Aus der Klinik für Psychiatrie und Psychotherapie der Ludwig-Maximilians-Universität
München

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Time Processing and Predictive Coding in Autism Spectrum Disorder

Dissertation
zum Erwerb des Doktorgrades der Medizin
an der Medizinischen Fakultät der
Ludwig-Maximilians-Universität München

vorgelegt von

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aus
Bad Homburg v.d.H.

Jahr
2022

Mit Genehmigung der Medizinischen Fakultät der
Ludwig-Maximilians-Universität zu München

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Dekan:	Prof. Dr. med. Thomas Gudermann
Tag der mündlichen Prüfung:	27.10.2022

‘It may often be rather hard to say how much of our apperceptions as derived by the sense of sight is due directly to sensation, and how much of them, on the other hand, is due to experience and training’

Hermann von Helmholtz (1866, v. 3, 10)

Table of Contents

I Abstract

Attenuated use of prior knowledge (predictive coding; in the context of the Bayesian framework) in some daily activities and more reliance on sensory evidence has often been demonstrated by individuals with Autism-Spectrum-Disorder (ASD)(Lawson, Rees, & Friston, 2014; Pellicano & Burr, 2012). This downweighing of prior beliefs may interfere and cause challenges when it comes to predicting future events and social motives. As impairments in social interaction and communication (American Psychiatric Association, 2013) provide the conditions for establishing a diagnosis of ASD, decreased sensitivity for temporal intervals (Falter, Noreika, Wearden, & Bailey, 2012) has also been associated with ASD, the reason for which is still unknown. Being aware of temporal (minute) changes in their environment has been described as one characteristic in both children and adults with ASD which are often unnoticed by their peers. This has been formally investigated by embedded figures tests (Muth, Hönekopp, & Falter, 2014; A Shah & Firth, 1983), also with typical feature search and conjunction search tasks (Kaldy, Giserman, Carter, & Blaser, 2016; Plaisted, O'Riordan, & Baron-Cohen, 1998).

Recently researchers have investigated predictive coding frameworks with time perception in ASD using the classical central tendency effect (Karaminis et al., 2016), a typical perceptual bias coming from integration of prior knowledge of sampled interval range with the sensory input (Jazayeri & Shadlen, 2010; Shi, Church, & Meck, 2013). Often shorter durations are overestimated, and longer duration underestimated, defined as the central tendency effect. Karaminis et al. (2016) found that ASD performed much worse in temporal discrimination tasks than their matched controls, and demonstrated a decreased central tendency in ASD than predicted. Recently it has been shown that the central tendency effect relies upon the volatility of the sequence (Glasauer & Shi, 2018). To date, it is not clear how volatility influences time perception in ASD.

Thus, the aim of this dissertation is to investigate the relevance of prior belief generation for interval timing in ASD using a duration reproduction task manipulating prior information on a trial-to-trial basis. We hypothesised that if individuals with ASD show less reliance on prior knowledge, the reproduction in the volatile (random) and involatile (random walk) environments should have less difference in the ASD group than in the typically developed (TD) control group. We found that the TD group adapts to a different environment more quickly and is influenced by the prior belief of that environment accordingly. By contrast, ASD individuals focused more on the sensory input, but were less influenced by prior knowledge of the environment, resulting in less flexibility in coping with the environment.

II Abstract (German)

In neueren Studien wurde gezeigt dass Personen, welche mit einer Autismus-Spektrum-Störung (ASS) diagnostiziert worden sind, sich in manchen täglichen Aktivitäten vermindert auf die eigenen Vorkenntnisse verlassen (prädiktive Kodierung; im Kontext des Bayesian Systems) und mehr Gewicht auf sensorische Reize der Umwelt legen (Lawson et al., 2014; Pellicano & Burr, 2012). Diese verminderte Wertung der eigenen Vorerfahrungen kann potentiell die Vorhersage zukünftiger Ereignisse und die Deutung sozialer Motive beeinflussen und limitieren. Obwohl ASS häufig mit verringerten sozialen und kommunikativen Kompetenzen einhergeht und diagnostiziert wird (American Psychiatric Association, 2013), wird zudem auch eine verminderte Sensitivität für die zeitliche Wahrnehmung, vor allem von zeitlichen Intervallen beobachtet (Falter, Noreika, Wearden, & Bailey, 2012). Der Grund hierfür ist bislang unklar.

Ein charakteristisches Phänomen, welches bei jüngeren autistischen Kindern und Erwachsenen beobachtet werden konnte, ist eine erhöhte Empfindlichkeit für kleineste Veränderungen ihrer Umgebung, welche bei gleichaltrigen ‚neurotypisch' entwickelten Probanden unbemerkt blieben. Dies wurde formell durch den ‚Embedded figure test'(Muth et al., 2014) und später ebenfalls durch simple und komplexere visuelle ‚Such-Tests' festgestellt (Kaldy et al., 2016; Plaisted et al., 1998).

Kürzlich haben Forscher das 'predictive coding' Prinzip im Kontext der Zeitwahrnehmung bei ASS unter Verwendung des klassischen zentralen Tendenzeffekts untersucht (Karaminis et al., 2016). Dies ist eine Wahrnehmungsverzerrung, die sich aus der Integration des eigenen Vorwissens über den gebotenen Intervallbereich mit den sensorischen Reizen ergibt (Jazayeri & Shadlen, 2010; Shi, Church, & Meck, 2013). Oft wird die kurze Dauer überschätzt und die lange Dauer unterschätzt, was als zentraler Tendenzeffekt bekannt ist. Karaminis et al. (2016) stellten fest, dass die ASS-Gruppe bei der zeitlichen Diskriminierung weitaus schlechter abschnitt als die Kontrollgruppe und dass die zentrale Tendenz bei ASS viel geringer war als durch theoretische Modelle vorhergesagt. Kürzlich wurde gezeigt, dass der zentrale Tendenzeffekt von der Flüchtigkeit der Sequenz abhängt (Glasauer & Shi, 2018). Derzeit ist jedoch nicht klar, wie sich die Volatilität auf die Zeitwahrnehmung bei ASS auswirkt.

Das Ziel dieser Dissertation ist es, die Relevanz der Bedienung eigener Vorkenntnisse in Bezug zur Wahrnehmung zeitlicher Intervalle mithilfe einer zeitlichen Reproduktionsaufgabe zu untersuchen. Dabei werden frühere Informationen von Versuch zu Versuch manipuliert. Unserer Hypothese nach sollten Individuen mit einer Autismus-Spektrum-Störung, welche vermindert auf Vorkenntnisse angewiesen sind und diese anwenden, ebenfalls weniger Unterschiede in der zeitlichen Reproduktionsaufgabe in unbeständigen (‚random' Sequenz) und in beständigen (‚random walk' Sequenz) Umgebungen aufweisen im Vergleich zu den ‚neurotypisch' entwickelten Individuen der Kontrollgruppe (TD Gruppe).

Unsere Ergebnisse zeigten eine schnellere Anpassung der TD Gruppe an neue Umgebungen, mit einer entsprechenden Beeinflussung der Vorkenntnisse aus dieser. Im Vergleich dazu fokussierte sich die ASS-Gruppe stärker auf sensorische Reize und wurde vermindert von den eigenen Vorkenntnissen über die Umwelt beeinflusst. Folglich zeigt dies eine herabgesetzte Flexibilität bei der Informationsbewältigung von den Reizen aus der Umgebung.

III List of Figures

IV List of Tables

V List of Abbreviations

A

ADI-R .... Autism Diagnostic Interview-Revised

ADOS-G .... Autism Diagnostic Observation Schedule-Generic

ANOVA .... Analysis of Variance

AQ .... Austism-Spectrum Quotient

ASD .... Autism Spectrum Disorder

D

DSM-V .... Diagnostic and Statistical Manual of Mental Disorders

E

EF .... Executive Functioning

EQ .... Empathy Quotient

E-S .... Empathizing-Systemising

I

ICD-10 .... International Classification of Diseases

INT .... Interpolation

L

LUT .... Lookup-table

M

MEG .... Magnetoencephalography

R

RWalk .... Random Walk Sequence

S

SES .... Socioeconomic Status

SQ .... Systemising Quotient

T

TD .... Typically Developed

ToM .... Theory of Mind

W

WCC .... Weak Central Coherence

WHO .... World Health Organization

1 Introduction

1.1 Background

Autism spectrum disorder (ASD) is a combination of several diverse developmental characteristics involving symptoms in social interactions, verbal and nonverbal communication, repetitive and stereotypical behaviour (American Psychiatric Association, 2013; Lieder et al., 2019; Mughal & Saadabadi, 2007; Wing & Gould, 1979). Individuals with ASD, in comparison to typically developed (TD) individuals, often find it more difficult to adapt to situations with overwhelming sensory stimulation (Crane, Goddard, & Pring, 2009; Leekam, Nieto, Libby, Wing, & Gould, 2007; Tomchek & Dunn, 2007). That unusual sensory processing may be causative for some autistic symptoms has recently been shown by an increasing body of evidence (Mottron, Dawson, Soulières, Hubert, & Burack, 2006; Simmons et al., 2009). In particular, several studies report connections between abnormal visual sensory processing and symptom severity (Bodgashina, 2016; Falter, Elliott, & Bailey, 2012). Furthermore, difficulties in predicting future events or having knowledge about past events and accordingly understanding time flow are known to be common in ASD (Allman, 2009; Boucher, 2001; Yu & Dayan, 2005). A decreased sense of time and time perception may be an obstacle when it comes to adapting to recurring situations and, as already mentioned, predicting future events (Allman & DeLeon, 2009).

Our perception is not purely driven by the given sensory information one receives, but is also heavily influenced by previous internal knowledge (Sciutti, Burr, Saracco, Sandini, & Gori, 2014). As early as 1867, Hermann von Helmholtz (1867) introduced the concept of unconscious inference (German: *unbewusster Schluss*). A hypothesis of visual perception, explaining that perception is not only determined by sensation alone but is also mediated by cognitive, sociocultural expectations and internal representations in order to form a complete picture. In uncertain situations the combination of new sensory and ambiguous information with previous experiences (e.g., *priors*) helps the brain to minimise overall noise and produce accurate judgements. Both Helmholtz's concept of 'perception as inference' and the hypothesis of Bernard Rimland[1] (1964), who stated that drawing a connection between new and old experiences is challenging in ASD have been renewed and updated by the 'Bayesian brain' theory and the predictive coding framework. Both theories share the idea of prediction error minimization through hierarchical neuronal levels of Bayesian inference in order to constantly reduce the occurring error of predictions of the sensory information the brain receives from the world (Friston, 2010; Hohwy, 2013). In other words, only the information that has induced a mismatch to preformed prediction (i.e., prediction errors) is useful and is being processed. Throughout the years of clinical research on ASD theories have been updated by adapting the Bayesian account and predictive coding framework in order to potentially explain autistic symptoms (Friston, 2010; Friston & Kiebel, 2009). The framework suggests that humans constantly form and update predictions on cerebral levels about perceived environmental sensory stimuli based on the individual's prior knowledge. Discrepancies between the physical environment (i.e., the actual sensory input) and expectations (i.e., the top-down prediction) – a so-called prediction error – are attempted to be reduced by integrating (top-down) previous knowledge and the incoming new information generated by the senses. The integration is effectively formed by the brain through generating an internal generative model by weighing the precision of each occurring prediction error.

[1] *Bernard Rimland (*1928 - †2006) was an American psychologist who supported controversial treatments and theories about the causes of autism, nevertheless he was known to be an influential researcher in the field of developmental disorders.

In a noisy, volatile environment prediction errors from sensory input are weighted with low precision and are not a reliable source of information. Contrary to this, in a stable environment the arising error indicates a serious prediction mismatch and thus, should be weighted as being high in precision. Through experience an individual learns how much weight should be given to certain inputs and predictive errors with an according precision and consequently mirrors the individual association with such inputs with decisions made in the past. The individual weighting for recent or past events reflects the person's learning curve (Dayan, Kakade, & Read Montague, 2000).

Indeed, individuals with ASD have been suggested to have broader priors, meaning that they rely more heavily on sensory evidence when interpreting stimuli (Lawson, Rees, & Friston, 2014b; Pellicano & Burr, 2012). Suppression of prior information can potentially account for a variety of autistic symptoms, such as impaired prediction of future events and interpretation of social behaviour. In this dissertation I will discuss whether relying less on prior knowledge – as a described tendency of individuals with ASD in comparison to TD individuals – would also be effective for perceptual decisions in time estimation and reproduction and the influence of volatility on abnormal patterns of interval timing in ASD.

To obtain a better understanding of existing research and state-of-the-art research on this subject, I will first give an overview on the history and development of ASD and then the classification will be briefly explored in the following subsections. Additionally, I will summarise the state of research on ASD with a focus on behavioural segmentations and neuropsychological models that aim to explain differences witnessed in ASD. Lastly, I am going to review temporal perception and the peculiarities in ASD, closing with a philosophical point of view.

1.1.1 History and Development

In 1911, the swiss psychiatrist Euger Bleuler (*1857 - †1939) introduced the term 'autism' in the framework of his studies on schizophrenia as 'a detachment from reality and a withdrawal in one's inner life' (Bleuler, 1911). Leo Kanner (*1896 - †1981), a Jewish Austrian-American child psychiatrist and one of the pioneers in the history and development of ASD as a condition, redefined the term 'autism' in 1943 using the term to define bizarre behavioural similarities in young children (aged three years and under) and called it 'early infantile autism' (ICD 10: F84.0). Kanner and Leon Eisenberg, an American child psychiatrist (*1922 - †2009), introduced five diagnostic characteristics describing the abnormal behaviour of children (Kanner, 1943; Kanner & Eisenberg, 1954; Wing, 1991).

In 1943, Hans Asperger (*1906 – †1980), an Austrian paediatrician, defined 'Asperger's syndrome' (ICD 10: F84.5) as "autistic psychopathy" (Asperger, 1938) in a published study in which individuals were presumed to suffer from specific autistic traits. Earlier in 1938, he considered a group of children that he observed with special characteristics as "autistic psychopaths" (Asperger, 1938). Asperger portrayed autistic children to have similarities and characteristics like adults, however, he explained that the children nevertheless had mental developmental deficits and 'retardation' (Frith, 1991). He describes the observed problems of social interaction as the result of the children's 'physical appearance, expressive functions and (…) their whole behaviour' (Frith, 1991, p. 37) being so severe 'that they overshadow

everything else, (Frith, 1991, p. 37). However, in his observation he discovered an ability to compensate, leading to a fulfilment of social pressure and achieving social roles during their development. Nevertheless, Asperger stressed the importance of guidance, commitment and education for these children.
The ability to express themselves (e.g., through words, eye contact, gesture, voice quality or non-verbal communication) is poorly developed in autistic children, according to Asperger. He highlighted that their movements are of a stereotypic nature, rather than having a revealing, interactive worth (Frith, 1991, p. 69). His clinical picture contained differences compared to TD peers regarding speech, non-verbal communication, social interaction, motor coordination, skills and interests (Wing, 1981).
Kanner and Asperger are known as for their pioneering studies on autistic children, however little attention has been given to Grunya Efimovna Sukhareva. Sukhareva (*1891 – †1981) was a female Jewish Kiev-based child psychiatrist and first published a research paper in 1926 which considered the autistic traits witnessed in a children, a study which was undertaken years before Kanner and Asperger (Manouilenko & Bejerot, 2015). In her initial paper she described the children's' traits as a form of "schizoid (eccentric) psychopathy" but replaced it with "autistic (pathological avoidant) psychopathy" (Manouilenko & Bejerot, 2015, p. 1) making Sukhareva the original, though overlooked, pioneer of research on the disorder. In her early detailed descriptions published in a scientific German journal, the clinical picture she drew of autistic traits in children resembles today's DSM-V descriptions (Sukhareva, 1926; Wolff & Ssucharewa, 1996). Not only did Sukhareva report on symptoms such as a lack of facial expressiveness, impulsive, odd behaviour and motor dysfunctions, but she also observed enhanced levels of intelligence.

Concerning linguistics, *autos* a Greek word for 'self', explains the origin of the name 'autism'. This means an impaired and solitary interaction with the environment in which an autistic individual is not constantly influenced by the inputs coming from their surroundings and, therefore, is limited in social interactions and has a disturbed relationship with their environment.
In his studies Asperger describes an extraordinary focus and interest for certain areas (e.g., fascination and memory of numbers or calculating) which indicated that children had higher levels of intelligence and/or special areas of high performance. However, often lacking the comprehension of the underlying meaning of the given task (Wing, 1981). These areas of interest had a significant impact on both Kanner and Asperger and revealed *isolated special abilities*. Throughout the years a few new autistic traits have been observed and collected to be part of the characteristics and diagnosis.

Among their work, they all introduced impairments in social interaction as a major characteristic in early infantile ASD. These impairments include the lack of interpreting and understanding other people's feelings, needs and intentions and behaving in a corresponding inappropriate manner. Kanner, moreover, described an intense desire for 'aloneness', portraying the children to be in peace when they were left alone (Kanner, 1943; Matson & Minshawi, 2006). Furthermore, an appeal for sameness and a repetition of activities in their daily routine, such as organizing items, fixation on objects, having routines and rituals in everyday procedures or in movements (e.g., finger/foot tapping, body rocking) has been shown to be common in his observed group of children. A third characteristic is the allure for certain objects and playing with them in an atypical way (e.g., lining up or flipping items) that was not commonly seen in other children. Kanner also observed an impairment of comprehension of language and the ability to interpret phrases or jokes. The children he observed were likely to understand language literally and they could not make sense of a metaphorical meaning of speech (Kanner, 1943). In order to have a full understanding of a situation they required brief, basic words and sentences. Some children tended to create new words and abstruse, nested sentences. Mutism was also often seen as an autistic trait. Lastly, the islets of ability embody the fifth feature. They are a special quality of skills children adapt early on, such as memory for music, numbers or a precise perspective. In 1956, Kanner and Eisenberg identified two key characteristics of the condition: the lack of emotional contact and interaction with other people and the desire for sameness (Eisenberg & Kanner, 1956).

1.1.2 Classification

According to the *World Health Organization* (WHO), 'Autism-Spectrum-Disorder' is classified as a Developmental Disorder in the international classification of diseases – version 10 – (ICD-10)(World Health Organization, 1993). Furthermore, in the U.S. the *Diagnostic and Statistical Manual* (DSM, American Psychiatric Association, 2013), a handbook for psychiatry, is used to compare symptoms and make diagnoses, describing the diagnoses of behavioural, mental and developmental disorders (American Psychiatric Association, 2013). Both diagnostic manuals provide relevant classification systems while the WHO classification is used internationally and the DSM is referenced more frequently in the United States. ASD can be diagnosed at any age, however signs and symptoms are often first seen in the early ages of life. Research data from the *Centre for Disease Control and Prevention* states that among 8-old children the likelihood of being born within the autism spectrum is 1:54 (in the United States of America in 2016, currently there is no data for Germany)(Maenner et al., 2020). ASD is 4.3 times more common amongst the male population and the diagnosis appears in all ethnicities and social groups (Christensen et al., 2016; Maenner et al., 2020).

1.2 The Learning-Style Theory and the Predictive Coding Account

Decisions made about new information are presumed to depend on the environmental circumstances and are further influenced by decisions made in the past presenting a similar feature of the current state (Behrens, Woolrich, Walton, & Rushworth, 2007; O'Reilly, 2013; Summerfield & Tsetsos, 2015). In order to achieve better performance TD individuals can determine how much importance new information and situations have depending on the individuals learning rate (Dayan et al., 2000; Manning, Kilner, Neil, Karaminis, & Pellicano, 2017). Behrens et al. (2007) have shown that in a stable environment, TD individuals demonstrated a low learning scale, that is that in situations that do not show a changing and volatile environment, the history and extended experience of outcomes reflect the prediction of the future more accurately, thus the learning rate must not adapt. As opposed to that in a more volatile environment TD individuals demonstrated a higher learning rate, taking more consideration of recent incidences as they influence the current circumstances leading to a modification of their behaviour. One hypothesis concerning ASD is that autistic individuals do not demonstrate a frequently updated prediction about the environmental circumstances in response to volatility, thus they are more biased towards recent incidences (Pellicano & Burr, 2012; van de Cruys, Evers, van der Hallen, van Eylen, Boets, de-Wit, et al., 2014). However, there have been some contrasting findings in the literature as shown by Manning et al. (2017) who discovered that autistic children where indeed able to interpret recent history outcomes. Furthermore, autistic children updated their current state and predictions according to a volatile environment in the same way as TD individuals. When it comes to Bayesian accounts and the predictive coding framework, the authors state that the accounts can be employed to explain atypical sensation and perception in ASD, however, one must take a critical look at employing them to explain learning mechanisms.

