dependent on contextual cues to predict how interactive patterns would unfold than the control [6]. The reluctance to use reliable contextual cues is generalizable across age groups. In another study, the ASD adults and the control were asked to play a virtual ball interception game. Both groups were provided with explicit semantic cues that were highly predictable of ball trajectories. However, the ASD adults showed less precise and more varied endpoint predictions than the control, which indicates they did not benefit from the semantic cues [7]. Importantly, it needs to be made clear that in all studies discussed above, both groups showed no difference in the familiarization phase when they were instructed to learn the cue-outcome association. This eliminates insufficient associative learning as a valid explanation for the result patterns.

The major conclusion can be reached that the ASD population is resistant to reliable contextual priors, but their associative learning machinery remains relatively intact. At the first glance, this conclusion is perfectly in line with ASD social communicative symptoms. In social settings, a reliable contextual environment usually implies a certain preferable way of behaving. Reluctancy to use these cues would make it hard for ASD individuals to decode the behaviours of others as well as properly adjust their own ways of behaving. Yet, a closer look at the sensory symptoms reveals a more complex picture: Some of the well-known autistic interests involve lining things up and being fascinated with light [1]. Interests like these must base on robust priors. Otherwise, ASD individuals would not know whether to look up or down if they are not confident in the fact that light always comes down from the top. Similarly, they won't be able to line things up in a 'line' without knowing anything about occlusion and basic geometry. Therefore, even though the reduced prior proposal is supported, this proposal is not generalizable to all previous knowledge and experience. This proposal is probably restricted to social priors which are distinct in important aspects from mathematical or physical priors. Without specifying the taxonomy of priors, no clear boundary of where the reduced prior is suitable can be demarcated.

Additionally, whether the ASD individuals are involved in actively using the contextual cues seems to explain some conflicting results in the existing literature. Contextual cues must be used as pieces of information to create meanings (e.g., inferring the correct behavioural outcome) rather than a medium through which two stimuli associate with one another. Therefore, based on this review, it is expected that past studies where experimental paradigms like the verbal association task were used should produce insignificant results, as those paradigms only tested for the knowledge of object associations but not the active use of context.

## **2.2 No Evidence of Inflexible Prediction Error Weighing**

Prediction errors can be categorized into those caused by real changes in the world, and spurious changes caused by noises that are unlikely to reoccur in the future [3]. In the original paper where the

inflexible weighing view was proposed, two sources of noise are identified: one is the uncertainty of the external world, and the other is the inherent noises caused by excessive neural excitation in the biological brain [3]. Because there was observation reporting reduced inhibitory signals in the ASD brains, ASD individuals are believed to be less efficient in suppressing cortical noises than neurotypical individuals [8]. This means that, even when the external noises are held constant, the mental representation of the same stimulus would be more varied in ASD brains than in neurotypical brains. Since neurotypical individuals can better differentiate between real prediction errors and prediction errors caused by external and internal noises, they can assign proper precision values and decide the correct timing to update their predictions. Therefore, based on the inflexible prediction error weighing view, the neurotypical population is always expected to produce less varied and more accurate predictions whereas the ASD population is always expected to produce more varied and less accurate predictions.

However, in opposition to the expectation of this view, the current evidence shows no differences in the handling of prediction errors in the ASD and neurotypical populations. In one study where both the ASD and the neurotypical groups were asked to lift some objects, prediction errors were created by violating previous estimations of object weights based on their sizes [9]. However, the results found no difference between the fingertip lifting forces exerted by both groups [9]. Likewise, in another study where both groups were asked to reproduce the force exerted on their index fingers to their subjective equivalence, prediction errors were created by a tiny discrepancy between the aimed force intensity and the actual self-generated force intensity [10]. Again, there was no difference between the pressing forces regenerated by both groups. Hence, neurotypical individuals seem to be no better at filtering out (internal) noises than ASD individuals.

Yet, it is suggested to not rush to denial of this view considering both the sample size of the papers reviewed and the potential value it may have in explaining variations in sensorimotor responses in the ASD population. In many studies, the sensorimotor data profiles of ASD groups are consistently more varied than the neurotypical groups. For example, among the studies reviewed here in this paper, ASD groups showed more variations in the endpoint predictions in the ball interception study and the finger interception data in the force reproduction study [7, 10]. However, vast variations in sensorimotor responses reveal not only in the unit of groups but also within the same individual. One of the characteristic symptoms of ASD is hyper- or hypo-reactivity to the stimulus [1]. These can be explained by atypical precision value assignment towards signal and noise by the prediction error view. Specifically, in hyper-reactivity, meaningful signals are assigned abnormally high precision values, which drives ASD individuals to pay excessive attention to upcoming sensory details and respond radically to them. Conversely, in hypo-reactivity, signals receive extremely low precision values and deficient amounts of attention, leading to retarded adjustment of self-behaviours.

### **2.3 The Role of Anxiety in the Predictive Process**

Interestingly, the current review indicates some relationship between elevated levels of anxiety in ASD individuals and the Bayesian prediction process. In ASD children, the parent-reported anxiety scores were negatively correlated with the probability of using the contextual cues and the probability of predicting the correct action unfolding as the cue-outcome association became stronger [6]. In ASD adults, when the environmental uncertainty increased because of violations of estimated weights, there was an absence of precise and context-sensitive gaze searches between objects which were probably attributable to differences in anxiety [9].