Learning in ASD has often been described as a different, atypical categorical way of learning, characterized by its slower and less context-dependent (hence, more local) nature compare to TD individuals (Alderson-Day & McGonigle-Chalmers, 2011; Church, Krauss, Lopata, Toomey, Thomeer, Coutinho, 2010; Dodd, 2005; Morgan & Morgan, 1996; Sapey-Triomphe, Sonié, Hénaff, Mattout, & Schmitz, 2018). A lack of generalisation and noticing a pattern of multiple experienced stimuli has been revealed in several clinical studies (e.g., Froehlich et al., 2012), in which ASD participants had difficulties detecting a hidden order (i.e., context-dependence) in the provided task.
A failure to distinguish connections between provided stimuli in tasks is described in the 'Reduced Generalisation Model' (Plaisted, 2001). This model is an effort to clarify the ASD defining atypical way of learning and perception. The hypothesis is that individuals with ASD, compared to TD individuals, tend to process unique elements well, however, abstracting common elements is less accurate which consequently leads to a deficiency in the recognition of similarities between situations or stimuli. A reduced generalisation between stimuli sharing similar features equals a reduction of importance of these elements (Plaisted, 2015). Plaisted discusses two mechanisms leading to reduced generalization. First, it is *latent inhibition (LI),* a phenomenon suggested by Lubow and Moore (1959). Two presented stimuli sharing common patterns are presented more often and consequently are latently inhibited more than unique feature of the stimuli, consequently a familiar stimulus requires more time than a novel one to gain importance and attention (Lubow, 1973). Secondly, being surrounded by frequently presented stimuli and situations one generates a *habituated* learning mechanism (Thompson & Spencer, 1966). As a consequence, in accordance with the *latent inhibition* leaning mechanism*, habituation* leads to the same phenomenon that presented unique elements are more noticeable than common ones and that *latent inhibition* and *habituation* increase relative to the repeated presented stimuli (Mitchell; Le Pelley, 2010). In conclusion, the 'reduced generalization model' postulates the idea of an inability to understand similarities at an attentional and perceptual level. Thus, attentional and perceptual impairments and abnormalities as a feature of ASD go hand in hand with an impaired ability to generalize and to abstract (Klinger & Dawson, 2001; Minshew & Meyer, 2002.; Plaisted, O'Riordan, & Baron-Cohen, 1998; Ropar & Peebles, 2007). Reduction in generalization may affect perception and it also plays a role in social understanding (Sapey-Triomphe et al., 2018), since social understanding requires learning an appropriate categorization, for example understanding body language such as facial, motor and verbal expressions (Church et al., 2010).

In 2011, Qian and Lipkin introduced two learning concepts: the interpolation (INT) and the *lookup-table* (LUT) (Qian & Lipkin, 2011). The INT learning style mainly focuses on extracting hidden patterns or consistency from a scenario or a social structure to generalize and abstract accordingly. Learned regularities can then be used to generalize new scenarios. By contrast, the LUT learning style focuses on learning each experience individually, without emphasizing it in a global underlying consistency, thus, not generalizing. The LUT style is a good learning technique when it comes to precise, local and individual contexts (such as memorizing numbers or names). According to the authors, TD individuals are more biased to the INT learning style, whereas ASD individuals are more likely to have developed the LUT learning style to adapt to their environmental tasks. However, a precise dedication to and storing of each experience and detail might be inefficient in a noisy, flexible, unpredictable environment (such as real-life situations: e.g., language, gaze and facial expressions and

intentions, movements or interpretation of sensory input). Therefore, in a noisy environment, the INT learning style is a more effective technique for perceiving the environment and being able to categorize and filter new impressions without having a too detailed focus for 'irrelevant' details (Sapey-Triomphe et al., 2018).
Moreover, an impaired filter – an impaired INT learning style – might lead to a sensory overload and flooding of information and noisy environmental stimuli, which in turn generates resistance to new situations and an inability to predict certain scenarios (Grandin, 2006; Qian & Lipkin, 2011).

In an ever-changing world, learning to interact with noisy situations yielding unknown and unpredicted information requires a mapping system. Since most human relations and daily situations are noisy and full of information, the interaction with and the perception of these circumstances requires a learning technique like the INT style in order to generate context dependence and the ability to habituate and to generalise. By memorising specific examples and circumstances autistic people match their memory to the present situation, in order to resolve the lack of generalization (Grandin, 2006; Kanner, 1943; Qian & Lipkin, 2011). As a consequence, a set of restricted behavioural routines and habits is acquired in order to create familiar situations (van de Cruys, Evers, van der Hallen, van Eylen, Boets, de-Wit, et al., 2014). Learning new sets and evolving the old ones might be challenging for ASD individuals. Accordingly, predictive errors based on old environments often lead to surprise, an overload of information and hypersensitivity. This leads to the suppression of stimuli (hypo-sensitivity) and a preference for stable environments (Dawson & Lewy, 1989; Kanner, 1943; Lawson, Mathys, & Rees, 2017; Qian & Lipkin, 2011).
Qian and Lipkin hypothesize that context independence or a deficit in contextual information processing in individuals with ASD causes the broad range of autistic behaviour (American Psychiatric Association, 2013; Leekam, Nieto, Libby, Wing, & Gould, 2007). The authors further regard the compromised stimulus suppression and capability to habituate as a corollary of the LUT learning style and account their theory as an approach for explaining the wide variety of autistic behavioural traits (Qian & Lipkin, 2011).
As previously mentioned, a changing and unstable environment requires the ability to react and respond appropriately to those changes. According to the predictive coding accounts of perception (Friston, 2010; Friston & Kiebel, 2009.; Haker, Schneebeli, & Stephan, 2016), volatility in environmental changes cause a tendency to overlearn about stable or unstable conditions in ASD, resulting in a lack of ability to predict surprising occurring circumstances. This creates an indifference and reduced surprised reaction when expectations are not met in order to build up stable conditions (Lawson et al., 2017). The Bayesian model of learning (i.e., Bayesian framework) originates form Hermann von Helmholtz's (1867) view of perception and unconscious inference. Von Helmholtz argued that ambiguity forms the basis of many impressions and in order to reduce this ambiguity one has to have prior knowledge about these impressions. The term 'unconscious inference' (German: unbewusster Schluss) refers to how our implicit prior knowledge affects what we perceive. Not only information from visual impressions and other sensory organs are adequate to recreate the environment but more importantly, knowledge established by experience plays an additional and crucial role when it comes to cognitive aspects of perception (Helmholtz, 1867).

Learning about volatility requires a constant match and adjustment of new impressions and prior anticipations. In ASD relative to TD individuals, an impaired weighting of prior anticipations compared to new impressions (e.g., sensory input) goes hand in hand with the suggested differences in perception (i.e., a greater focus on detailed environmental aspects without the ability to generalize and seeing the bigger picture by building up meaningful connections) (Friston, Lawson, & Frith, 2013; Lawson et al., 2017, 2014; Palmer, Lawson, &

Hohwy, 2017; Pellicano & Burr, 2012; van de Cruys, Evers, van der Hallen, van Eylen, Boets, De-Wit, et al., 2014). As an individual – TD or ASD – is exposed to an environment with constant omnipresent volatility every new and surprising event and whether to take a certain situation seriously underlies a calculation and combination of prior experiences and prediction of upcoming situations. This balance and value depends on the individual's assumptions about volatility (Lawson et al., 2017). Pellicano and Burr (2012) provided another explanation as to why precision is less modified by prior knowledge and more by sensory input in ASD, referred to as 'hypo-prior' hypothesis, which assumes that priors in ASD are weakened and broader - and, therefore, less reliable when compared to TD individuals. These 'hypo-priors' consequently resolve in a greater reliance on the *bottom-up* sensory input, leading to an enhancement of sensory stimuli. The authors highlight the enhancement of sensory stimuli and conclude that autistic people "tend to perceive the world more accurately" (Pellicano & Burr, 2012, p. 509, in *Trends in Cognitive Sciences*, Vol. 16, No,10.).

An attempt to describe and explain autistic cognition and the perceptual and learning abnormalities was by gaining more knowledge about the differences between autistic and 'typical' functional organisation of the brain and the latter has been described as *predictive coding* (Clark, 2012; Friston, 2005; Friston & Kiebel, 2009; Haker et al., 2016). Applying predictive coding and the 'Bayesian model of learning' offers an approach in computational models for experimental studies on autistic research and might cast more light on understanding the diagnosis (Haker et al., 2016).

According to Bayesian inference, the brain is able to form predictions about future events and create a learning style by constantly matching incoming *bottom-up* new sensory input with *top-down* prior assumptions or experiences (Mumford, 1992). This hierarchical model describes how *top-down* cues and *bottom-up* prediction errors are resolved in hierarchical cortical areas in the brain (Efron & Morris, 1973; Friston & Kiebel, 2009). All hierarchical levels match their information and predictions until the prediction errors are minimised (i.e., the discrepancy between the predicted and sensory input, inducing a surprise reaction)(Friston, 2005; Rao & Ballard, 1999).

In order to decrease prediction errors, cortical processing has to have a precise working Bayesian hierarchical structure model (Friston, 2002, 2003; Haker et al., 2016). Errors that are due to noisy, volatile sensory stimuli are presumed to have low precision and a low effect on the representations in the hierarchical structure since they are less informative. On the other hand, a prior that emerges to be highly precise will be less suppressed and will have greater impact on the sensory inputs, since it contains greater evidence about an internal mismatch and thus has a greater input on predictions (Friston, 2002, 2003).

Prediction errors are presumed to be less precise in ASD compared to TD individuals resulting in a disbalance of weighting sensory input and prior beliefs (Haker et al., 2016; Lawson et al., 2014). Haker et al. addressed the 'Bayesian brain', in which new sensory input (*likelihood)* updates a prior belief into a posterior belief. A combination and balance of *bottom-up* and *top-down* aspects result in a new revised version of predicting future events. In case of disbalance, the posterior belief can either be dominated by the prior belief or, as in most cases of ASD, by the sensory input. Minimising prediction errors – and, therefore, surprise – is a key feature in the 'Bayesian brain' theory and can either be generated by learning or by action. Essentially, not every sensory input has a significant impact on neuronal processing when it comes to real-life situations. This uncertainty could lead to an overload and over-updating of sensory noisy input, highlighting the importance of a balance between knowledge about uncertainty of the sensory input and uncertainty of the prior belief. Otherwise, the disbalance results in the predicament of identifying the difference between informative and irrelevant inputs and environmental changes, which is typical in ASD (Haker et al., 2016).

As will be discussed in the following chapter (1.3 The Weak Central Coherence Account), ASD individuals often rely excessively on small details, such as changes in timing and situations, developing a feeling of uncertainty (Haker et al., 2016; Pellicano & Burr, 2012). As a result, they are drawn to stable environments, that embrace knowledge and preparedness about the outcome without prediction errors.

1.3 The Weak Central Coherence Account

Individuals with ASD are able to notice minimal changes in their environment and often focus more on local, detailed perceptual irregularities (Frith & Happe, 2006; Kanner, 1943; Plaisted, 2001). As mentioned in Chapter 1.2, this detail-focussed processing structure, which is common in ASD, might lead to an inability to generalise and to extract a global meaning from sensory inputs and the environment resulting in perceptual and behavioural differences compared to TD individuals (Klinger & Dawson, 2001; Minshew et al., 2002; Plaisted et al., 1998; Plaisted, Swettenham, & Rees, 1999; Ropar & Peebles, 2007). Kanner described this detail-focus in his earlier studies from an observation of a mother of an autistic child: "On one of the bookshelves, we had three pieces in a certain arrangement. When this was changed, he always rearranged it in the old pattern" (Kanner, 1943, 1973, p. 9; Plaisted, 2001). In 1989, Uta Frith examined the 'Weak Central Coherence' (WCC) theory. Frith stated that weak coherence is the central cause of impairments in social understanding (e.g., 'theory of mind') in ASD, as individuals with ASD cannot comprehend holistic and contextual stimuli (Frith, 1989).
Central coherence is the ability to extract knowledge and meaningful connections out of details in order to comprehend the larger context (Frith & Happe, 2006). The original idea of a deficit in a global understanding of aspects and a tendency towards a local focus leading to social and cognitive deficits has been shifted to the idea of a superior processing of details. This *deficit* is also rather now seen as a preference or talent in precise perception. Additionally, it is suggested that weak coherence is not the origin of untypicalities in ASD, but rather an independent cofactor of the syndrome and, thus, enhances already existing social abnormalities. Moreover, Frith and Happé argue that often a *local coherence* is sufficient enough to solve the task by linking one item to the next (Frith & Happe, 2006). Today, the local bias is no longer considered to be the direct result of a global deficit, ultimately it does not even have to coexist (Mottron, Burack, Iarocci, Belleville, & Enns, 2003).

In studies conducting the 'Embedded Figures Task' autistic participants succeeded with speed and accuracy in spotting hidden forms among a larger meaningful figure (Jolliffe & Baron-Cohen, 1997; A Shah & Firth, 1983). The 'Group Embedded Figures Test' was designed in 1971 by Witkin and colleagues and pictures from Gottschaldt, a German psychologist and pioneer in the *gestalt psychology and theory*, were attached (Gottschaldt, 1926). The test contains 18 manifold elements and figures which the participant has use to identify a simple underlying form in order to resist the overall *gestalt.* The figure the participant has to identify contains some elements that are corresponding to the overall picture and some that are unique to the target element (Witkin, Oltman, Raskin, & Karp, 1971). It has been shown that individuals with ASD, in reference to the WCC, rely on a more detail-focussed perception and therefore have a superior performance in the test, as they see segments rather than the full picture (Frith & Happe, 1994; Jolliffe & Baron-Cohen, 1997; Shah & Frith, 1993).

Another empirical evidence is the *Block Design* test, a subset of the Wechsler Intelligence Scales (Wechsler, 1949, 1981). Here, a superior performance of ASD participants has also been observed in comparison to control participants. Participants have to match and rearrange segments in order to create a pattern, adjusted from the original test invented by Samuel Calmin Kohs in 1923 at the Stanford University (Hutt, 1932; Kohs, 1923). Not only does the test aim to indicate visuo-spatial abilities of the participant, but also the speed and accuracy of ASD participants (Caron, Mottron, Berthiaume, & Dawson, 2006; Groth-Marnat & Teal, 2000; A Shah, 1988). As a consequence, these test results can serve to emphasize the framework of the WCC in ASD.
Importantly, it has been demonstrated that participants with high-functioning ASD do not show local preferences on certain tasks, such as visual spatial processing (Burnette et al., 2005) and consequently is not an overall aspect in ASD. Nevertheless, a weak central coherence in young autistic children may contribute to impaired social skills and social cognitive skills and thus leads to dysfunctions in the *theory of mind*. Therefore, the WCC may indirectly be linked and account for crucial aspects of autistic symptoms and the extent to which they affect the triad of social, communication and imagination and in non-social impairments.

1.4 Theory of Mind

Being able to predict the behaviour of someone else and to represent foreign cognitive mental states in one's own cognitive system is called the *theory of mind (ToM)* (Leslie, 1987; Leslie & Frith, 1988; Woodruff & Premack, 1987). During a child's development, between the ages of three and five years, the child acquires the skill to emphasize with another human being and to acknowledge another one's beliefs and mental state. Predicting another individual's behaviour is a key feature of the *theory of mind* (see pioneers Simon Baron-Cohen, Leslie, & Frith, 1985; Wimmer & Perner, 1983). Furthermore, pretend play is an early manifestation of the ability to acquire mental state expressions and to influence one's own and other people's beliefs about information of the environment (Leslie, 1987; Piaget, 1962). Therefore, a number of authors have addressed the connection between pretend play and the *ToM* and have seen severe impairments in ASD (Baron-Cohen, 1987; Baron-Cohen et al., 1985; Baron-Cohen, Leslie, & Frith, 1986; Kanner, 1943, 1971; Leslie, 1987; Wing, Gould, Yeates, & Brierley, 1977). Without these abilities, impairments and problems in social interaction might arise as often noticed in individuals with ASD. In studies, participants with ASD fail in experiments that require a *ToM,* therefore the assumption of a deficit in individuals with ASD is substantiated (Baron-Cohen, 1995; Baron-Cohen, Leslie, & Frith, 1985). However, in other studies the development of some skills of a *ToM* to meet the surrounding requirements has been suggested in children with ASD (Baron-Cohen et al., 1985; Tager-Flusberg et al., 1994).

Higher-order theories of consciousness suggest that a *ToM* embodies perception of so-called first-order and second-order mental states (Carruthers, 1989; Rosenthal, 1986; Tager-Flusberg et al., 1994). The theory of first-order mental states which is developed approximately around the age of 4 years (Wimmer & Perner, 1985), represent knowledge about another person's beliefs and perception in relation to the environment. Second-order mental states, developed around the age of approximately 6/7 years (Wimmer & Perner, 1985), on the other hand, imply another person's beliefs about another individual's perception about reality (i.e., beliefs about beliefs (Dennett, 1978). Younger children, around the age of two to three years, do not pass the *false-belief* test (see *Figure 1.*), as they do not comprehend the fact that different people do not share the same belief about certain situations (i.e., they are not able to reach

second-order mental states) (Baron-Cohen et al., 1985). In Baron-Cohen et al.'s study 80% of children with ASD (mean age 11 years) failed the *false-belief* task. This implies their deficit in predicting another person's beliefs and how it may differ from their own belief. Importantly, this way of thinking requires a more complex understanding of social behaviour (Tager-Flusberg et al., 1994).
In further experimental studies ASD participants revealed difficulties in answering first- and second-order tasks. However, some participants with Asperger's syndrome did not show an impairment in completing second-order tasks. In fact, the study has shown that participants with Asperger's syndrome displayed an existing *theory of mind*, albeit they could not explain their reasoning (see also Ozonoff, Rogers, & Pennington, 1991). Tager-Flusberg et al. argue that the impairment in ASD is justified by a different information-processing style and deficits in executive functioning (see also Frith & Happe, 1994). Nevertheless, there has been more evidence that a deficit of *ToM* is a plausible explanation for some abnormalities witnessed in ASD (Simon Baron-Cohen, O'riordan, Stone, Jones, & Plaisted, 1999).

Consequently, a reduction or deficit in predicting other mental states and behaviour plays a role with an attenuated *theory of mind* (Baron-Cohen et al., 1985). Leslie suggested a link between pretend play and 'mindreading' (i.e., the *ToM)* and emphasized the role of pretending in childhood as a possible indicator of the *theory of mind* (Leslie, 1987; further see Rogers & Pennington, 1991). The origin of a reduced *ToM* is supposedly either a disturbed self-perception and the perception of others or a dysfunction in the 'mirror neurons' ('mirror neurons' function as cortical processing of observations, detecting goals and matching them with motor actions) (Gallese & Goldman, 1998; Iacoboni et al., 2005, 1999; Rizzolatti, 2005; Rizzolatti, Fogassi, & Gallese, 2001; Rogers & Pennington, 1991; Whiten & Brown, 1998; Williams, Whiten, Suddendorf, & Perrett, 2001).
This suggests that a *theory of mind* is a possible underlying cause for the ASD and some of the ASD inherent differences can be understood by this approach. However, further knowledge and studies must investigate associations of the *ToM* and the complexity of the disorder.

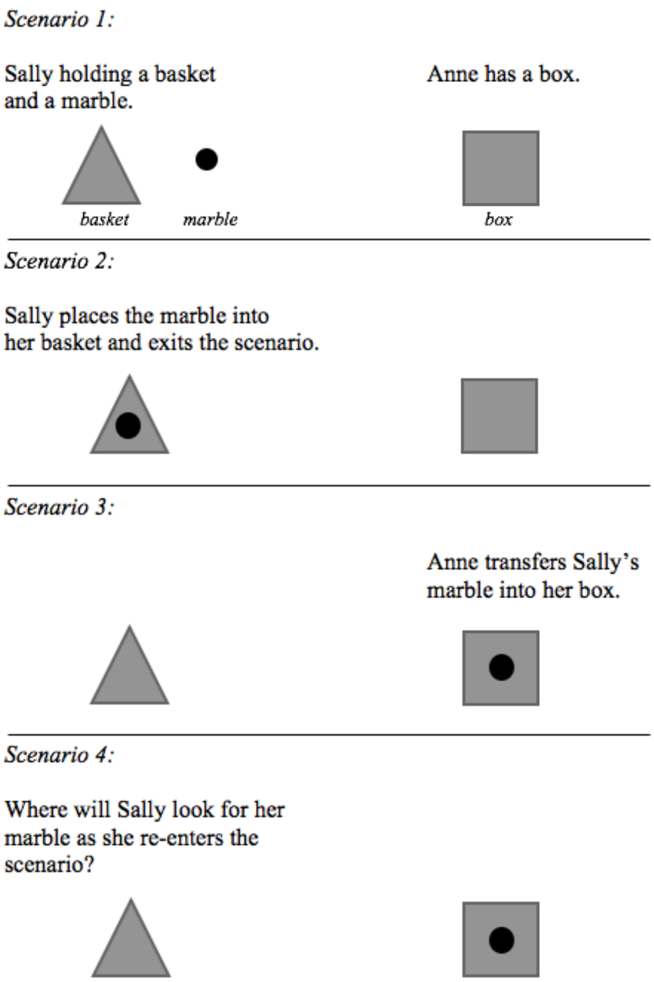


Figure 1. Adjusted image of the Sally-Anne test originally introduced in 1983 by Hein Wimmer and Josef Perner (Wimmer & Perner, 1983) and later modified by Simon Baron-Cohen, Alan M. Leslie and Uta Frith in 1985 (Baron-Cohen et al., 1985). The *Sally-Anne* test is a psychological test about social cognitive abilities and false beliefs of others in children evaluating the establishment of a *theory of mind*. In the experimental scenario 4 the participant is asked where Sally imagines finding her marble. If the answer is the original position of the marble – the basket – the participant passes the test. However, if the response is the current position – the box – the answer is incorrect, since the belief of Sally is not taken into consideration, as she is not aware of Anne's action. Consequently, the participant cannot take an alternative perspective, respectively has developed a *theory of mind*. Furthermore, it is assessed whether the participant is aware of the current location (4) of the marble and of the original one (2).