Anxiety could be an influential moderator in the predictive process. On the one hand, emotional surprises caused by prediction errors in the lower-level areas can inhibit top-down attention which is crucial to the comprehension of sensory data [5]. On the other hand, anxiety could change the subjective confidence towards the correct memory, which could potentially change the shape of the probabilistic distribution of the Bayesian prior [11]. Currently, there has been a lack of focus on the emotional factors and their potential influence on the Bayesian Inferential process. In fact, whether a test paradigm is complex enough to trigger anxiety in ASD participants could confound some of the

insignificant results in the existing literature. For example, some experimenters operationalized priors as the short-term memory of a simple pattern (e.g., the stimulus was always presented at the right of the screen) learnt during the familiarity session and expected ASD groups to be less biased by this pattern in later test trials. While it could be that the ASD population is only impaired on a subtype of priors (like what has been discussed previously), it could also be that paradigms like this do not expose ASD participants to enough novelty and uncertainty where anxiety arises.

### **3. The Bayesian and Inflexible Prediction Error Weighing Views in Neuroscience of Autism**

One of the most influential models of the neuroscience of ASD postulates that the increase of the E/I ratio in the major brain circuits (e.g., sensory, emotional, mnemonic) is the neurological cause of ASD [12]. The idea is that a balance between neural excitation and inhibition is required for the proper functioning of the brain. In order to prevent over-excitation of one area, the marginal areas have to send inhibitory signals to quiet it down. However, because it was observed that inhibitory signals in the ASD brains are reduced, excessive neural excitations occur frequently in the ASD neural circuits and create louder neural noises [12]. Proper neural inhibition could enhance the neural representation of useful signals and promote goal-directed behaviours [12, 13]. Conversely, insufficient neural inhibition not only makes the ASD brains unable to selectively enhance the representation of meaningful signals but also makes normal signal communication in the ASD brains to be frequently disrupted by irrelevant noises. Thus, both the sensory and social interactive symptoms are believed to result from insufficient cortical inhibitions that disturb the E/I ratio balance in the relevant circuits.

Increased E/I ratio suggests atypical functional and structural connectivity, which might be the neural mechanism underlying reduced Bayesian prior. A brief revisit of the definition of Bayesian prior indicates that it is the top-down information that needs to be communicated from the higher-level areas through interareal neural conduits to lower-level areas. For the communications of Bayesian priors to occur, two areas must activate synchronously and send top-down signals through the interconnected neuronal pathways within the same timeframe so that they can stand out from the cortical background and "shout out loud" to one another. Conversely, insufficient interareal communication and structural connections would be revealed by increased areal asynchrony in which case top-down signals from the two areas could not be temporally bound together, leading to attenuated influence of priors and severe impairments in sensorimotor coordination. Consistent with the expectation, recent brain imaging studies showed that the ASD population had more asynchronous activations between the visual and motor cortical areas, with more intense asynchrony predicting worse performance in motor tasks [14].

In terms of the prediction error view, the imbalanced E/I ratio is particularly in line with it because a noisier cortical environment shows an inability to properly filter out noises.

Since prediction errors that should be ignored are weighed heavily, every observation comes to ASD individuals as new learning, making their predictions especially prone to inherent environmental noises. In consequence, there should be more cortical representations of noises expressed as excessive neural excitation in ASD brains. However, recent studies seem to suggest a much more complicated picture: BOLD activities of both groups during a simple sensory task showed no difference in transient responses in presence of the stimuli, which suggests no expected difference in the cortical representations [15]. But after the stimuli disappeared from eyesight, the ASD group showed an absence of undershoot in BOLD activity which is still thought of as relating to cortical inhibition but through a mechanism other than GABAergic neurons [15].

While the notion of E/I ration imbalance remains popular in the field, it is important to keep in mind its deficiency: the E/I ratio is an overly simplified and static model of neural activities which ignores the temporal and spatial complexity of brain events. The vast variations of ASD symptoms over the spectrum probably suggest that this ratio is not generalizable to the global brain or across a full temporal scale. Nevertheless, despite the mixed results on the E/I ratio imbalance theory, the

current field still agrees that ASD individuals experience some sort of impairments in cortical inhibition, which underlies the diagnostic symptoms of autism.

#### 4. Conclusion

The present review paper examined the credibility of the Bayesian view and the prediction error view of autism in the context of recently published empirical and neuroscientific evidence on sensorimotor predictions. Overall, current evidence is consistent with the reduced prior but not the high weighing of prediction error. Specifically, the ASD population is reluctant to draw on reliable contextual priors even though their associative learning may remain intact. And the increased E/I ratio is in keeping with the reduced prior proposal by revealing atypical interareal connectivity. In addition, the review also suggests that anxiety probably moderates the Bayesian inferential process.

One possible limitation is that this paper primarily focuses on the evidence in sensorimotor processing and one might be cautious to generalize the conclusions to the domain of social impairments. With that being said, this paper provides some guidance in the experimental design and general directions for future studies. First, future studies should aim at specifying the taxonomy of priors and whether the influence of different kinds of priors is attenuated to different degrees in autism. Second, future studies should also keep in mind that the E/I ratio is more likely a temporal rather than a permanent disturbance and restrict the theory to certain brain circuits or temporal stages. Third, future studies should explore the role of anxiety in moderating the Bayesian prediction in ASD. In addition, they should also be aware that ASD individuals should be involved in the active use of context to create meanings in the experimental design.

The present review has important implications for promoting sensorimotor learning outcomes in autism. Since many ASD individuals are not impaired in learning action association, they are able to build their own repertoires of internal action models but have problems with applying the models according to contexts. Therefore, educators should avoid passive demonstrations of a sensory or motor skill independent of its context. Rather, they should try to replicate the environment where the skill typically happens and encourage synchronous imitations of the skill in that environment. Through context-dependent imitations, the predictive value of context can be enhanced in the ASD predictive system, which better helps ASD individuals to connect what they have learned to the outside world. This review can provide some guidance for future intervention research in ASD.

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