1.5 Time Perception

The sense of time is an essential estimation tool when it comes to decision-making, human relations, behavioural context or motion sequence and it shapes the individual's daily life(Allman, 2009). Not only is it important to have temporal understanding of current states, but also to have knowledge about the course of time and creating past or future forms of the present situation (Bechara, Tranel, Damasio, & Damasio, 1996; Kotz, Schwartze, & Schmidt-Kassow, 2009.; Nussbaum, Liberman, & Trope, 1990). Timing has been known to be dependent on several aspects, such as perception, sensation, neuronal processing and cognitive functioning (Buhusi & Meck, 2005). However, in contrast to the other senses, the sense of time does not have a unique sensory organ (Wearden, 2009). Consequently, the human brain must construct a processing mechanism to conduct temporal understanding, for example such as the *internal clock* model. Time has been a long-standing fundamental element in human civilisation and the subjective experience of time has always been a challenge and controversy in psychological research and philosophy (Pöppel, 1978). Recently, the field of research has been undergoing a change from the understanding of a role of an internal clock model (Church, 1984) to an understanding of temporal perception that is influenced mutually by emotional and cognitive elements (Wittmann, 2016). Time judgement and behavioural characteristics change in accordance with developments in mental and cognitive state, consequently, temporal alterations result in modified cognition and emotions. According to Wittmann (2016), subjective temporal perceptions heavily rely on the individual's cognitive skills, emotional participation and variety.

In the beginning of the 20th century, the 'internal clock' model was suggested by Marcel Francois (1927) and Hudson Hoagland (1933, 1935) in individual studies. They both expressed the idea of a connection between the body temperature and subjective time perception. In experimental studies an increase in body temperature led to an increase in temporal judgment (for reviews, see Wearden, 2009; Wearden & Penton-Voak, 1995). Therefore, it is presumed that time perception must be controlled by an internal chemical mechanism, such as a *chemical internal clock,* however, an exact understanding of the mechanism of the model was not demonstrated at the time.
In the 1960s more scientific work and a definite understanding of the *internal clock* was provided by Creelman (Creelman, 1962) and Treisman (Treisman, 1963). In their studies the authors illustrated that temporal perception is created by three stages, namely clock (i.e., temporal integration of a temporal signal into a meaningful manner by a *peacemaker-accumulator internal clock*), memory (i.e., lasting storing of the *clock stage* information with two memory mechanisms, one that saves the duration perception temporarily and another memory that stores a benchmark that can be used for the duration of the experiment) and decision stages (i.e., comparison of the new integrated information to previously stored information) (Church, 1997; Treisman, 1963). Referred to as a 'generalised timing model' (GTM) in which all stages are highly interrelated (Matell, Meck, & Nicolelis, 2003). Matell et al. (2003) argued that temporal predictions and the individual's behaviour rely mostly on the 'decision stage'. This model of *information-processing* (IP), first proposed by Treisman in 1963, describes how interval timing is mediated in humans (Church, Miller, Meck, & Gibbon, 1991; Gibbon, Church, & Meck, 1984; Treisman, 1963; Wearden & McShane, 1988).

In 1977, John Gibbon introduced the *scalar expectancy theory* (SET) (see *Figure* 2), a timing model that combines the internal clock as a structure that contains a 'pacemaker' generating pulses at a high rate, an 'accumulator' estimating these pulses during the presented duration intervals of the experiment and a lasting memory stage storing the counted intervals (Gibbon, 1977). Originally the SET was used in animal studies to examine their behaviour in temporal performance. However, it was suggested that it could be easily transferred to human timing studies (Machado & Pata, 2005; Wearden & McShane, 1988). The SET differs from the classical internal clock model in two aspects; firstly, the *mean accuracy* meaning that presumed individual temporal calculations of a given duration tend to have an accurate mean. Secondly, the *scalar property,* that the temporal precision is proportional to the mean accuracy (Wearden, 2003), is naturally incorporated in the SET.

The scalar expectancy theory (SET)

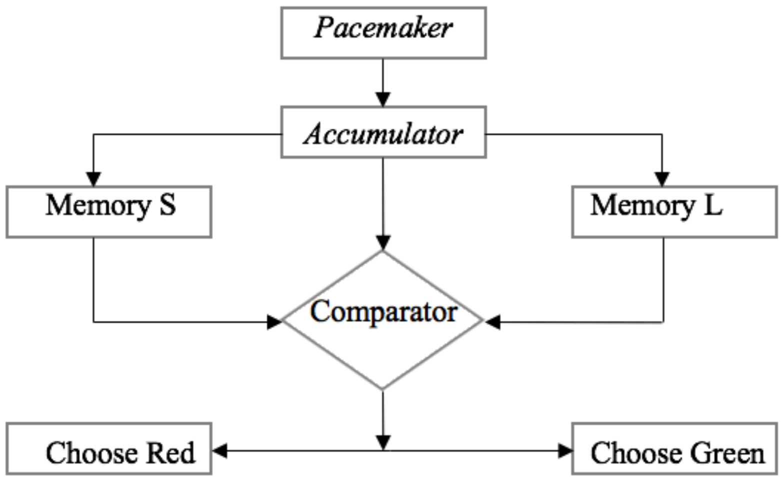


Figure 2. Modified structure of the scalar expectancy theory (SET) according to Machado et al. (2005). Created for the bisection procedure. After generating pulses in the *pacemaker,* the *accumulator* acquires/counts these pulses, while two memory systems store the counts in either the short-term memory (S) or the long-time memory (L). In the authors experiment rats had to choose a key. After comparing the presented account with the stored memory in each S and L the rat decided which sample is more similar and picked the corresponding key (red or green).

Neurobiological studies have shown that attentional shifting and interval timing behaviour are both generated in the frontal cortex and basal ganglia (Gibbon, Malapani, Dale, & Gallistel, 1997). In a study by Harrington et al. (1998) patients with frontal lesions (i.e., patients with focal left and patients with right hemisphere cortex lesions) were compared with control participants in two-time perception. Patients with left prefrontal lesions indicated attentional deficits, they did not, however, present deficits in interval timing. Yet, patients with right hemisphere lesions displayed deficits in temporal perception. Therefore, the authors concluded that the right hemisphere is involved and essential when it comes to temporal processes and timekeeping structures (Harrington, Haaland, & Knight, 1998; Husain, Shapiro, Martin, & Kennard, 1997; Roland, Skinhbj, & Lassen, 1981). Further studies use functional magnetic resonance imaging (fMRI) techniques which tracked brain activity while participants were taking part in experimental tasks (i.e., judging durations as longer or shorter as a previously presented duration), the experimenter could indeed identify these regions as significant for temporal judgement (Rao, Mayer, & Harrington, 2001). Identifying the basal ganglia as a neurological processing structure has additional importance due to its relation to other developmental disorders, such as Attention Deficit/Hyperactivity Disorder (ADHD) and Parkinson's disease (PD), since both disorders are presumed to often demonstrate deficient time perception (Barkley, Koplowitz, Anderson, & Mcmurray, 1997; Rao & Haaland, 2000; Rao et al., 2001).

As temporal research has grown over the past decades, Wearden and colleagues (1998) have conducted experiments which study the duration of auditory and visual stimuli. During their experiment they discovered a longer subjective judgment for auditory stimuli (500-Hz tone) than for the visual cues (14-cm blue squares), drawing attention to the original research by Goldstone and Lhamon (1972; 1974) which found that *"sounds are judged longer than lights"*(Goldstone & Lhamon, 1974, w63; Wearden, Edwards, Fakhri, & Percival, 1974).

Throughout the years research on temporal perception has shown an influence of external non-temporal factors, such as modality, size, loudness, repetition, and temporal structure etc. on duration judgement. Thomas and Brown (1974) have explored the 'filled duration illusion' (in which durations with more elements tend to be perceived longer than durations with less stimuli, see Fraisse, 1963), meaning external factors such as 'filled', continuous tones are judged to be longer than 'empty' tones regardless of their length. Thomas and Brown adopted the 'illusion' theory from previous studies, for example those of Ornstein (1969) and Buffardi (1971) who conducted independent studies with 'filled' stimuli (e.g., durations with more elements; 'filled' with *clicks,* Penton-Voak, Edwards, Percival, & Wearden, 1996). Another example for an external factor is that moving stimuli are perceived longer than motionless stimuli (Brown, 1995; Goldstone & Lhamon, 1974; Wearden et al., 1998).

In many studies on experimental psychology the *Weber's law*, which considers several timing theories, has been investigated. Studies have looked at whether the judgement of sensory stimuli, especially temporal judgment, is influenced by changes in presented stimuli. As previously mentioned, temporal precision is proportional to the mean accuracy and human behaviour can be seen as suitable scalar properties (Wearden, 2003). In the SET, in accordance with the *Weber's law*, the standard deviation of estimates increases linearly for the extent of the judged temporal durations – the scalar property of time. However, a violation of scalar property, a constant variability to time ratio, in time perception studies has often been identified (Grondin, Laflamme, Bisson, Hasuo, & Kuroda, 2006). Violations might occur when intervals are from certain duration ranges or when certain participant collectives are being tested, highlighting the importance of contextual calibration in theoretical timing theories ((Shi, Church, & Meck, 2013). When applied for long durations a violation of the Weber's law has been demonstrated (Getty, 1976), as in scalar variability the measurement of long intervals leads to more uncertainty. In accordance with the Bayesian framework these circumstances call for the reliance on internal prior expectations in order to eliminate this uncertainty and to improve judgment performance (Jazayeri & Shadlen, 2010; Shi, Church, et al., 2013). Shi et al (2013) have shown that the Bayesian framework with its three components; the likelihood, prior distribution and the loss function is closely associated to the three components of cognitive processing of the SET; the clock, the memory and the decision stage.

The *Weber's law* was coined by Ernst Heinrich Weber in the 19th century, referring to human perception and the response given to physical stimuli. Weber's student Gustav Theodor Fechner formulated the Weber's law and the Fechner's law in 1860 in his first famous published work *"Elements of Psychophysics"* in accordance with Weber's earlier findings (Fechner, 1860). The "Weber-Fechner" law states that changes in perception are in constant ratio to the initial stimuli. Furthermore, the *'Just Noticeable Difference'* was addressed in the studies, explaining the procedure of how much a stimulus intensity has to be changed in order to be detected as noticeable variations in sensory perception. The size of the *'Just Noticeable Difference'* is proportional to the original sensory cue and explains the fraction for discriminating differences in stimuli changes (such as brightness, length, noise) and can be measured individually. Differences in presented stimuli are easier to detect if they are quiet and less noisy, however, if they are louder than the *'Just Noticeable Difference'* they are more difficult to identify. Therefore, the amount of sensory discrimination needed can be regarded as the Weber's fraction (Wearden, 2009). A small Weber's fraction equals a detection of fine, sensitive differences between sensory stimuli and consequently with a large Weber's fraction the difference between two stimuli must be larger to be detectable.

1.6 The Central Tendency Effect

In accordance with the "Weber-Fechner" law sketched in the previous subchapter on how much judgment of sensory cues– and especially the temporal stimuli – are influenced by changes in presented stimuli, this subsection will concentrate on the reproduction peculiarities of interval timing and the connections of the predictive coding hypothesis of ASD (Pellicano & Burr, 2012) and the central tendency effect (Hollingworth, 1910), depending on the volatility of the sequence (Glasauer & Shi, 2018).

In his book "Der Zeitsinn nach Versuchen (The Experimental Study of Time Sense)" published in 1868, Karl Vierordt, introduced the proposition that shorter durations are overestimated and longer durations are underestimated (Vierordt, 1868). Later, this became known as the 'Vierordt's law'. This results in a central mean described as an *indifference point,* at which the given time was accurately reproduced (i.e., reproduction error is zero) (Lejeune & Wearden, 2009; Treisman, 1963; Vierordt, 1868). The *indifference point* is presumed to be not an absolute value, but rather is dependent on the variety of the given intervals (Lejeune & Wearden, 2009). A couple of years later, in 1910, Harry Levi Hollingworth framed the concept of the *indifference point* as the 'central tendency' effect, which plays a role in "judgments of magnitude, duration and intensity" (Hollingworth, 1910, p. 461) always being drawn to a mean degree.

The key idea behind the central tendency effect in the Bayesian framework approach – considering duration reproduction – is to reduce overall reproduction errors by integrating all the available temporal information and, thus, the *bottom-up* new sensory information with the *top-down* prior (i.e., mean and standard deviation of stimuli) (Jazayeri & Shadlen, 2010b; Shi & Burr, 2016a; Shi, Church, et al., 2013). Jazayeri and Shadlen illustrated that the 'central tendency' effect is best shown at temporal duration reproductions of two different ranges, with the same duration (e.g., 850 milliseconds) leading to different regression biases. In addition, reliability of the sensory stimulus essentially influences the magnitude of the tendency biases (Guido Marco Cicchini, Arrighi, Cecchetti, Giusti, & Burr, 2012). Biasing the feedback toward the mean of the earlier perceived stimuli is a response in order to enhance consistency in a noisy environment (i.e., low precision) (Friston, 2010; Shi & Burr, 2016). The noisier the sensory input is, the more reliance is generated towards prior knowledge when it comes to building up final perceptions. However, the consequence is a reduction in accuracy of the reproduction task. Therefore, in a Bayesian model approach, previously perceived stimuli influence the perception and reproduction of a following stimulus estimation (Cicchini et al., 2012; Jazayeri & Shadlen, 2010). In these studies, it has been shown that the same stimulus duration was reproduced as longer when the mean of the stimuli was long and, consequently, as shorter when the mean of the stimuli was short.

The 'central tendency' effect is shown in TD children and presumed to decline with age (Karaminis et al., 2016; Sciutti et al., 2014). An impairment in regression was shown in an interval reproduction task with TD children between the age of 7 and 10 years in a study by Sciutti et al. (2014), illustrating a greater impact towards extracting information of sensory stimuli in order to judge previous incidents, suggesting an early founding of context-dependency in brain development. With age, temporal discrimination improves, consequently younger children have poorer temporal judgment and, therefore, rely on narrower, much stronger priors in order to reduce errors (Sciutti et al., 2014). Hence, the quality and the extent of the built-up prior is dependent on the attainable sensory information.
By contrast, Karaminis et al. (2016) used an experimental duration reproduction task previously employed by Cicchini et al. (2012), that measures 'central tendency' failure in

accuracy and temporal reliability. The task revealed that autistic children, relative to TD peers, show reduced levels of 'central tendency', because of their impaired ability to suppress sensory noise. Therefore, the authors concluded that autistic children do not resort to internal information about a mean stimulus, in the perceived temporal reproduction tasks, in order to compensate for their poor temporal judgement and to reduce errors.

The close relation between the 'central tendency' effect and Bayesian inference has also been demonstrated by Cicchini et al. (2012) with two groups of people: participants with low levels of musical expertise and participants with high levels of musical expertise. Non-percussionists presented a typical, strong 'central tendency' effect, while percussionists conducted the reproduction experiment with high precision (i.e., veridical accuracy in temporal reproduction). The authors concluded that the 'central tendency' effect observed by Jazayeri and Shadlen (Jazayeri & Shadlen, 2010) cannot be generalised to all time reproduction and perception forms, but instead relies on environmental circumstances.
Temporal judgment in volatile conditions can, therefore, benefit from the 'central tendency' effect, under involatile conditions, however, giving up accuracy by gravitation towards a mean is not profitable.

1.7 Time Perception in ASD

The topic of time perception in individuals with ASD – and in general perceptual abnormalities – has gained more attention and has been frequently referenced in either experimental studies or has been mentioned by relatives of participants or first-hand from autistic individuals. It has been hypothesised that impairments in interval timing and temporal perception might affect abnormalities and diagnostic attributes of ASD and, therefore, might be a further potential diagnostic tool of ASD (Allman, 2009; Allman, DeLeon, & Wearden, 2011).
Noticing local, minimal changes in the environment, having superior visuospatial or auditory senses and performing superior in visual search tasks have recently been described as a feature of ASD (Bonnel et al., 2003). In recent years, sensory abnormalities have been documented in studies with autistic participants. The incoming sensory stimuli requires a complex processing of manifold modalities which is often seen to be deficient in ASD and leads to noticeable differences in comparison to TD individuals. Moreover, individuals with ASD often find it more challenging to adapt to situations with overwhelming sensory stimulations compared to TD individuals (i.e., hypo- or hypersensitivity) (Crane, Goddard, & Goldsmiths, 2009; Leekam, Nieto, & Libby, 2007; Tomchek & Dunn, 2007). Unusual sensory processing is considered to be a cause of many symptoms of ASD (Mottron et al., 2006; Simmons et al., 2009). In particular, several studies reported correlations between abnormal visual sensory processing and symptom severity (Bodgashina, 2016; Falter, Elliott, et al., 2012).

According to Montangero and colleagues (1992), the ability to think back in time and ahead of time is called *diachronic tendency.* Montangero described the *diachronic transformation* as the understanding that things can appear through time without changing its character or quantity and rather keep their consistency over time (e.g., process of human development from childhood to maturity). Finally, Montangero et al. discussed the *diachronic synthesis,* a theory which implies the understanding of the temporal succession of things that belong a higher-level event (Montangero, 1992; Jacques Montangero & Pownall, 1996). Making assumptions about the passage of time and comprehending past or future forms of the current situation (i.e., an episodic memory) is known to be deficient in ASD (Allman, 2009; Boucher, Pons, Lind, & Williams, 2007; Pennington & Ozonoff, 1996; Wing, 1991). Boucher and colleagues tested the ability of children with ASD to understand changes in temporal perception and used tests of *tendency, transformation* and *synthesis* (Boucher et al., 2007). The authors conducted information about impairments in children with ASD to think diachronically and to adapt temporal concepts. Deficits in *synthesis* could arise from a general lack of central coherence.

Allman and DeLeon (2009) postulated that stereotypical autistic behaviour may be the result of this lack of temporal understanding. ASD individuals might use their repetitive behaviours (such as finger tapping, counting, etc.) as a coping technique to adapt to temporal changes. This temporal structure is developed during infancy by early action and rhythmic repetitive behaviour, which helps infants adapt to their environment (Levin & Zakay, 1989; Lewkowicz, 1989). Repetitive motor actions help infants to measure the duration of certain events and functions as a strategy to pass temporal delay while waiting (see Pouthas, 1985). This relationship has been shown to decrease in older children (4-7 years), suggesting that repetitive behaviour as a means to estimate duration, is being replaced by other strategies (Pouthas, Droit, Jacquet, & Wearden, 1990). Allman and DeLeon (2009) further explained that failing to create a sense of temporal contingencies in a child's development might explain the persistence of stereotypic behaviours in autistic individuals into adult life. Deficits in interval timing reproduction are mentioned in a study by Szelag et al. (2004) where high-functioning children with ASD aged from 9-16 years showed impairments in reproducing given duration intervals (1-5s). A decreased sense of time and time perception may be an obstacle when it comes to adapting to recurring situations and, as previously mentioned, predicting future events (Allman, 2009). Boucher et al. (2007) reported that autistic children (7-16 years) faced difficulties when creating former or future forms of a present situation and had difficulties acknowledging that things could change or develop over time (Montangero, 1992). Boucher (2001) suggested that there is a correlation between the length of repetitive behaviour and the ability to estimate time frames. Shorter and less complex rituals can be observed in low-functioning individuals with ASD and more complex and longer rituals in individuals with high-functioning ASD. This suggests that having a more complex and larger variety of repetitive motor behaviours goes hand in hand with a better understanding and perception of duration and that repetitive behaviour might be an effective strategy in order to reduce and compensate disorientation in time (Allman & Falter, 2015). Allman and Falter (2015) postulate an enhanced time perception and accuracy in short time intervals (millisecond) and a decreased accuracy (i.e., "increased variability") in longer durations. Abnormal interval timing has been demonstrated in several studies, for instance Szelag and colleagues discovered a deficit in intervals ranging from 1-5.5 seconds and Barkley and colleagues observed impairments in reproduction tasks in a range from 2-60 seconds. (Szelag et al., 2004.)

Recent clinical research has demonstrated the importance and impact of a better understanding of temporal perception in ASD, as an impairment in time processing might influence and mediate autistic features and consequently lead to social (Striano, Henning, & Stahl, 2006; Trevarthen & Daniel, 2009), linguistic (Tallal, Miller, & Holly Fitch, 1993) and cognitive functioning deficits (Baron-cohen, 1988; Hermelin & O'connor, 1970; Rutter, 1983) that are common in individuals with ASD. Contrary to the findings of impaired temporal perception in ASD, further experimental studies have shown that intact time perception has been demonstrated in ASD compared to matched TD individuals. In a study conducted by Wallance and Happé (the participants were twenty-five school-age children with ASD) results showed a superior time reproduction among individuals with ASD in comparisons with TD individuals. In their study, time perception consisted of three randomised features: perception, estimation and reproduction. In contrast to Szelag et al. (2004) who showed impairments in accuracy in short time intervals (2-3 seconds), the authors highlighted the accuracy in time estimation in intervals in a range up to 45 seconds and even an improvement as duration increased, a similar time production of both groups across all durations and a better performance of time reproduction as the duration increased in ASD (Wallace & Happé, 2008). The authors concluded revealing difficulties in shorter durations, which is consistent with findings of Allman and Falter (Allman & Falter, 2015).

Therefore, a better understanding and further research in temporal processing and perception in individuals with ASD compared to TD individuals is required in order to establish the potential influence of secondary symptoms (e.g., impaired time perception) for primary symptoms (e.g., abnormalities in human relations, communication, behavioural restrictions). Nevertheless, abnormal time processing and temporal reproduction abilities are not universally seen in ASD, often individuals with ASD did not perform atypically. Therefore, the assumption of an overall deficit in ASD is not entirely accurate (Falter & Noreika, 2011; Jones et al., 2009; Wallace & Happé, 2008).

1.8 Hypothesis and Aim

The aim of the dissertation is to investigate the influence of volatility on abnormal patterns of interval timing in ASD. Given that volatility influences not only affect the learning rate but also prior formation. It is known that prior information can heavily influence subjective judgements (see review above). One famous example of this systematic bias invoked by prior knowledge is the central tendency effect outlined in the subsection 1.6 (Hollingworth, 1910; Jazayeri & Shadlen, 2010b; Shi, Church, et al., 2013). When asked to reproduce a duration from a set of durations, participants tend to overestimate the *short* and underestimate the *long* durations (Lejeune & Wearden, 2009; Vierordt, 1868). A recent study showed that volatility in the trial sequence indeed influences this central tendency effect (Glasauer & Shi, 2019). High volatility, as compared to low volatility induced a stronger central tendency effect. Crucially, more research on investigating the influence of volatility on abnormal patterns of interval timing in ASD is necessary and future studies must consider whether ASD individuals indicate less reliance on prior information compared to TD individuals. When it comes to predicting future events, making assumptions about recurring situations or comprehending the order of events, requires well-functioning computational skills of the brain (Yu & Dayan, 2005). These skills are explained in the Bayesian statistical theory and the 'Bayesian brain' perspective (Friston, 2010; Friston & Kiebel, 2009; Haker, Schneebeli, & Stephan, 2016). The Bayesian principles assume that information is unreliable, therefore new acquired information must be combined with old prior knowledge to work as a reliable source of predicting environmental circumstances. The Bayesian theory in ASD explains a different way of perception in ASD, meaning a "disbalance in the precision of prediction errors (sensory noise) relative to the precision of prediction (prior beliefs)" (Haker et al., 2016, p. 1). As a result, the awareness of the environment is perceived by sensory inputs rather than by using prior knowledge (top-down processing). As Pellicano and Burr (Pellicano & Burr, 2012) indicate, priors in ASD are not as heavily influenced by past experiences as they are in TD individuals. Top-down processing in the context of predictive coding requires calculating prior knowledge about the environment by using sensory input. A predictive error (sensory noise) occurs when there is a misunderstanding between the top-down cue and the sensory cue, e.g., a higher level of uncertainty in the environment. As a result, perception is transferred to a greater detailed focus of the environment, rather than to a calculation according to the Bayesian theory and therefore difficulties in obtaining a proper understanding and interaction with the environment occur.

Based on the studies reviewed above, our experiment investigated the learning of volatility in duration reproduction in ASD and evaluated if ASD individuals have atypical prior formation regarding the volatility or atypical prediction mechanism within a volatility environment and, therefore, produce a reduced central tendency effect, when compared to the TD group. In order to test the predictive coding theory of ASD (Pellicano & Burr, 2012) we employed a previously tested duration reproduction paradigm (Glasauer & Shi, 2019; Shi, Ganzenmüller, & Müller, 2013). This paradigm contained two types of duration sequences with the same sampled distributions, but with different trial-to-trial volatilities. A greater understanding of temporal perception and processing might help to clarify and increase knowledge about ASD characteristic behavioural traits and differences.
And we used the central tendency effect and trial-to-trial serial dependence as two measures for the long term prior and local prior updating.

2 Methods

2.1 Participants

Via the database of the Outpatient Clinic for Autism Spectrum Disorders at the Department of Psychiatry, LMU Munich along with advertising through the local ASD network twenty-six adults diagnosed within the autism spectrum were recruited (12 females, 14 males, aged between 18 and 67 years, mean= 30.08; SD= 13.1) (Allenmark et al., 2020). Through the database of the LMU Faculty of Psychology and Pedagogics and through local medical students the twenty-six TD adults (11 females, 15 males, age from 18 to 70 years, mean= 31.2*,* SD= 14.5*)* were enlisted in the study. Due to the lack of a certified diagnosis according to ICD-10 (World Health Organization, 1992), five participants from the ASD group and their matched control participants were excluded from further analysis. Any history of mental illnesses or had neurological deficits was an exclusion criterion for the TD group (Allenmark et al., 2020). Two groups of participants were matched using a test of crystallized intelligence (‘Wortschatztest’, hereafter called WST, (Schmidt & Metzler, 1992) IQ-Scale (ASD group mean= 108.2; TD group mean= 108.7*)*. Both groups completed the Autism-Spectrum Quotient (AQ, (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001)), Empathy Quotient (EQ, (Baron-Cohen & Wheelwright, 2004)), Systemising Quotient (SQ, (Baron-Cohen, Richler, Bisarya, Gurunathan, & Wheelwright, 2003)), Beck's Depression Inventory (BDI) (Hautzinger, Bailer, Worall, & Keller, 1995; Hautzinger, Keller, & Kühne, 2009) (for an explanation of the diagnostic tools, read more in Chapter 2.2*).* The two groups did not show any significant difference regarding IQ, age or BDI. However, the two groups differed significantly on AQ, EQ, and SQ measures (see *Table 1*.). Prior to the experiment all participants had to sign a written informed consent and understood their right to quit the experiment at any time (Allenmark et al., 2020). They were compensated for their time and participation with 10 euros per hour. The study was approved by the Ethics Board of the Faculty of Pedagogics and Psychology, LMU Munich, Germany.

Measures	***ASD (n=26)***	***TD (n=26)***	***Group comparison***
Age	30.08 (13.1)	31.2 (14.5)	$t(50) = -0.12$, $p = 0.45$,
IQ score	108.2 (9.7)	108.7 (12.6)	$t(50) = -0.46$, $p = 0.32$,
Autism-Spectrum Quotient score	37 (7.6)	15.4 (6.7)	$t(50) = 10.87$, $p < 0.001$,
Empathy Quotient score	27.3 (13.2)	53 (14.9)	$t(50) = -6.7$, $p < 0.001$,
Systemising Quotient score	36.7 (15.5)	25.4 (9.2)	$t(50) = 2.7$, $p < .05$,
Beck’s Depression Inventory score	8.5 (6.4)	6.4 (8.1)	$t(50) = 1.30$, $p = 0.09$,

Table 1. Descriptive characteristics for the ASD and the TD control group (Allenmark et al., 2020).

2.2 Diagnostics

2.2.1 Self-rating Questionnaires Assessing Autistic Traits

The *Autism-Spectrum Quotient* (AQ) (see Appendix) is a questionnaire used to determine the autistic traits an individual presents (Baron-Cohen et al., 2001). The score one can accomplish during the questionnaire varies from 0 – 50. The cut-off for measuring significant autistic traits is set with a final score of over 32+ points. The AQ consists of 50 questions, while each set of 10 questions portrays 5 different fields, such as *social skills, attention switching, attention to detail, communication* and *imagination*.
An individual responding to an answer revealing an autistic trait or abnormal behaviour (e.g., poor social skills, poor imagination skills) scores 1 point for each answer. In order to prevent a response bias, the authors created the responses to be in either agreement or disagreement with the statement and answers were randomised. While completing the AQ, individuals should work by themselves as quickly as possible, to prevent overthinking and pre-judging their responses. Response choices range from *definitely agree, slightly agree, definitely disagree* to *slightly disagree.* Furthermore, the authors analysed whether IQ and socio-economic status (SES) influence the AQ, by selecting a group of Cambridge students matching a general population group as participants. However, they did find that IQ or SES influenced the responses of the participants (Baron-Cohen et al., 2001). In the author's pilot testing trials of the questionnaire, they investigated if sex influenced whether or not participants scored higher levels in the AQ. 40% of the male participants scored levels over 20+, while only 21% of the female participants scored these levels. To support this, their data shows that autistic traits are higher in the male population than in the female population (Baron-Cohen et al., 2001).

The *Empathy Quotient* (EQ) (Baron-Cohen & Wheelwright, 2004) is a diagnostic tool used to measure participants' level of empathy. The questionnaire consists of 60 questions, presenting 4 different answers to choose from *('strongly agree', 'slightly agree', 'strongly disagree', 'slightly disagree*'). A participant scores 2 points when they choose *'strongly'* and only 1 point when they respond with *'slightly'*.
The *Sympathising Quotient* (SQ) (Baron-Cohen, Richler, Bisarya, Gurunathan, & Wheelwright, 2003) contains 60 items, while 40 items aim to clarify the systemising aspects of participants' character traits. 20 items are designed to be filler questions unrelated to systemising. Similar to the AQ, half of the items are designed in an agreement manner and half in a disagreement manner, for the purpose of avoiding a response bias. Response choices are developed in the same style as the other questionnaires *('strongly agree', 'slightly agree', 'strongly disagree', 'slightly disagree*'). Furthermore, the participants rating is constructed in an identical way (see above).

We conducted all of the above surveys on both groups, and the mean values are shown in *Table 1.*

2.3 Design and Procedure

The experiment was conducted in a sound-reduced experimental cabin at the Faculty of Pedagogics and Psychology, LMU Munich, Germany (Allenmark et al., 2020). Participants received instructions in written form and verbally.

Participants took a test containing five test trials to make sure they fully understood the experiment. The experiment was divided in two blocks and during the break participants filled out the questionnaires.

The visual stimulus was a yellow disk patch (diameter: 4.7° of visual angle; luminance: 21.7 cd/m^2), which was presented on a 21-inch LACIE CRT monitor with a screen resolution of 1024 x 768 pixels and a refresh rate of 85 Hz (Allenmark et al., 2020). The experimental software was developed using the Matlab Psychophysics Toolbox (Kleiner et al., 2007).

A typical production-reproduction trial (see *Figure 3* for an example) started with a fixation cross (size: 0.75° of visual angle) in the centre of the screen for 500 ms, which was followed by a white dot (diameter: 0.2°), prompting participants to press and hold the mouse button (either left or right) to start the production phase. Directly after pressing the mouse button, a yellow circle was shown on the screen for a specific duration, ranging from 400 ms to 1800 ms (see below), and disappeared. After 500 ms a white dot appeared on a blank screen, prompting participants to reproduce the duration that they experienced by pressing the mouse button for the same duration as the yellow circle was displayed earlier, and then releasing it. Immediately after pressing the mouse button, a visual feedback with a yellow disk was presented on the screen and disappeared immediately after releasing the mouse button. A feedback display with an indication of the relative reproduction error was then shown for 500 ms at the end of each trial. The relative reproduction error consisted of highlighting, in green or red, one of the five horizontal arranged disks which, from the left to the right, were mapped to the relative error ranges: less than -30%, between [-30%, -5%], (-5%, 5%), [5%, 3%], and greater than 30%, respectively (Glasauer & Shi, 2021). The three circles in the middle were highlighted in green, and the outer left and right circles in red, the latter indicating a large error that should be avoided (Glasauer & Shi, 2021).

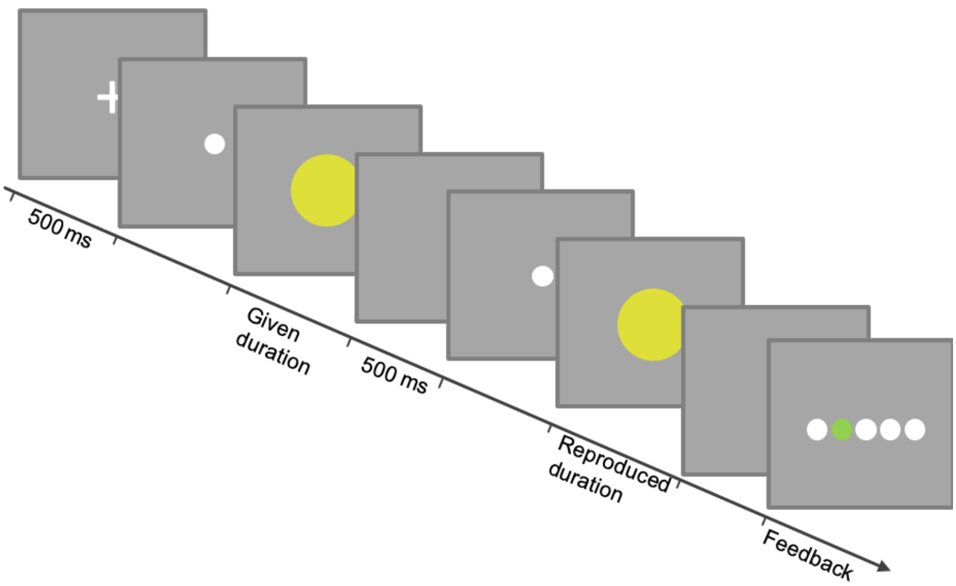
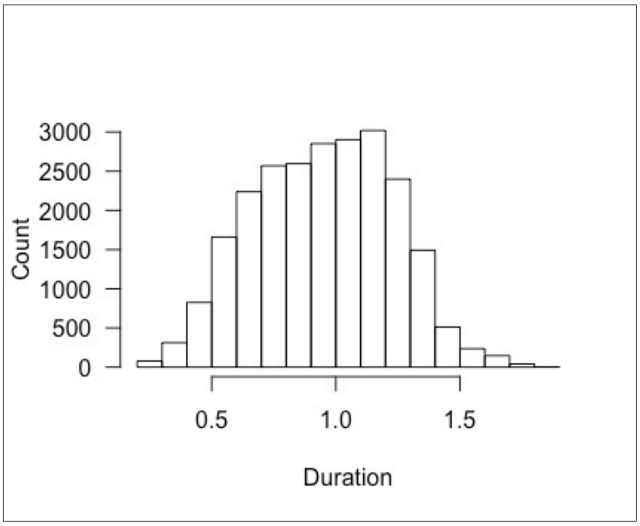


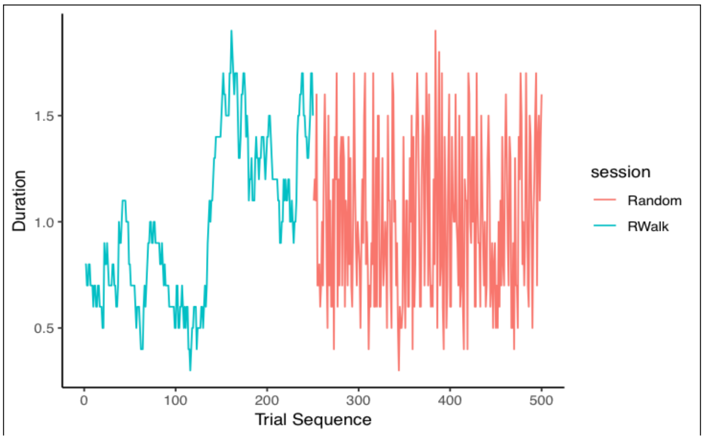
Figure 3. Schematic illustration of the trial sequence used in the production-reproduction task. See a detailed description in the main text.

2.4 Experimental Design

The experiment consisted of two sessions. Both sessions comprised the same set of stimulus durations but differed in their probing order. Each session consisted of 10 mini-blocks with each block containing 25 trials. In one session, the order of the duration sequence was generated by a Wiener process (after the random walk session). We then normalised and scaled the durations to the range of [100 - 2000 ms] and discretised the duration to 100 ms, such that we could have multiple repetitions across different intervals. In the random condition, the durations from the random walk condition were randomised. *Figure 4* (A) shows the overall histogram of sampled durations (the mean of 1000 ms and the standard deviation of 280 ms), and *Figure 4* (B) illustrates a typical sequence of two sessions. The sequences of two sessions were generated prior to the experiment, and the order of the two sessions (i.e., random and random walk) was counterbalanced across participants. Additionally, the same sequence was used for the paired participants between ASD and the TD control groups, such that any differences we observed truly reflected the difference between the two groups.



(A)



(B)

Figure 4. (A) The histogram of the sampled durations pooled over the valid dataset. The mean of the sampled duration was 1000 ms, and the standard deviation 280 ms. (B) An example sequence of two sessions. The first session, marked by cyan, is a random walk sequence (RWalk), and the second session, marked by red, was a randomised sequence. Both sessions contained the same durations, but the volatility was different.

In addition, all participants had to complete a training session with an individualised number of trials in order to make sure they understood the instructions. After a confirmation from the experimenter that the participant understood the task, the formal experiment started and lasted for around 60 minutes.

2.5 Analysis

For statistical analysis, we conducted repeated measures of analyses of variance (ANOVAs) and *t*-tests in our study. Concerning ANOVAs, we examined the between-subject factors Group (ASD vs. TD) and Session Order, and the within-subject factor Volatility (random walk vs. random). The ANOVAs were applied to the central tendency effects and general biases, which were calculated from regression analyses. For each statistical result, we additionally provided the effect size with the generalized eta squared (ηg^2).
For AQ-test analysis and the differences in IQ-scores of the ASD and the TD group, we conducted *t*-tests and calculated correspondent *t* and *p* values.

3 Results

3.1 Pre-processing of the Data

The raw data was first pre-processed with individual data investigation and outlier screening. Reproduced durations falling outside the range [D/3, 3D] were regarded as outliers, where D is the given duration. With this outlier criterion, we found two individuals from the ASD group that show quite different reproduction patterns. Both individuals produced the duration similarly across the entire range of the given durations in the random condition, but not in the random walk condition (see *Figure 5*), suggesting that in the random condition, they were not able to reproduce the duration they received and instead kept producing an average duration throughout the randomised sequence. The fact that they could reproduce the duration in the random walk condition suggests they understood the task. The feedback from the session breaks also confirmed that participants understood the task, which effectively ruled out that this “flat” reproduction in the random condition was merely due to misunderstanding the task. Given that this pattern was completely different from other participants, we excluded data from these two individuals from further analysis, but we give a full account in the supplementary material.

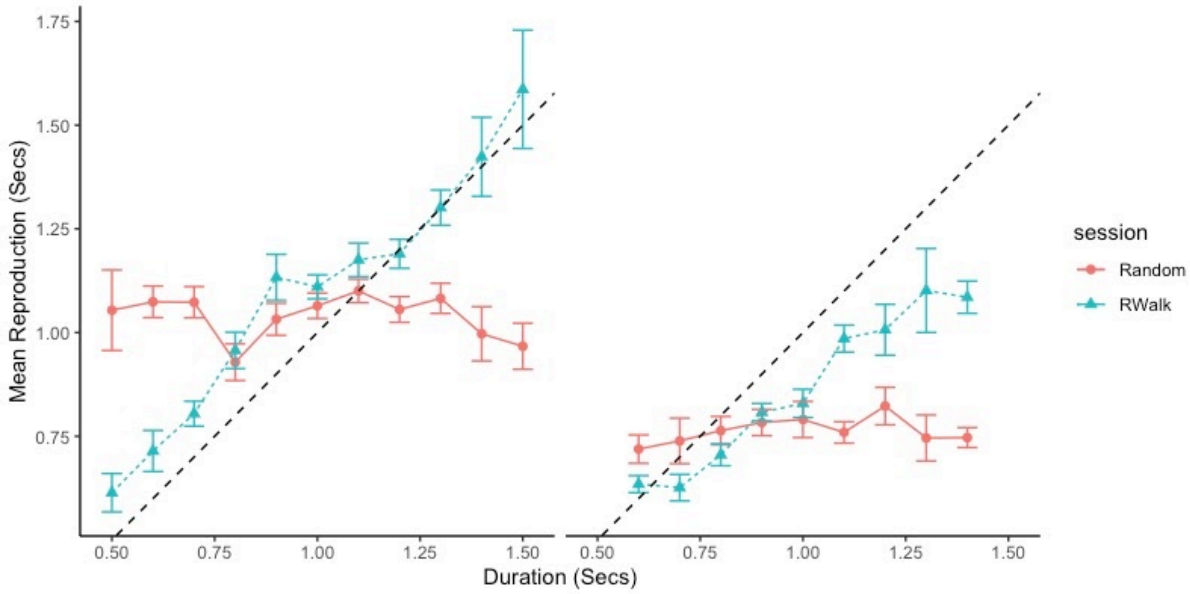


Figure 5. The two outliers from the ASD group, who reproduced durations similarly across all given durations in the random condition (red line), while following the given duration in the random walk condition (cyan line).

3.2 Mean Reproduction

The following analyses were based on 24 matched pairs of participants. *Figure 6* shows two typical participants (one from the ASD group and the other from the TD control group), who reproduced durations as a function of the sampled intervals, separated for the random walk and random conditions. By analysing the data, we can see that there are two types of biases. First, both participants had a general overestimation of the durations as most intervals were overestimated (above the diagonal dashed line). Second, the participant from the TD group (the right panel) shows a 'flatter' performance across the test durations as compared to the participant from the ASD group (the left panel). This pattern of the 'flattened' reproduction is known as the classical central tendency effect (Glasauer & Shi strongway, 2019; Karaminis et al., 2016; Shi, Church, et al., 2013).

To quantify these two types of effects, we estimated the overall reproduced bias at the mean of the sample distribution, which was around 1000 ms with some between-subject variations. For the central tendency, we adopted the central tendency index (r) as the difference in slope between the ideal reproduction (slope of 1) and the best linear fit to the reproduction duration over the stimulus duration (Cicchini et al. 2012). An index of 0 means no central tendency, while an index of 1 would indicate a strong central tendency bias.
Figure 7 illustrates the mean overestimation and mean slope as a function of two sequences for two groups. On average the ASD group over-reproduced by 43 ms and the TD control group by 20 ms. However, a further repeated measure ANOVA with the factors of session and group failed to reveal any significance [Group: $F(1,46) = 1.74$, p= .19, η_g^2=.04; Session: $F(1,46)$ = 2.67, p= .11, η_g^2=.007 ; Interaction: $F(1,46)$ = 0.33, p= .57, η_g^2=0.007]. By contrast, the repeated-measure ANOVA on the slopes revealed that both main factors were significant [Group: $F(1,46)$ = 4.68, p= .03, η_g^2=0.09; Session: $F(1,46)$ = 43.05, p< 0.001, η_g^2=.49], but not their interaction, $F(1,46)$ = 0.59, p= .45, η_g^2=.013. The central tendency effect was stronger in the random session than in the random walk session, suggesting that the sequential volatility did in fact influence the central tendency bias. More interestingly, the ASD group produced less

central tendency effect than the TD group, confirming our hypothesis that the ASD group relies more on the sensory input than on prior information.

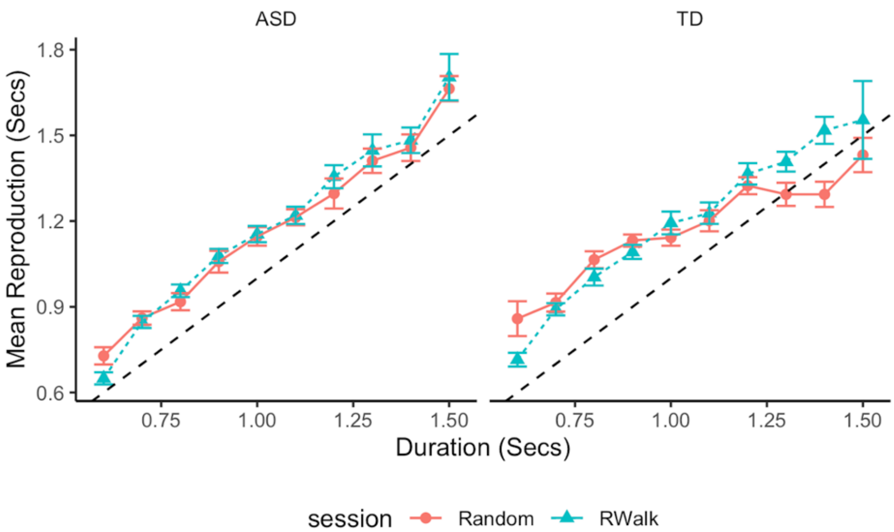


Figure 6. Mean reproduced durations as a function of the sampled intervals, separated for the random walk (cyan) and random (red) conditions. The left panel was produced by an ASD individual and the right panel by a TD participant. Both participants received the same duration sequence. The diagonal dashed line indicates the veridical reproduction. Performance above the diagonal line indicates an overestimation and below the diagonal line an underestimation.

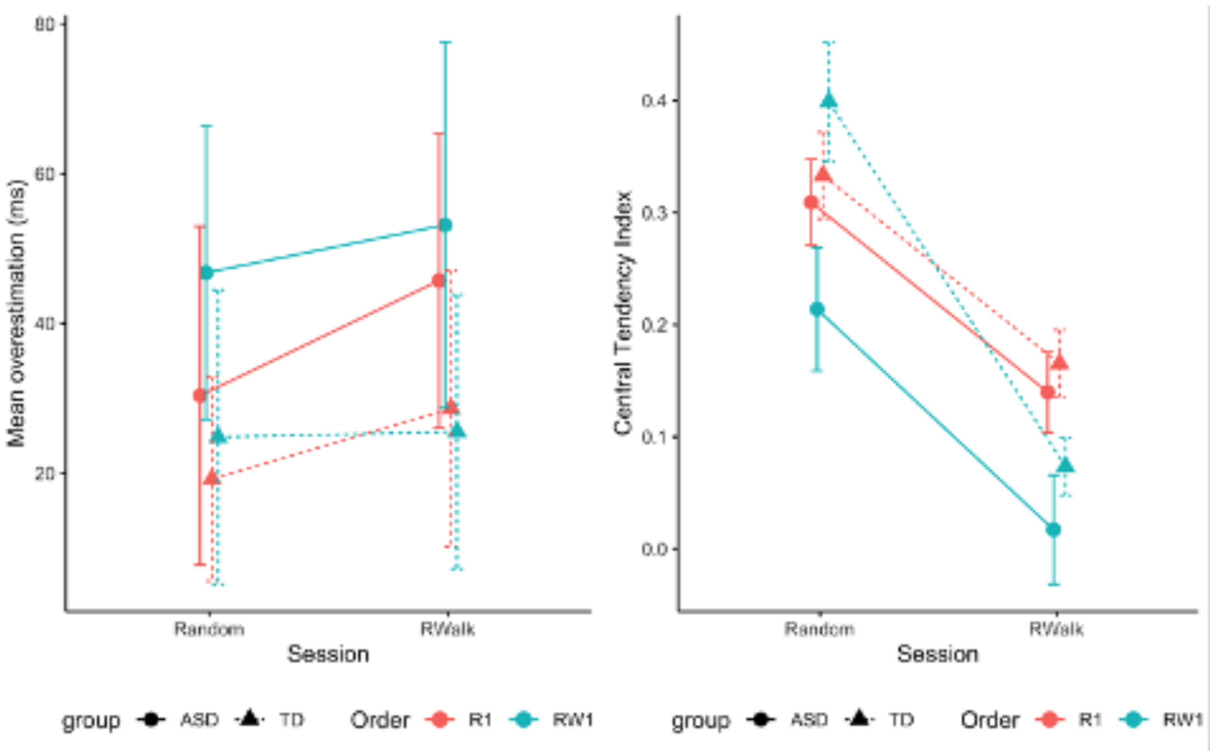


Figure 7. (Left) The mean overestimation as a function of session, separated for the ASD and TD groups. (Right) The mean central tendency index as a function of session, separated for the ASD and TD groups. A smaller slope indicates a stronger central tendency bias.

To further examine if there were any differences in the reproduction variability, we averaged the standard error in reproduction for different sequences and groups (*Figure 8*). A repeated measure ANOVA with the factors of session and group revealed that the main effect of session was significant, $F(1,46) = 17.9$, $p < 0.01$, η_g^2=.046. Neither the main effect of group [$F(1,46)$ = 0.04, p = 0.84, η_g^2=.001], nor the interaction between the session and group [$F(1,46)$ = 1.27, p = 0.26, η_g^2=.03] were significant. The significance of the main effect of session suggests that trial-to-trial volatility also influenced reproduction variability. However, the trial-to-trial volatility did not engender differential reproduction variability between the two groups.

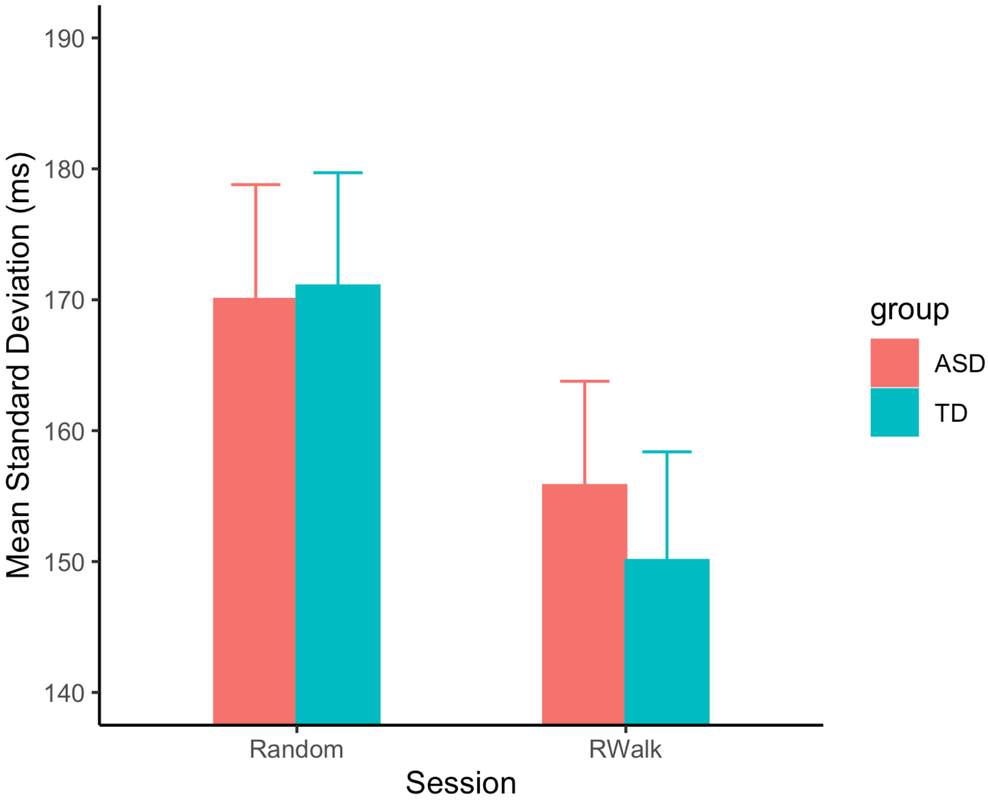


Figure 8. The average standard deviation of reproduced durations for the different sequences and groups. Error bars depict the standard error of the mean.

3.3 AQ and the Central Tendency Effect

To examine whether there was any relation between the AQ score, as a proxy of symptom severity, and the central tendency effect, we conducted linear regression on the regression slope as a function of the AQ score, separate for both groups (see *Figure 9*). The regression analysis revealed there was no significant linear trend for both groups (the coefficients of AQ were -0.0036 and -0.006 for the ASD and TD groups respectively, all p >0.1), but the intercepts were both significant (0.96 and 0.86 for the ASD and TD groups respectively, all p <0.001). The results suggest that the central tendency effect is insensitive to the AQ score, but the ASD group overall showed a less significant central tendency effect than the TD control group.

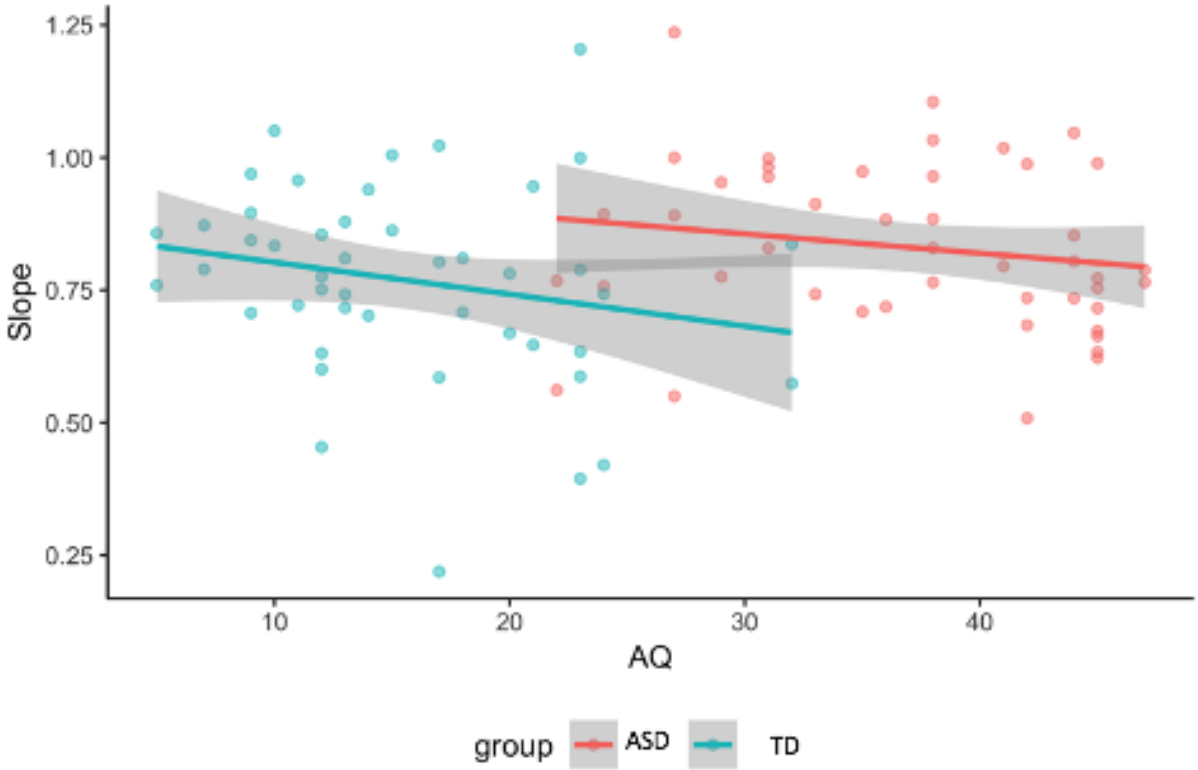


Figure 9. The central tendency effect, reflected in the reproduction slope, as a function of the AQ score. The cyan dots represent individual slopes in the TD group, the red dots individual slopes in the ASD group. The line and shaded area represent their linear regression and 95% confidence interval, respectively.

3.4 The Effect of Session Order

Since each participant performed the random and random walk sessions in more or less immediate succession, it seemed plausible that expectations about the statistical properties of the stimulus sequence learned during the first session could be carried over to the second session. We therefore analysed whether the order in which the sessions were performed affected the central tendency effect. *Figure 10* shows how the mean slope depends on the session, the session order and the participant group. A mixed-effects ANOVA with session as within-participant factor and session order and group (ASD or control) as between-subject factors revealed significant main effects of session ($F(1, 44) = 47.4$, $p < .001$, $\eta_g^2 = .29$) and group ($F(1, 44) = 5.13$, $p = .029$, $\eta_g^2 = .067$) and a significant interaction between order and session ($F(1, 44) = 4.81$, $p = .034$, $\eta_g^2 = .041$). No other effects were significant (all ps>.1). The interaction between order and session results from the slope in the random walk session being significantly larger if this session was performed first compared to if the random session was performed first (0.95 vs. 0.85; $t(37.7) = 2.37$, $p < 0.05$) while the slope in the random session was numerically, but not significantly smaller if the random walk session was performed first compared to if the random session was performed first (0.71 vs 0.73; $t(32.0) = -0.43$, $p = 0.67$).

One possible explanation of these results could be that when the random session was performed before the random walk session, participants learned to expect an unpredictable sequence. Therefore, they would at least at first not take advantage of the higher short-term predictability of the sequence (i.e., that the duration of any trial is likely to be close to that of the previous trial) when doing the random walk session. However, participants might keep using the overall, long-term, frequency distribution, learned during the random session, as a prior.

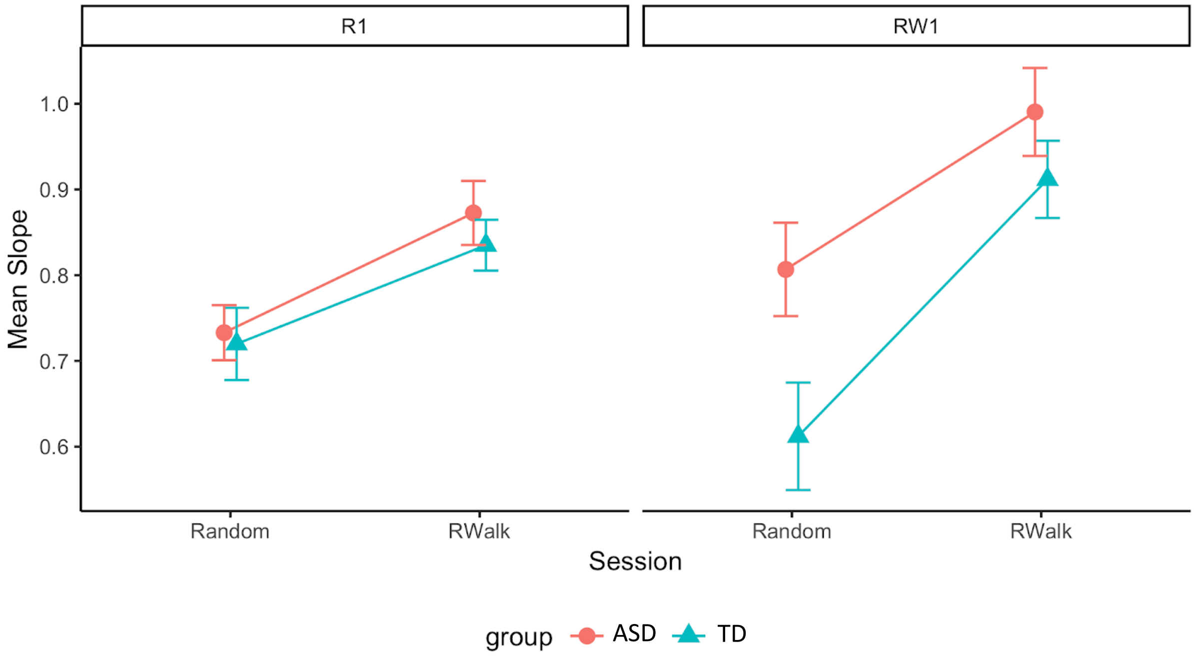


Figure 10. The mean slope as a function of session and the order of the sessions (R1: random session performed first, RW1: random walk session performed first), separated for the ASD and TD groups. A smaller slope indicates a stronger central tendency bias.

4 Discussion

4.1 The Theory of Learning-Style and the Predictive Coding Account

According to the Bayesian inference both prior knowledge and sensory stimuli provide information for human timing behaviour and determine its decision making processes (Shi, Church, et al., 2013; Zhang & Zhou, 2017). The idea of the Bayesian brain hypothesis is that the brain constantly updates models of the world and of posterior beliefs by using sensory stimuli (Dayan, Hinton, Neal, & Zemel, 1994; Friston, 2010; Knill & Pouget, 2004; Zemel & Hinton, 1995). Consequently, the brain uses sensory information effectively to optimise judgements and to form predictions (Dayan et al., 1994; Gregory, 1980). Consistent with the predictive coding framework, prediction errors that occur in noisy, volatile environmental conditions would be valued with low precision and are not a reliable factor to adjust the internal model of our ASD participants. Thus, our ASD group did not adapt to the changing environment, demonstrated in the more volatile "random" condition.
Researchers have considered predictive coding for a better comprehension of interval timing perception. According to the Bayesian framework, current circumstances are represented in a posterior calculation, combining information conducted from past and present sensory inputs with previously memorized knowledge (Knill & Pouget, 2004; Pouget, Beck, Ma, & Latham, 2013b; Zhang & Zhou, 2017). In several studies with experimental tasks it has been suggested and demonstrated that interval timing, as a basis for perception and motor action, embraces the Bayesian inference (Cicchini et al., 2012; Jazayeri & Shadlen, 2010; Zhang & Zhou, 2017). Through this framework an internal image of temporal estimates is generated and frequently updated in order to optimise temporal judgement and performance.

To demonstrate whether priors in interval timing are understandable within a Bayesian framework, we manipulated sensory modalities (the random and the random walk condition). The results show that in the random (uncertain and noisy) condition TD participants rely more heavily on prior information, resulting in a greater distribution towards the mean and the central tendency biases (Hollingworth, 1910) (for further explanation see Subchapter 4.5 in the discussion section). The error, as in differences between the expected – reproduced duration – and the presented interval of the given tasks and temporal variability are dependent on the volatility of the sequences (Glasauer & Shi, 2019; Lawson et al., 2017). The findings provide more information on how the brain processes temporal judgements and influences volatility. This model of higher-level processing of Bayesian modelling can be universalised beyond interval timing (Zhang & Zhou, 2017). Priors represent information about past and present environmental circumstances through extracting sensory stimuli and updating them with previous knowledge in order to form predictions of future outcomes (K. Friston, 2003, 2005, 2008). Thus, atypical processing as expected in ASD individuals an impaired utilisation of priors might lead to temporal and sensory sensation differences and disorientation.

Every prediction made of the environment is subject to two forms of uncertainty, expected as well as unexpected uncertainty (Yu & Dayan, 2005). In our study, unpredictable changes in the environment were created in the 'random condition'. The 'random walk condition' represents a relatively stable environment. Yu and Dayan further discussed the role of the neuromodulators acetylcholine and norepinephrine in the brain's calculation of uncertainty and its role in predictive coding. While acetylcholine stimulates the synapses in expected uncertainty, norepinephrine stimulates the brain in unexpected uncertain situations (Yu & Dayan, 2005). The results show that both neuromodulators interact within the perception of the environment and modulate calculating sensory input and top-down processing (Usher, Cohen, Servan-Schreiber, Rajkowski, & Aston-Jones, 1999). The importance and potential differences in neuromodulator interactions could be an interesting approach in temporal resolution tasks in ASD for future studies.

A recent study has shown that individuals with ASD have less surprised reactions in comparison to TD individuals when there is a violation of expectations (Lawson et al., 2017). The authors wanted to investigate how ASD individuals learn about volatility changes and whether the learning effect is compromised compared to TD individuals. They hypothesised that individuals with ASD would respond more to environmental volatility, learning to overestimate the volatility of the environment, and consequently be less sensitive to probabilistic relationships (because in a highly volatile environment these cannot be trusted). They evaluated this in a discrimination task in which a cue probabilistically predicted the upcoming stimulus. Participants with ASD showed a smaller difference in response time depending on whether the stimulus matched or violated the prediction based on the cue, and a reduction in surprise response to the unexpected violations of the cue-outcome contingency. The surprise response was demonstrated in pupil size changes (measured with an eye-tracker) which are thought to reflect neurological processing (noradrenaline, activity in the locus coeruleus) (Laeng, Sirois, & Gredebäck, 2012). In comparison to TD participants, participants with ASD showed smaller pupil size increases to violations of the cue-outcome contingency, but a larger pupil size increase in response to changes in the volatility of the stimulus sequence. The authors interpreted these findings as evidence that individuals with ASD have a greater "gain (precision) on cortical responses (prediction errors) under conditions of uncertainty" (Lawson et al., 2017, p. 10). "Adopt[ing] a high or low learning rate about volatility" (Lawson et al., 2017, p. 9) is crucial for creating long-term anticipations in a changeable environment and learning whether to heed a certain situation or not and, therefore, whether they rely more on prior knowledge or on the pure sensory intake.

This general tendency of ASD individuals to place greater importance on perceptual prediction errors compared to TD individuals is in accordance with the findings of Allenmark et. al (2020). In this study, more weight is given to prediction errors (distractors in an 'unlikely', unexpected position) in a visual decision-making task even though these errors should have been valued as irrelevant noise without any impact in learning rate in decision making. These findings, as well as our results of temporal processing, highlight the theory of an altered predictive-coding framework, sensory abnormalities and oversensitivity in ASD.

As a result of the 'reduced generalisation model' put forward by Plaisted (2001) and the impaired ability to draw connections of presented patterns as meaningful representations, ASD individuals often have restricted and overly detailed portrayals of observations. These poor abstract representations and a precise memory of certain situations consequently lead to a cascade of recalling a memory that best matches a new situation resulting in common rigid behaviour and diminished understanding of social customs (Sapey-Triomphe et al., 2018). The *lookup-table* (LUT) learning style, that focuses on learning each experience individually without extracting a globule consistency, is often overrepresented in ASD (Qian & Lipkin, 2011). In contrast, the interpolation (INT) learning style that mainly targets the ability to abstract and generalise and is more optimal for processing social habits than the LUT style, is prevalent in TD individuals. The LUT style results in poor prediction, overwhelming of sensory information (hypersensitivity) and resistance to change (Grandin, 2006).

4.2 The Weak Central Coherence Account (WCC)

When it comes to a conflict between the two levels of processing, individuals with autism favour the local processing style and as a result they have an increased local bias. Our results have shown that the influence from the previous experimental session was larger for the TD group than for the ASD group, thus in line with the WCC that the ASD individuals are more biased towards to recent "local" environmental cues.
Frith (2006) discusses a cognitive processing style regarding individuals in the autism spectrum tending to lack generalisation skills and not being able to see the bigger picture. The weak central coherence refers to a cognitive processing style containing a greater bias towards local processing, often resulting in a failure to extract the global meaning. It also focuses on explanations of the autistic impairments and on perceptual and attentional differences. The bias towards local processing provided the foundation for different learning styles, as discussed by Qian and Lipkin (Qian & Lipkin, 2011).

The argument that individuals are drawn to stable conditions where local cues can guide the perception of an accordingly 'safe' environment is also consistent with our findings. Our results show that the ASD group adapts less quickly to a different environment and is not influenced by prior beliefs. Instead, the ASD group shows a greater focus on sensory, local information. Furthermore, the ASD group showed less flexibility in coping with new environments. The findings can be seen as a result of an underlying weak central coherence and the lack of generalisation in addition to the predictive coding hypothesis (Friston, 2010; Friston & Kiebel, 2009).

4.3 The Central Tendency Effect

Judgement of time duration, or other quantities gravitates towards a mean value (Vierordt, 1868). Central tendency describes the effect of an overestimation of short intervals and an underestimation of long intervals, being drawn to a mean. Additionally, a context-dependency of estimated intervals is seen in temporal judgement, that is an estimation of same time intervals depends on the context in which they are presented (range of shorter or longer intervals influences and over- or underestimation) (Jazayeri & Shadlen, 2010a; Karaminis et al., 2016; Sciutti et al., 2014; Shi et al., 2013). This context-dependency is crucial when it comes to experimental settings as prior knowledge of a given sampled interval range can influence duration judgements. Not only in experimental settings, but also to accurately adapt and cope in an ever-changing sensory environment, predictive coding and the generation of a stable and reliable representation of the surrounding is beneficial.
Therefore, it has been argued that central tendency integrates the noisy sensory information with prior knowledge as a means to improve performance. As autistic perception is assumed to rely less on priors, central tendency effects should be decreased in individuals with ASD (Karaminis et al., 2016).

Our results reflect this theory, while we found that the central tendency effect was larger in the (high volatility) 'randomised' and less predictable condition and that it was indeed smaller for participants with ASD compared to the TD group, however not significant. Furthermore, our findings support our hypothesis and the aim of our experiment to investigate the influence of volatility on abnormal patterns of interval timing in ASD. That is that high volatility (random condition) in comparison to low volatility ('random-walk condition) leads to a stronger central tendency effect.

Additionally, we wanted to test whether higher scores in the AQ, indicating ASD symptom severity, has any relation to the central tendency effect (see *Figure 10*), however our analysis revealed no significant trend. Nevertheless, it showed a general reduction in a central tendency effect in the ASD group.

Bayesian theory can be applied in order to explain central tendency effects in interval duration reproduction tasks. Noisy sensory information (*likelihood)* is calculated with internal *prior* knowledge about the mean to postulate a final (perceptual) judgment *(posterior)*. Final judgments rely more heavily on the prior as the likelihood gets noisier. Therefore, accuracy is given up for a better reliability in a noisy situation. Strong and reliable priors generate a better outcome in noisy unstable situations and reduce incoming errors. Pellicano and Burr argued the more accurate perception of the world of individuals with ASD, as they do not rely as much on priors as TD individuals and focus more on the sole sensory stimulus (Pellicano & Burr, 2012).
Additionally, in accordance with Allenmark et. al (2021), findings discussed in Chapter 4.1 concerning altered decisions about where to direct attention in ASD and the oversensitivity to perceptual errors, further indicate why the ASD group showed a reduced central tendency effect in the noisier conditions in our experiment.

The results of Karaminis et. al.'s study (2016) revealed that autistic children show reduced use of priors and a decreased and insufficient regression towards the mean in order to have optimal perception and compensate their attenuated temporal resolution. Difficulties in keeping track of time are considered to be a characteristic in ASD. It is thought they can account for some autistic symptoms such as inflexibility when plans are changed or verbal communication. Meaning that autistic children do not use internal representations of a mean value (central tendency effect) in order to cope with noisy temporal resolution in comparison to TD children. On the one hand, this result could describe and explain difficulties of temporal perception and further explain autistic symptoms such as overwhelming sensations that uncertain and sensory overloaded situations bear.

4.4 Time Perception

Atypical time perception in ASD has been the focus of experimental research resulting in mixed opinions and findings. Our study aimed to shed light on timing processes in ASD and whether they are linked to ASD symptoms such as secondary symptoms that have been shown to be diminished in ASD (Hill, 2004) (e.g., perceptual dysfunctions or incomprehension of future outcomes).

In contrast to Szelag et al. (2004), who observed a reduced accuracy in reproduction of interval timing (reproduction of visual and auditory cues) in children with high-functioning ASD (the children produced durations of approx. 3,000 ms for all ten different durations ranging from 1,000-5,000 ms), we could not find comparable results that show a decreased performance of adults with ASD in reproduction. Instead, we witnessed a general overestimation of durations in both groups (see *Figure 7*).
Szelag et. al additionally discovered a relatively accurate reproduction of durations around 2-3 seconds in TD children, leading to the hypothesis of a few second intervals for storing information in the sensory system and neuronal processing of temporal integration (Szelag, Kowalska, Galkowski, & Pöppel, 2004; Szelag, Kowalska, Rymarczyk, & Pöppel, 2002). This finding is in accordance with the proposed *internal clock* model by Treisman and

colleagues, that suggests an internal pacemaker producing pulses according to the individual's arousal and that duration judgment is in proportion to the pulses (see more in Chapter 1.6) (Treisman, 1963; Treisman, Faulkner, Naish, & Brogan, 1990; Michel Treisman, Cook, Naish, & MacCrone, 1994). A possible interpretation is that different forms of arousal, memory, attention, emotion or other factors play an important role in psychological models of temporal perception and judgment (Szelag, Kowalska, Galkowski, & Pöppel, 2004). Consequently, an unpredictable arousal, differences in attention, working memory and focus might lead to an imprecise reproduction of time intervals and a greater variance in individuals with ASD (Dawson & Lewy, 1989; Kinsbourne, 1987; Martin, Poirier, & Bowler, 2010).
An unpredictable arousal and environment were demonstrated in the 'random' condition of our experiment. The performance of two ASD participants has shown a flattened pattern of duration reproduction in this condition. Both individuals reproduced the duration similarly across the random condition, however, not in the random walk condition (see *Figure 6*). As previously discussed, a mere misunderstanding of the task can be ruled out, since the two participants could reproduce the duration of the random walk condition. A possible explanation could be the mentioned different forms of arousal. That is, that individuals with ASD who experience secondary symptoms such as a heightened sensual sensitivity and an uncertainty about future outcomes might get disorientated in the random condition. However, after examining the AQ-test results of the two outliers, bearing in mind that a high AQ can be considered as a measurement of ASD traits and symptom severity, only one result has shown a convincingly high score (*46*, the other outlier *29*). This shows that a high symptom severity can also be ruled out as an explanation of the flattened pattern. Such peculiar reproduction behaviour warrants further investigation.
Other studies have indicated an impaired sensitivity and precision in interval timing in ASD participants (Allman et al., 2011; Brodeur, Gordon Green, Flores, & Burack, 2014; Gowen & Miall, 2005; Martin et al., 2010) and also led to the assumption of task-specific altered interval timing in ASD and an impaired ability to use predictive coding (see more Falter, Noreika, Wearden, & Bailey, 2012; Lambrechts, Falter-Wagner, et al., 2018). Different researchers have found no evidence of differences between temporal perception and reproduction in ASD compared to TD individuals and even a superior performance in longer durations (Gil, Chambres, Hyvert, Fanget, & Droit-Volet, 2012; Mostofsky, Goldberg, Landa, & Denckla, 2000; Wallace & Happé, 2008). These inconsistent findings could come from the different sample sizes used in the different studies and from different IQ-levels of the participants. Nevertheless, more insight is needed to gain a more homogeneous understanding of temporal perception.

The ability to perceive time is presumed to underlie sensory integration, motorcoordination and communication (Fraisse, 1963; Lambrechts, Falter-Wagner, et al., 2018; Szelag, Kowalska, Galkowski, & Pöppel, 2004). As timing is proposed to be diminished in ASD, the suggestion of atypicalities in motor behaviour, such as clumsiness, difficulties in social communication and interaction and sensory differences is comprehensible, since all these aspects include and require timing factors (e.g., production of speech and the ability to communicate effectively in social situations, eye gaze, sensory integration or correct joint movement and control) (Allman, 2011; Allman et al., 2011; Boucher, 2012; Lambrechts, Falter-Wagner, et al., 2018; Lord et al., 2000; Luyster et al., 2009).
It is difficult to determine the relationship between secondary symptoms such as interval timing abnormalities and cognitive or developmental disorders. However, it is plausible that impaired temporal perception in ASD could be causative for developmental processes that require and rely on accurate timing skills (Falter, Noreika, Wearden, & Bailey, 2012).

Temporal perception as in predicting future events, making assumptions about recurring situations or comprehending the order of events requires well-functioning computational skills of the brain (Yu & Dayan, 2005). These skills are explained in the Bayesian statistical theory and the 'Bayesian brain' perspective (Friston, 2010; Friston & Kiebel, 2009; Haker, Schneebeli, & Stephan, 2016). The Bayesian theory in ASD explains a different form of perception, meaning a "disbalance in the precision of prediction errors (sensory noise) relative to the precision of prediction (prior beliefs)" (Haker et al., 2016, p. 1). As a result, awareness of the environment is perceived by sensory inputs rather than by using prior knowledge (top-down processing). Top-down processing in the context of predictive coding requires calculating prior knowledge about the environment by using sensory input. A predictive error (sensory noise) occurs when there is a misunderstanding between the top-down predictions and the sensory input, e.g., a higher level of uncertainty in the environment.

As a result, perception is transferred to a greater detailed focus of the environment, and therefore difficulties in a proper understanding and interaction with the environment occur. Deficits in time processing might modify the ASD brain leading to difficulties in speech, social and cognitive functioning and influence of higher-level cognitive areas (Allman & Falter, 2015).

The literature and findings of many researchers shows that an altered time perception can be observed in ASD individuals. However, evidence is still rare, and the findings are controversial, which might be due to different modalities, the IQ of the participants and the environment individuals are in. Nonetheless, it has become clear that there is a difference in autistic time processing compared to TD individuals. Further and more extensive studies must be conducted in order to obtain more knowledge about this topic and importantly to embrace the relationship of time processing and higher cognitive functioning (e.g., executive functions) and a possible association with and origin of ASD characteristic symptoms.

4.5 From a Philosophical Point of View

> "That all our knowledge begins with experience there can be no doubt. For how is it possible that the faculty of cognition should be awakened into exercise otherwise than by means of objects which affect our senses, and partly of themselves produce representations, partly rouse our powers of understanding into activity, to compare, to connect, or to separate these, and so to convert the raw material of our sensuous impressions into a knowledge of objects, which is called experience? In respect of time, therefore, no knowledge of ours is antecedent to experience, but begins with it. But though all our knowledge begins with experience, it by no means follows that all arises out of experience."
> (Kant, 1781, AA28, translated by Meiklejohn).

Immanuel Kant (*1724 – †1804), the famous German philosopher, argues in his work *The Critique of Pure Reason* (German: *Kritik der reinen Vernunft*) (1781) that knowledge is limited by the human's capacity of perception and is a product of empirical knowledge one gains from experience – *a posteriori* – and knowledge that is derived from impressions – *a priori*. *A priori* describes a circumstance that is independent from experience or perception, purely obtained from reason through logical thinking.

Through knowledge derived from experience humans believe that things run accordingly in a certain manner, however, it does not teach that things could possibly exist otherwise (Kant, 1781). Kant discussed the existence of time and space. That is, that the representation and origin of space must be formed as a foundation in pure intuition and cannot be derived from

external experience, thus, the perception of space can only be given through internal representations of space *a priori* (see more in AA28-30 in Kant, 1781).
Consequently, Kant argues that objects can only be perceived and individually seen as such through an underlying internal concept or concerning Bayesian inference *prior knowledge* of space.
Concerning time, Kant postulates that without the *a priori* representation of time, individuals would not be able to have a sense of succession or coexistence, therefore, he rules out any other form of time perception from experience. Kant highlights the focus on given *a priori* sensuous intuition of time and of the individual's internal state and argues that "if this representation were not an intuition (internal) a priori, no conception, of whatever kind, could render comprehensible the possibility of change" (Kant, 1781, §§6).
Kant, however, names differences between the elements of time and space and the other senses. He argues that senses like taste, scent and colour perception can vary in peculiarity from individual to individual. In contrast, space and time are objective and are a given phenomenon.
The most important connection one can draw from the predictive coding frameweork back to Kantanism is the idea of the *top-down* prior generation of percepts and the brain's role. Which is, to use sensory inputs that are being processes and interpreted within a hierarchical structure to make sense of the world. While being exposed to random and unpredictable changes in the environment an organism must constantly updates it's believes and predictions about what is going to happen next in order to reduce surprising violations of its predictions (K. Friston, 2010; Karl, 2012).

"It may often be rather hard to say how much of our apperceptions as derived by the sense of sight is due directly to sensation, and how much of them, on the other hand, is due to experience and training."
(Helmholtz, 1866, v. 3, 10)

In his early studies the German physicist and physiologist Hermann von Helmholtz (*1821 – †1894) argues that through experience and external impressions humans learn to interpret spatial ideas and sensual perception. According to Helmholtz, representations of spatial concepts derive through physical alterations (such as binocular vision) and a combination of memories and experiences of sensations and he concludes that "the qualities of sensations belong only to our nervous system and do not extend at all into the space around us" (Helmholtz, 1867). He further argues that the mind adjusts as 'unconscious inference' in a way that a mediation of percept and internal processing is made before a conscious recognition. In a familiar environment 'unconscious inference' is helpful and efficient to perceive sensory inputs, since only few stimuli are necessary to build up an impression. However, Helmholtz concludes that in an unfamiliar environment 'unconscious inference' may often result in false assumptions (E G Boring, 1929) and consequently one might speculate that relying on the pure sensory input might be more reliable. This means that the prior often wrongly deceives perception, leading to false assumptions about the stimulus features. Thus, a mere reliance on the stimulus, as seen in ASD, would lead to a more accurate perception of the environment, as perception is not modulated by experience. Concerning ASD, this approach might support the idea of Pellicano and Burr's hypothesis about *hypopriors* (Pellicano & Burr, 2012). Our results are in line with this hypothesis, since the ASD group showed less reliance on prior knowledge and a reduced central tendency effect, meaning that one might argue that the ASD individuals see the world "more accurately" as Pellicano and Burr propose which can be in fact linked back to Helmholtz.

As Kant hypothesised that the process of perception is innate, Helmholtz agrees in a way that he believed that a sensory input is processed and interpreted in the brain prior to the subjective contact with it (Helmholtz, 1867). On the contrary, his "most important claim was, perhaps, that many of these inferences are learned rather than innate" (Oxenham, 2011, p. 1). Accordingly, unconscious processes analyse the present sensory cue while acknowledging the prior experience and its interpretation is the individual's perception (Boring, 1929; Kahl, 1971). In his famous work Helmholtz concludes that there is a difference between perception derived from pure sensory input and internal concepts of recognising these sensual stimuli, following the idea of a hierarchical model that incudes recognition through learned experiences. In modern research of cortical responses and processing the Helmholtzian perceptive of the brain "refers to a device or scheme that uses a generative model to furnish a recognition density and learns hidden structures in data by optimising the parameters of generative models" (Friston, 2010, p. 9). Modern computational neuroscience and cognitive processing, such as "predictive coding" (Clark, 2012; Friston, 2005; Friston & Kiebel, 2009; Haker et al., 2016), is presumed to have root in the Kantian and Helmholtzian approach (Swanson, Lebedev, Perlovsky, & De Vijver, 2016).

Consequently, the Bayesian model of learning (i.e., Bayesian framework) has roots in Hermann von Helmholtz's view of perception and unconscious inference (Helmholtz, 1867). He argued that ambiguity forms the basis of many impressions and in order to reduce this ambiguity one has to have prior knowledge about these impressions. The term 'unconscious inference' (German: unbewusster Schluss) refers to how our implicit prior knowledge affects what we perceive. Not only, information from visual impressions and other sensory organs are adequate to recreate the environment, but more importantly, knowledge established by experience plays an additional and crucial role when it comes to cognitive aspects of perception (Helmholtz, 1867). The hypothesis is in line with our results of an atypical processing in ASD individuals, the ASD group focused more on the sensory input rather than on prior knowledge, indicating less flexibility to adapt to a changing environment and no recognition through learned experience. As mentioned earlier, Helmholtz's belief and hypothesis that in an unfamiliar environment 'unconscious inference' might hinder the perception and interpretation of the world and could lead to false interpretations of the environment. Thus, atypical predictive coding in autism with broader priors or *hypopriors* results in a more "accurate" or in a less prejudged perception of the world as Pellicano and Burr and in a way Helmholtz discussed (Helmholtz, 1867; Pellicano & Burr, 2012).
In our experiment the ASD group was well able to solve the given task even with an attenuated reliance on prior knowledge. However, when it comes to generation of predictions in complex and social situations were a reliance on the posterior belief leads to a reduced violation of predictions, the Bayesian framework provides an explanation why certain perceptual deficits (such as the oversensitivity of sensory cues that is characteristic of ASD) arise.

4.6 General Discussion

The experiment was designed to examine interval timing performance in ASD and matched TD controls employing a paradigm allowing for variations of volatility with the same set of tested durations. In one condition (the random walk condition) the presented order of intervals was created by a Wiener process (see *Figure 5* (B)) and thus was more predictable, i.e., involatile. In the other condition, the order of presented intervals was randomised and thus was less predictable (the random condition), i.e., more volatile. The results show that the TD group adapts to a different environment more quickly and is influenced by the prior belief as expected (Shi, Church, et al., 2013). However, according to our hypothesis, individuals with ASD focused more on the sensory input and were less influenced by prior knowledge of the environment, showing less flexibility in coping with a changing environment.
Overall, the pattern of performance in the ASD group in comparison to the TD group confirms the predictive coding hypothesis of ASD (Pellicano & Burr, 2012). Predictive coding refers to the neurocognitive mechanisms by which prior sensory experience and knowledge is taken to shape interpretations of new incoming sensory information in order to allow for quick adaptation to an ever-changing sensory environment. Prior knowledge of a sampled interval range can influence duration judgements. Often shorter durations are overestimated; longer durations underestimated, this is known as the central tendency effect (Jazayeri & Shadlen, 2010; Shi, Church, & Meck, 2013). Recently, it has been shown that the central tendency effect depends on the volatility of the sequence (Glasauer & Shi, 2018) and therefore lends itself neatly to testing the predictive coding hypothesis of ASD (Pellicano & Burr, 2012).

Nevertheless, while we found a consistent performance across the ASD group, there were two individuals with ASD (<10% of the sample) showing a marked deviation with a pattern of opposite performance in the highly volatile condition (see *Figure 6*). In a relatively stable and predictable environment (the random walk condition) those individuals produced time intervals accurately. However, in a volatile and unpredictable environment (the random condition), they kept reproducing the same duration time and again across all trials and all presented intervals. Notably, this complete shutting down of external sensory input and sole dependence on an overly strong internal prior duration was only observed in the highly volatile, i.e., highly unpredictable, condition. In the involatile, i.e., predictable condition, they showed a reproduction pattern according to the pattern of the other 24 participants with ASD. Thus, a mere misunderstanding of the instruction is ruled out as a valid explanation of the deviant pattern of performance. Importantly, the different styles of randomisation in the two conditions are not discernible by participants and influence their performance implicitly. Indeed, all participants were asked in the debriefing whether they had spotted any difference between sessions, which were counterbalanced, and denied any such conscious differentiation. Another explanation of the outliers' performance could be that in the experimental design it is possible to perform well at the random walk condition entirely based on the given feedback after a completed trial without having understood the task, but not at the random condition. The participant always changes their produced duration according to the feedback from one trial to the next, regardless of the presented duration. In a random walk condition this might be a functional approach to solve the given task, however, in the random – more volatile – condition it might not work.

With respect to interval timing, ASD has been associated with decreased sensitivity for temporal intervals (e.g., Falter, Elliott, & Bailey, 2012; Isaksson et al., 2018 for sub second intervals; Martin, Poirier, & Bowler, 2010; Szelag, Kowalska, Galkowski, & Pöppel, 2004), the reason for which might be reduced task-specific allocation of neuronal resources

(Lambrechts, Falter-Wagner, & Wassenhove, 2018). However, several studies failed to show an abnormal pattern of interval timing in ASD (e.g., Isaksson et al., 2018 for suprasecond intervals; Jones et al., 2009; Mostofsky, Goldberg, Landa, & Denckla, 2000; Wallace & Happé, 2008). In line with these latter studies, we did not find a significant group difference with respect to overall accuracy, although the ASD group overestimated all durations to a greater, but not significant, extent when compared to the TD group (see *Figure 7*). This means that although individuals with ASD relied more on sensory input and less on prior knowledge in the current task, this did not result in a significantly decreased performance. It might well be, however, that stronger reliance on perceived durations and more veridical responding might lead to sufficient or decreased performance depending on task requirements, instructions and the exact range of durations tested.

5 Conclusion

The Bayesian inference or decision theory refers to the neurocognitive mechanisms that human predictions made about the environment are a result of combining the incoming sensory stimulus and the innate prior knowledge (Beck, Ma, Pitkow, Latham, & Pouget, 2012; Friston, 2010; Fuster, 2015; Pouget, Beck, Ma, & Latham, 2013). Our experimental findings are in line with the suggestions on characteristic alterations in hierarchical information processing in ASD: an under-utilisation of prior information and an increased focus on the sensory perception (Pellicano & Burr, 2012).
Pellicano and Burr propose that the Bayesion account can be transferred to and potentially explain the origins of perceptual differences such as temporal resolution seen in ASD.

On this ground, we aimed to analyse how ASD and TD individuals differentially cope with trial-to-trial differences in high and low volatility environments and the change of volatility. Prior knowledge of a sampled interval range can influence duration judgement. Our results confirmed – while directly investigating the learning of volatility in duration reproduction – the predictive coding hypothesis of ASD and suggested that individuals with ASD relied more on sensory information than on prior knowledge when performing interval reproduction tasks (Allenmark et al., 2020). The participants with ASD were able to solve the task in the current experimental study and can acquire high or low volatility changes. Hence, a different processing style of interpreting environmental stimuli, such as the lack of understanding the global meaning and a greater focus on (the sensory) details can be regarded as a cognitive style sometimes leading to a sufficient performance, as in the current task. It can also even lead to superior performance, as in the increased temporal resolution of events (e.g., Falter et al., 2012).
Nevertheless, consequences for understanding complex and fast-paced social situations with reduced reliance on prior knowledge could lead to difficulties in social functioning and management of an interpersonal world.
To summarise, these different perceptual-inference processes are understandable within the 'predictive-coding' framework (Friston, 2010; Friston & Kiebel, 2009). The association of sensory integration and social skills relies on hierarchical processing levels (Thye, Bednarz, Herringshaw, Sartin, & Kana, 2018). Thus, altered information processing and especially atypical predictive coding of time in ASD remains a reasonable attempt to explain differences in sensual perception.

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7 Appendix

7.1 Autism-Spectrum Quotient (AQ)

1. I prefer to do things with others rather than on my own.	strongly agree	slightly agree	slightly disagree	strongly disagree
2. I prefer to do things the same way over and over again.	strongly agree	slightly agree	slightly disagree	strongly disagree
3. If I try to imagine something, I find it very easy to create a picture in my mind.	strongly agree	slightly agree	slightly disagree	strongly disagree
4. I frequently get so strongly absorbed in one thing that I lose sight of other things.	strongly agree	slightly agree	slightly disagree	strongly disagree
5. I often notice small sounds when others do not.	strongly agree	slightly agree	slightly disagree	strongly disagree
6. I usually notice car number plates or similar strings of information.	strongly agree	slightly agree	slightly disagree	strongly disagree
7. Other people frequently tell me that what I've said is impolite, even though I think it is polite.	strongly agree	slightly agree	slightly disagree	strongly di sagree
8. When I'm reading a story, I can easily imagine what the characters might look like.	strongly agree	slightly agree	slightly disagree	strongly disagree
9. I am fascinated by dates.	strongly agree	slightly agree	slightly disagree	strongly disagree
10. In a social group, I can easily keep track of several different people's conversations.	strongly agree	slightly agree	slightly disagree	strongly disagree
11. I find social situations easy.	strongly agree	slightly agree	slightly disagree	strongly disagree
12. I tend to notice details that others do not.	strongly agree	slightly agree	slightly disagree	strongly disagree
13. I would rather go to a library than to a party.	strongly agree	slightly agree	slightly disagree	strongly disagree
14. I find making up stories easy.	strongly agree	slightly agree	slightly disagree	strongly disagree
15. I find myself drawn more strongly to people than to things.	strongly agree	slightly agree	slightly disagree	strongly disagree
16. I tend to have very strong interests and I get upset if I cannot pursue them.	strongly agree	slightly agree	slightly disagree	strongly disagree
17. I enjoy social chitchat.	strongly agree	slightly agree	slightly disagree	strongly disagree
18. When I talk, it is not always easy for others to get a word in edgewise.	strongly agree	slightly agree	slightly disagree	strongly disagree
19. I am fascinated by numbers.	strongly agree	slightly agree	slightly disagree	strongly disagree

20. When I’m reading a story, I find it difficult to work out the characters’ intentions.	strongly agree	slightly agree	slightly disagree	strongly disagree
21. I do not particularly enjoy reading fiction.	strongly agree	slightly agree	slightly disagree	strongly disagree
22. I find it hard to make new friends.	strongly agree	slightly agree	slightly disagree	strongly disagree
23. I notice patterns in things all the time.	strongly agree	slightly agree	slightly disagree	strongly disagree
24. I would rather go to the theater than to a museum.	strongly agree	slightly agree	slightly disagree	strongly disagree
25. It does not upset me if my daily routine is disturbed.	strongly agree	slightly agree	slightly disagree	strongly disagree
26. I often find that I don’t know how to keep a conversation going.	strongly agree	slightly agree	slightly disagree	strongly disagree
27. I find it easy to “read between the lines” when someone is talking to me.	strongly agree	slightly agree	slightly disagree	strongly disagree
28. I usually concentrate more on the whole picture, rather than on the small details.	strongly agree	slightly agree	slightly disagree	strongly disagree
29. I am not very good at remembering phone numbers.	strongly agree	slightly agree	slightly disagree	strongly disagree
30. I do not usually notice small changes in a situation or a person’s appearance.	strongly agree	slightly agree	slightly disagree	strongly disagree
31. I know how to tell if someone listening to me is getting bored.	strongly agree	slightly agree	slightly disagree	strongly disagree
32. I find it easy to do more than one thing at once.	strongly agree	slightly agree	slightly disagree	strongly disagree
33. When I talk on the phone, I’m not sure when it’s my turn to speak.	strongly agree	slightly agree	slightly disagree	strongly disagree
34. I enjoy doing things spontaneously.	strongly agree	slightly agree	slightly disagree	strongly disagree
35. I am often the last to understand the point of a joke.	strongly agree	slightly agree	slightly disagree	strongly disagree
36. I find it easy to work out what someone is thinking or feeling just by looking at their face.	strongly agree	slightly agree	slightly disagree	strongly disagree
37. If there is an interruption, I can switch back to what I was doing very quickly.	strongly agree	slightly agree	slightly disagree	strongly disagree
38. I am good at social chitchat.	strongly agree	slightly agree	slightly disagree	strongly disagree
39. People often tell me that I keep going on and on about the same thing.	strongly agree	slightly agree	slightly disagree	strongly disagree

40. When I was young, I used to enjoy playing games involving my imagination.	strongly agree	slightly agree	slightly disagree	strongly disagree
41. I like to collect information about categories of things (e.g., types of cars, birds, trains, plants).	strongly agree	slightly agree	slightly disagree	strongly disagree
42. I find it difficult to imagine what it would be like to be someone else.	strongly agree	slightly agree	slightly disagree	strongly disagree
43. I like to carefully plan any activities I participate in.	strongly agree	slightly agree	slightly disagree	strongly disagree
44. I enjoy social occasions.	strongly agree	slightly agree	slightly disagree	strongly disagree
45. I find it difficult to work out people's intentions.	strongly agree	slightly agree	slightly disagree	strongly disagree
46. New situations make me anxious.	strongly agree	slightly agree	slightly disagree	strongly disagree
47. I enjoy meeting new people.	strongly agree	slightly agree	slightly disagree	strongly disagree
48. I am diplomatic.	strongly agree	slightly agree	slightly disagree	strongly disagree
49. I am not very good at remembering people's date of birth.	strongly agree	slightly agree	slightly disagree	strongly disagree
50. I find it very easy to play games with children that involves pretending.	strongly agree	slightly agree	slightly disagree	strongly disagree

7.2 The Empathy Quotient (EQ)

1. I can easily tell if someone else wants to enter a conversation.	strongly agree	slightly agree	slightly disagree	strongly disagree
2. I prefer animals to humans.	strongly agree	slightly agree	slightly disagree	strongly disagree
3. I try to keep up with current trends and fashions.	strongly agree	slightly agree	slightly disagree	strongly disagree
4. I find it difficult to explain to other things that I understand easily, when they do not understand it the first time.	strongly agree	slightly agree	slightly disagree	strongly disagree
5. I dream most nights.	strongly agree	slightly agree	slightly disagree	strongly disagree
6. I really enjoy caring for other people.	strongly agree	slightly agree	slightly disagree	strongly disagree
7. I try to solve my own problems rather than discussing them with others.	strongly agree	slightly agree	slightly disagree	strongly di sagree
8. I find it hard to know what to do in a social situation.	strongly agree	slightly agree	slightly disagree	strongly disagree

9. I am at my best first thing in the morning.	strongly agree	slightly agree	slightly disagree	strongly disagree
10. People often tell me that I went too far in driving my point home in a discussion.	strongly agree	slightly agree	slightly disagree	strongly disagree
11. It doesn't bother me too much if I am late meeting a friend.	strongly agree	slightly agree	slightly disagree	strongly disagree
12. Friendships and relationships are just too difficult, so I tend not to bother with them.	strongly agree	slightly agree	slightly disagree	strongly disagree
13. I would never break a law, no matter how minor.	strongly agree	slightly agree	slightly disagree	strongly disagree
14. I often find it difficult to judge if something is rude or polite.	strongly agree	slightly agree	slightly disagree	strongly disagree
15. In a conversation, I tend to focus on my own thoughts rather than on what the listener might be thinking.	strongly agree	slightly agree	slightly disagree	strongly disagree
16. I prefer practical jokes to verbal humor.	strongly agree	slightly agree	slightly disagree	strongly disagree
17. I live life for today rather than the future.	strongly agree	slightly agree	slightly disagree	strongly disagree
18. When I was a child, I enjoyed cutting up worms to see what would happen.	strongly agree	slightly agree	slightly disagree	strongly disagree
19. I can pick up a topic quickly if someone says one thing but means another.	strongly agree	slightly agree	slightly disagree	strongly disagree
20. I tend to have very strong opinions about morality.	strongly agree	slightly agree	slightly disagree	strongly disagree
21. It is hard for me to see why some things upset people so much.	strongly agree	slightly agree	slightly disagree	strongly disagree
22. I find it easy to put myself in other people's shoes.	strongly agree	slightly agree	slightly disagree	strongly disagree
23. I think that good manners are the most important thing a parent can teach their child.	strongly agree	slightly agree	slightly disagree	strongly disagree
24. I like to do things on the spur of the moment.	strongly agree	slightly agree	slightly disagree	strongly disagree
25. I am good at predicting how someone will feel.	strongly agree	slightly agree	slightly disagree	strongly disagree
26. I am quick to spot when someone in a group is feeling awkward or uncomfortable.	strongly agree	slightly agree	slightly disagree	strongly disagree
	strongly agree	slightly agree	slightly disagree	strongly disagree

27. If I say something that someone else is offended by, I think that it is their problem, not mine.				
28. If anyone asked me if I liked their haircut, I would reply truthfully, even if I didn’t like it.	strongly agree	slightly agree	slightly disagree	strongly disagree
29. I can’t always see why someone was offended by a remark.	strongly agree	slightly agree	slightly disagree	strongly disagree
30. People often tell me that I am very unpredictable.	strongly agree	slightly agree	slightly disagree	strongly disagree
31. I enjoy being the center of attention at any social gathering.	strongly agree	slightly agree	slightly disagree	strongly disagree
32. Seeing people cry doesn’t really upset me.	strongly agree	slightly agree	slightly disagree	strongly disagree
33. I enjoy having discussions about politics.	strongly agree	slightly agree	slightly disagree	strongly disagree
34. I am very blunt, which some people find rude, even though this is unintentional.	strongly agree	slightly agree	slightly disagree	strongly disagree
35. I do not find social situations confusing.	strongly agree	slightly agree	slightly disagree	strongly disagree
36. Other people tell me I am good at understanding how they are feeling and what they are thinking.	strongly agree	slightly agree	slightly disagree	strongly disagree
37. When I talk to people, I tend to talk about their experiences rather than my own.	strongly agree	slightly agree	slightly disagree	strongly disagree
38. It upsets me to see an animal in pain.	strongly agree	slightly agree	slightly disagree	strongly disagree
39. I am able to make decisions without being influenced by people’s feelings.	strongly agree	slightly agree	slightly disagree	strongly disagree
40. I can’t relax until I have done everything, I had planned to do that day.	strongly agree	slightly agree	slightly disagree	strongly disagree
41. I can easily tell if someone else is interested or bored with what I am saying.	strongly agree	slightly agree	slightly disagree	strongly disagree
42. I get upset if I see people suffering on news programs.	strongly agree	slightly agree	slightly disagree	strongly disagree
43. Friends usually talk to me about their problems because they say that I am very understanding.	strongly agree	slightly agree	slightly disagree	strongly disagree
44. I can sense if I am intruding, even if the other person does not tell me.	strongly agree	slightly agree	slightly disagree	strongly disagree
	strongly agree	slightly agree	slightly disagree	strongly disagree

45. I often start new hobbies, but quickly become bored with them and move on to something else.				
46. People sometimes tell me that I have gone too far with teasing.	strongly agree	slightly agree	slightly disagree	strongly disagree
47. I would be too nervous to go on a big rollercoaster.	strongly agree	slightly agree	slightly disagree	strongly disagree
48. Other people often say that I am insensitive, though I do not always see why.	strongly agree	slightly agree	slightly disagree	strongly disagree
49. If I see a stranger in a group, I think that it is up to them to make an effort to join in.	strongly agree	slightly agree	slightly disagree	strongly disagree
50. I usually stay emotionally detached when watching a film.	strongly agree	slightly agree	slightly disagree	strongly disagree
51. I like to be very organized in day-to-day life and often make lists of the chores I have to do.	strongly agree	slightly agree	slightly disagree	strongly disagree
52. I can tune into how someone else feels rapidly and intuitively.	strongly agree	slightly agree	slightly disagree	strongly disagree
53. I don't like to take risks.	strongly agree	slightly agree	slightly disagree	strongly disagree
54. I can easily work out what another person might want to talk about.	strongly agree	slightly agree	slightly disagree	strongly disagree
55. I can tell if someone is masking their true emotions.	strongly agree	slightly agree	slightly disagree	strongly disagree
56. Before making a decision, I always weigh up the pros and cons.	strongly agree	slightly agree	slightly disagree	strongly disagree
57. I do not consciously work out the rules of social situations.	strongly agree	slightly agree	slightly disagree	strongly disagree
58. I am good at predicting what someone will do.	strongly agree	slightly agree	slightly disagree	strongly disagree
59. I tend to get emotionally involved with a friend's problems.	strongly agree	slightly agree	slightly disagree	strongly disagree
60. I can usually appreciate the other person's viewpoint, even if I do not agree with it.	strongly agree	slightly agree	slightly disagree	strongly disagree

7.3 The Systemising Quotient (SQ)

1. When I listen to a piece of music, I always notice the way it is structured.	strongly agree	slightly agree	slightly disagree	strongly disagree
2. I adhere to common superstitions.	strongly agree	slightly agree	slightly disagree	strongly disagree

3. I often make resolutions, but I find it hard to stick to them.	strongly agree	slightly agree	slightly disagree	strongly disagree
4. I prefer to read non-fiction than fiction.	strongly agree	slightly agree	slightly disagree	strongly disagree
5. If I were buying a car, I would want to obtain specific information about its engine capacity.	strongly agree	slightly agree	slightly disagree	strongly disagree
6. When I look at a painting, I do not usually think about the technique involved in making it.	strongly agree	slightly agree	slightly disagree	strongly disagree
7. If there was a problem with the electrical wiring in my home, I'd be able to fix it myself.	strongly agree	slightly agree	slightly disagree	strongly di sagree
8. When I have a dream, I find it difficult to remember precise details about the dream the next day.	strongly agree	slightly agree	slightly disagree	strongly disagree
9. When I watch a film, I prefer to be with a group of friends, rather than alone.	strongly agree	slightly agree	slightly disagree	strongly disagree
10. I am interested in learning about different religions.	strongly agree	slightly agree	slightly disagree	strongly disagree
11. I rarely read articles or webpages about new technology.	strongly agree	slightly agree	slightly disagree	strongly disagree
12. I do not enjoy games that involve a high degree of strategy.	strongly agree	slightly agree	slightly disagree	strongly disagree
13. I am fascinated by how machines work.	strongly agree	slightly agree	slightly disagree	strongly disagree
14. I make a point of listening to the news each morning.	strongly agree	slightly agree	slightly disagree	strongly disagree
15. In math, I am intrigued by the rules and patterns governing numbers.	strongly agree	slightly agree	slightly disagree	strongly disagree
16. I am bad at keeping in touch with old friends.	strongly agree	slightly agree	slightly disagree	strongly disagree
17. When I am relating a story, I often leave out details and just give the gist of what happened.	strongly agree	slightly agree	slightly disagree	strongly disagree
18. I find it difficult to understand instruction manuals for putting appliances together.	strongly agree	slightly agree	slightly disagree	strongly disagree
19. When I look at an animal, I like to know the precise species it belongs to.	strongly agree	slightly agree	slightly disagree	strongly disagree
20. If I were buying a computer, I would want to know exact details about its hard drive capacity and processor speed.	strongly agree	slightly agree	slightly disagree	strongly disagree
21. I enjoy participating in sport.	strongly agree	slightly agree	slightly disagree	strongly disagree

22. I try to avoid doing household chores if I can.	strongly agree	slightly agree	slightly disagree	strongly disagree
23. When I cook, I do not think about exactly how different methods and ingredients contribute to the final product.	strongly agree	slightly agree	slightly disagree	strongly disagree
24. I find it difficult to read and understand maps.	strongly agree	slightly agree	slightly disagree	strongly disagree
25. If I had a collection (e.g., CDs, coins, stamps), it would be highly organised.	strongly agree	slightly agree	slightly disagree	strongly disagree
26. When I look at a piece of furniture, I do not notice the details of how it was constructed.	strongly agree	slightly agree	slightly disagree	strongly disagree
27. The idea of engaging in "risk-taking" activities appeals to me.	strongly agree	slightly agree	slightly disagree	strongly disagree
28. When I learn about historical events, I do not focus on exact dates.	strongly agree	slightly agree	slightly disagree	strongly disagree
29. When I read the newspaper, I am drawn to tables of information, such as football league scores or stock market indices.	strongly agree	slightly agree	slightly disagree	strongly disagree
30. When I learn a language, I become intrigued by its grammatical rules.	strongly agree	slightly agree	slightly disagree	strongly disagree
31. I find it difficult to learn my way around a new city.	strongly agree	slightly agree	slightly disagree	strongly disagree
32. I do not tend to watch science documentaries on television or read articles about science and nature.	strongly agree	slightly agree	slightly disagree	strongly disagree
33. If I were buying a stereo, I would want to know about its precise technical features.	strongly agree	slightly agree	slightly disagree	strongly disagree
34. I find it easy to grasp exactly how odds work in betting.	strongly agree	slightly agree	slightly disagree	strongly disagree
35. I am not very meticulous when I carry out D.I.Y.	strongly agree	slightly agree	slightly disagree	strongly disagree
36. I find it easy to carry on a conversation with someone I've just met.	strongly agree	slightly agree	slightly disagree	strongly disagree
37. When I look at a building, I am curious about the precise way it was constructed.	strongly agree	slightly agree	Slightly disagree	strongly disagree
38. When an election is being held, I am not interested in the results for each constituency.	strongly agree	slightly agree	slightly disagree	strongly disagree

39. When I lend someone money, I expect them to pay me back exactly what they owe me.	strongly agree	slightly agree	slightly disagree	strongly disagree
40. I find it difficult to understand information the bank sends me on different investment and saving systems.	strongly agree	slightly agree	slightly disagree	strongly disagree
41. When travelling by train, I often wonder exactly how the rail networks are coordinated.	strongly agree	slightly agree	slightly disagree	strongly disagree
42. When I buy a new appliance, I do not read the instruction manual very thoroughly.	strongly agree	slightly agree	slightly disagree	strongly disagree
43. If I were buying a camera, I would not look carefully into the quality of the lens.	strongly agree	slightly agree	slightly disagree	strongly disagree
44. When I read something, I always notice whether it is grammatically correct.	strongly agree	slightly agree	slightly disagree	strongly disagree
45. When I hear the weather forecast, I am not very interested in the meteorological patterns.	strongly agree	slightly agree	slightly disagree	strongly disagree
46. I often wonder what it would be like to be someone else.	strongly agree	slightly agree	slightly disagree	strongly disagree
47. I find it difficult to do two things at once.	strongly agree	slightly agree	slightly disagree	strongly disagree
48. When I look at a mountain, I think about how precisely it was formed.	strongly agree	slightly agree	slightly disagree	strongly disagree
49. I can easily visualise how the motorways in my region link up.	strongly agree	slightly agree	slightly disagree	strongly disagree
50. When I'm in a restaurant, I often have a hard time deciding what to order.	strongly agree	slightly agree	slightly disagree	strongly disagree
51. When I'm in a plane, I do not think about the aerodynamics.	strongly agree	slightly agree	slightly disagree	strongly disagree
52. I often forget the precise details of conversations I've had.	strongly agree	slightly agree	slightly disagree	strongly disagree
53. When I am walking in the country, I am curious about how the various kinds of trees differ.	strongly agree	slightly agree	slightly disagree	strongly disagree
54. After meeting someone just once or twice, I find it difficult to remember precisely what they look like.	strongly agree	slightly agree	slightly disagree	strongly disagree
55. I am interested in knowing the path a river takes from its source to the sea.	strongly agree	slightly agree	slightly disagree	strongly disagree

56. I do not read legal documents very carefully.	strongly agree	slightly agree	slightly disagree	strongly disagree
57. I am not interested in understanding how wireless communication works.	strongly agree	slightly agree	slightly disagree	strongly disagree
58. I am curious about life on other planets.	strongly agree	slightly agree	slightly disagree	strongly disagree
59. When I travel, I like to learn specific details about the culture of the place I am visiting.	strongly agree	slightly agree	slightly disagree	strongly disagree
60. I do not care to know the names of the plants I see.	strongly agree	slightly agree	slightly disagree	strongly disagree

7.4 Beck Depression Inventory (BDI) (applied German Version)

Dieser Fragebogen enthält 21 Gruppen von Aussagen. Bitte lesen Sie jede Gruppe sorgfältig durch. Suchen Sie dann die eine Aussage in jeder Gruppe heraus, die am besten beschreibt, wie Sie sich in dieser Woche einschl. heute gefühlt haben und kreuzen Sie die dazugehörige Ziffer (0,1,2 oder 3) an. Falls mehrere Aussagen einer Gruppe gleichermaßen zutreffen, können Sie auch mehrere Ziffern markieren. Lesen Sie auf jeden Fall alle Aussagen in jeder Gruppe, bevor Sie Ihre Wahl treffen.

0 Ich bin nicht traurig
1 Ich bin traurig
2 Ich bin die ganze Zeit traurig und komme nicht davon los
3 Ich bin so traurig oder unglücklich, dass ich es kaum noch ertrage

0 Ich sehe nicht besonders mutlos in die Zukunft
1 Ich sehe mutlos in die Zukunft
2 Ich habe nichts, worauf ich mich freuen kann
3 Ich habe das Gefühl, dass die Zukunft hoffnungslos ist und dass die Situation nicht besser werden kann.

0 ich fühle mich nicht als Versager
1 Ich habe das Gefühl, öfter versagt zu haben als der Durchschnitt
2 Wenn ich auf mein Leben zurückblicke, sehe ich bloß eine Menge Fehlschläge.
3 Ich habe das Gefühl, als Mensch ein völliger Versager zu sein

0 Ich kann die Dinge genauso genießen wie früher
1 Ich kann die Dinge nicht mehr so genießen wie Früher
2 Ich kann aus nichts mehr eine echte Befriedigung ziehen
3 Ich bin mit allem unzufrieden oder gelangweilt
0 Ich habe keine Schuldgefühle
1 Ich habe häufig Schuldgefühle
2 Ich habe fast immer Schuldgefühle
3 Ich habe immer Schuldgefühle

0 Ich habe nicht das Gefühl, gestraft zu sein
1 Ich habe das Gefühl vielleicht bestraft zu werden
2 Ich erwarte bestraft zu werden
3 Ich habe das Gefühl bestraft zu gehören.

0 Ich bin nicht von mir enttäuscht
1 Ich bin von mir enttäuscht
2 Ich finde mich fürchterlich
3 Ich hasse mich

0 Ich habe nicht das Gefühl schlechter zu sein als die anderen
1 Ich kritisiere mich wegen meiner Fehler und Schwächen
2 Ich mache mir die ganze Zeit Vorwürfe wegen meiner Mängel
3 Ich gebe mir für alles die Schuld, was schiefgeht

0 Ich denke nicht daran, mir etwas anzutun
1 Ich denke manchmal an Selbstmord, ich würde es nicht tun

2 Ich möchte mich am liebsten umbringen
3 Ich würde mich umbringen, wenn ich es könnte

0 Ich weine nicht öfter als früher
1 Ich weine jetzt mehr als früher
2 Ich weine jetzt die ganze Zeit
3 Früher konnte ich weinen, aber jetzt kann ich es nicht mehr, obwohl ich es möchte

0 Ich bin nicht reizbarer als sonst
1 Ich bin jetzt leichter verärgert oder gereizt als früher
2 Ich fühle mich dauernd gereizt
3 Die Dinge, die mich früher geärgert haben, berühren mich nicht mehr

0 Ich habe nicht das Interesse an Menschen verloren
1 Ich interessiere mich jetzt weniger für Menschen als früher
2 Ich habe mein Interesse an anderen Menschen zum größten Teil verloren
3 Ich habe mein ganzes Interesse an anderen Menschen verloren

0 Ich bin so entschlussfreudig wie immer
1 Ich schiebe Erledigungen jetzt öfter als früher auf
2 Es fällt mir jetzt schwerer als früher, Entscheidungen zu treffen
3 Ich kann überhaupt keine Entscheidungen mehr treffen

0 Ich habe nicht das Gefühl, schlechter auszusehen als früher
1 Ich mache mir Sorgen, das ich alt und unattraktiv aussehe
2 Ich habe das Gefühl, dass in meinem Aussehen Veränderungen eintreten
3 Ich finde mich hässlich

0 Ich kann so gut arbeiten wie früher
1 Ich muss mir einen Ruck geben, bevor ich eine Tätigkeit in Angriff nehme 2 Ich muss mich zu jeder Tätigkeit zwingen
3 Ich bin unfähig zu arbeiten

0 Ich schlafe so gut wie sonst
1 Ich schlafe nicht mehr so gut wie früher
2 Ich wache 1-2 Stunden früher auf als sonst, und es fällt mir schwer, wieder einzuschlafen
3 Ich wacher mehrere Stunden früher auf als sonst und kann nicht mehr einschlafen

0 Ich ermüde nicht stärker als sonst
1 Ich ermüde schneller als früher
2 Fast alles ermüdet mich
3 Ich bin zu müde, um etwas zu tun

0 Mein Appetit ist nicht schlechter als sonst
1 Mein Appetit ist nicht mehr so gut wie früher
2 Mein Appetit hat stark nachgelassen
3 Ich habe überhaupt keinen Appetit mehr

0 Ich habe in letzter Zeit kaum abgenommen

1 Ich habe mehr als 2 Kilo abgenommen
2 Ich habe mehr als 5 Kilo abgenommen
3 Ich habe mehr als 8 Kilo abgenommen

Ich esse absichtlich weniger, um abzunehmen
[ ] ja [ ] nein

0 Ich mache mir keine größeren Sorgen um meine Gesundheit als sonst
1 Ich mache mir Sorgen über körperliche Probleme, wie Schmerzen, Magenbeschwerden oder Verstopfung
2 Ich mache mir große Sorgen über gesundheitliche Probleme, dass es mir schwerfällt, an etwas anderes zu denken
3 Ich mache mir große Sorgen über gesundheitliche Probleme, dass ich an gar nichts anderes mehr denken kann

0 Ich habe in letzter Zeit keine Veränderung meines Interesses an Sex bemerkt
1 Ich interessiere mich weniger für Sex als früher
2 Ich interessiere mich jetzt viel weniger für Sex
3 Ich habe das Interesse an Sex völlig verloren

Auswertung:
0-8 keine Depression(Summenwert)
9-13 minimale Depression
14-19 leichte Depression
20-28 mittelschwere Depression
29-63 schwere Depression

Gültig für 11 – 99 Jährige

7.5 Wortschatztest (WST)

Due to copy right, the applied test of crystallized intelligence (WST) cannot be demonstrated in the appendix.

7.6 Recruitment Text (applied German Version)

Liebe Probandin, lieber Proband,

Im Rahmen einer Studie zur visuellen und zeitlichen Wahrnehmung und Autismus-Spektrum-Störungen (ASS) suchen wir noch interessierte TeilnehmerInnen zwischen 18-65 Jahren. Sollten Sie schon einmal einen Krampfanfall erlitten haben oder an Epilepsie leiden, können Sie leider nicht an der Studie teilnehmen.

Ablauf des Experiments:

Es handelt sich hierbei um ein Wahrnehmungsexperiment, welches aus zwei Teilen besteht: *1.) visuelle Wahrnehmung 2.) zeitliche Wahrnehmung.* Dabei sollen Sie bestimmte Stimuli entdecken und diese per Knopfdruck bestätigen.

Der Zweck der Studie ist eine Untersuchung der Einflüsse von vorherigen Annahmen/ Erfahrungen (prior beliefs) auf die Wahrnehmung von Zeit und auf die visuelle Aufmerksamkeit. Es soll die Frage beantwortet werden, ob und wie diese Wahrnehmungs- und Aufmerksamkeitsaspekte sich bei Menschen mit einer ASS von typisch-entwickelten Probanden unterscheiden.

Zeitaufwand:

Jedes Experiment dauert jeweils ca. 60 Minuten – zwischen den Experimenten haben Sie ca. 60 Minuten Pause. Die Gesamtdauer beträgt somit ca 3 1/2 Stunden, dabei inbegriffen ist die Pause.

Ort:

Das Experiment findet in unserem Universitätslabor im Untergeschoss in der Leopoldstr. 13, München statt. Wir werden Sie an einem ausgemachten Treffpunkt in Empfang nehmen.

Aufwandsentschädigung:

Für Ihre Teilnahme erhalten Sie 10 € pro Stunde .

Terminfindung:

Wir können für Sie folgende Termine anbieten:

01. August 2018 - 10. September 2018 Montag bis Samstag von 9:00 Uhr - 18:00 Uhr.

Bitte melden Sie sich per E-Mail (studie.psy.lmu@gmail.com) bei den unten angegeben Ansprechpartnern, um genaue Termine festzulegen.

Bitte teilen Sie uns Ihren Wunschtermin mit. Wir schicken Ihnen dann eine Bestätigung, ob dieser Termin bzw. alternative Termine noch verfügbar sind.

Mit freundlichen Grüßen

Dr. Zhuanghua Shi
Dr. Christine Falter-Wagner
Dr. Fredrik Allenmark

Experimentdurchführung und Ansprechpartner für die Terminfindung:

Department Psychologie, LMU
Doktoranden:
Laura Alena Theisinger (0151-41469811)
Rasmus Lenz Pistorius (0176-31301575)
E-Mail: studie.psy.lmu@gmail.com

7.7 Explanation of the Experiment (applied German Version)

Experiment zur zeitlichen Wahrnehmung von Stimuli

Ihre Aufgabe in diesem Experiment ist es die **zeitliche Dauer von einem visuellen Stimulus** (ein gelber Kreis) **einzuschätzen,** welcher in der Mitte des Computerbildschirms abgebildet ist.

Ablauf einer Sitzung:

Legen Sie Ihr Kinn bitte in die dafür vorgesehene Halterung. Diese soll Ihnen helfen den Bildschirm optimal zu fixieren. Finden Sie eine für Sie angenehme Position bevor das Experiment startet.

Zu Beginn der Sitzung wird Ihnen kurz ein Fixierungs-Kreuz in der Mitte des Bildschirms angezeigt. Bitte fixieren Sie dieses Kreuz. Nach einer sehr kurzen Zeit wird anstelle des Kreuzes ein Punkt zu sehen sein. Das bedeutet, dass die Präsentation der Stimuli beginnen kann.

Mit **Pressen der Maustaste** beginnt die visuelle Präsentation der Stimuli. Bitte **halten** Sie jetzt die Maustaste so lange gedrückt wie der Stimulus (gelber Kreis) Ihnen angezeigt wird.

Der Stimulus (gelber Kreis) verschwindet automatisch. Sobald der Stimulus verschwindet, lassen Sie die Maustaste wieder los.

Bitte beachten Sie die ***genaue Zeitdauer*** des präsentierten Stimulus. Diese Dauer sollen Sie nun reproduzieren können.

Es erscheint wieder ein kleiner Punkt in der Mitte des Bildschirms. Halten Sie nun die **Maustaste so lange gedrückt, wie Sie die zeitliche Dauer der visuellen Präsentation eingeschätzt haben.**

Als Orientierungshilfe sehen Sie, während Sie die Maustaste gedrückt halten, wieder den gelben Kreis (Stimulus).

Nach jeder Sitzung bekommen Sie ein schnelles **Feedback**, wie gut Ihre Reproduzierung der zeitlichen Dauer war.

Dabei sehen Sie 5 Punkte in der Mitte des Bildschirms.
- Falls der äußerste linke Punkt aufleuchtet (rot), haben Sie die Taste zu kurz gedrückt.
- Falls der äußerste rechte Punkt aufleuchtet (rot) haben Sie zu lange gedrückt.
- Falls der Punkt in der Mitte aufleuchtet (grün) war Ihre Einschätzung perfekt.

Bitte beachten Sie, dass wir **zwei Sitzungen** haben, die jeweils aus 10-Mini-Blocks bestehen. Falls Sie möchten können Sie nach jedem einzelnen Block kurz pausieren (eventuell Ihre Sitzposition anpassen; Augen reiben; erneut konzentrieren usw.)

Nachdem Sie eine vollständige Sitzung beendet haben (10-Mini-Blocks) wird Ihnen dies auf dem Bildschirm angezeigt. Wir empfehlen Ihnen kurz die Tür zu öffnen und eine Pause zu machen bevor Sie die zweite Sitzung starten.

8 Note of Thanks

I would like to thank Professor Falkai, medical director of the clinic for psychiatry and psychotherapy of the Ludwig Maximilian University of Munich, for having the opportunity to conduct my dissertation at his clinic.
Further, I am very grateful for the supervision and help from my doctoral supervisor Professor N. Koutsouleris.

My special thanks go to my other doctoral supervisors Professor C. M. Falter-Wagner, Professor Z. Shi and Dr F. Allenmark for handing over this exciting topic and the excellent supervision of my thesis. Their outstanding expertise and constructive ideas were the foundation of the progress and success of this work. Thank you for your constant willingness to help and active support during the entire project, especially to Professor Z. Shi for your unconditional assistance.

At this point, I would like to acknowledge the time and effort of the participants to find the time in their schedules and the interest to take part in the experiments. It was a pleasure to make an acquaintance with each one of the participants.

I am exceptionally grateful for my colleague, research partner and boyfriend Rasmus Lenz Pistorius, without his support the conduction of the data and the discussion about the topic would not have been possible. Thank you for your endless encouragement and assistance.

An exceptional and heartfelt expression of thanks to my parents Karin and Martin Theisinger and to my entire family for their unconditional support and love throughout my entire life.

9 Affidavit

LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Promotionsbüro
Medizinische Fakultät

Eidesstattliche Versicherung

Theisinger, Laura Alena

Name, Vorname

Ich erkläre hiermit an Eides statt, dass ich die vorliegende Dissertation mit dem Titel:

Time Processing and Predictive Coding in Autism Spectrum Disorder

selbständig verfasst, mich außer der angegebenen keiner weiteren Hilfsmittel bedient und alle Erkenntnisse, die aus dem Schrifttum ganz oder annähernd übernommen sind, als solche kenntlich gemacht und nach ihrer Herkunft unter Bezeichnung der Fundstelle einzeln nachgewiesen habe.

Ich erkläre des Weiteren, dass die hier vorgelegte Dissertation nicht in gleicher oder in ähnlicher Form bei einer anderen Stelle zur Erlangung eines akademischen Grades eingereicht wurde.

Zürich, 28.10.2022 — Laura Alena Theisinger

Ort, Datum — Unterschrift Doktorandin ~~bzw. Doktorand~~

10 Publikationsliste

in Arbeit	Poster/Case Report: “Incidental Findings of Benign Pneumatosis Intestinalis in the Elderly; a Presentation of Three Cases”.
in Arbeit	Poster/Case Report: “Postinterventional Occurrence of Leiomyomatosis Peritonealis Disseminate after Myoma Enucleation with Morcellation; a Rare Finding.”
in Arbeit	“Predictive coding in ASD: Rigidity in adaptation rather than difficulties in learning about volatility” Shi, Z., Theisinger, L. A., Allenmark, F., Pistorius, R. L., Müller, H. J. & Falter-Wagner, C. M.
29.12.2020	“Acquisition and Use of 'Priors' in Autism: Typical in Deciding Where to Look, Atypical in Deciding What Is There.“Allenmark, F., Shi, Z., Pistorius, R. L., Theisinger, L. A., Koutsouleris, N., Falkai, P., Müller, H. J. & Falter-Wagner, C. M. (2020). *Journal of autism and developmental disorders*, 1-15.