Temporal parameters of communication in typically-developed individuals and individuals with autism spectrum disorder

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Note on the use of language

In autism studies, the use of an adequate manner of designation for the individuals concerned is an important issue for the stakeholders. There is currently no definite consensus on the preference for 'identity-first' or 'person-first' language. There are several studies showing that a majority in English-speaking countries endorse 'identity-first' language (Keating et al., 2022; Kenny et al., 2016). This contrasts with studies showing a majority preference for 'person-first' in non-English-speaking samples (Buijsman et al., 2022). Additionally, people with a higher experience of stigma rated 'identity-first' as offensive (Bury et al., 2022) and although a majority showed a preference for 'identity-first' language, minorities also endorsed 'person-first' language in the aforementioned studies (Keating et al., 2022; Kenny et al., 2016). In addition, even if one strives to be respectful of the identity and integrity of the individuals concerned, this can lead to different results depending on the perspective of the person making the statement (e.g., researchers; clinicians; people on the spectrum) (Kenny et al., 2016; Tepest, 2021).

In assembling the study samples of the current thesis, the presence of a clinically confirmed autism diagnosis was a main inclusion criterion. Based on this it seems appropriate to use ‘person-first’ language and referring to ‘Autism Spectrum Disorder’ (ASD) in alignment with the current designation in the ICD. An exception is Study 2, in which 'identity-first' language was used (see "Additional Information" section in Bloch, Viswanathan, et al., 2023 for an explanation of this decision). In addition, practical suggestions for respectful language are applied when applicable (Monk et al., 2022).

Notes on the text design

Please note that in the first part of the thesis, individual terms, sentences or parts of sentences are printed in bold to emphasize important aspects and thus improve the reading flow. To facilitate the distinction between *inter*- (between individuals) and *intra*- (within individuals) in the reading flow, these prefixes are highlighted in italics throughout the thesis. Cross-references to specific sections are indicated in bold with the section number and title.

Abbreviations

ASD	Autism Spectrum Disorder
MEA	Motion Energy Analysis
TD	Typically-Developed
JA	Joint Attention
SMS	Sensorimotor Synchronization
ITI	Inter-Tap-Interval
IOI	Inter-Onset-Interval
SCE	Synchronization Error
PCA	Principal Component Analysis
OSF	Open Science Framework
SP	Social Pointing
SCE	Synchronization Error

Studies and author contributions

Perspective article 1 (*published*):

Bloch, **C.**, Vogeley, K., Georgescu, A. L., & Falter-Wagner, C. M. (2019). INTRApersonal synchrony as constituent of INTERpersonal synchrony and its relevance for autism spectrum disorder. *Frontiers in Robotics and AI*, *6*, 73. https://doi.org/10.3389/frobt.2019.00073

Personal contribution to the results of the collaboration: CB conducted a literature review, wrote the first manuscript version, and implemented the comments of co-authors and reviewers in the final manuscript version.

Study 1 (*published*):

Bloch, **C.**, Tepest, R., Jording, M., Vogeley, K., & Falter-Wagner, C. M. (2022). Intrapersonal synchrony analysis reveals a weaker temporal coherence between gaze and gestures in adults with autism spectrum disorder. *Scientific Reports*, *12*(1), 1-12. https://doi.org/10.1038/s41598-022-24605-8

Personal contribution to the results of the collaboration: CB contributed to the design of the study protocol, wrote the experimental codes to collect and analyze the data, collected and analyzed the data, drafted the manuscript, created the figures, and implemented the comments of co-authors and reviewers in the final manuscript version.

Study 2 (*published*):

Bloch, **C.**, Viswanathan, S., Tepest, R., Jording, M., Falter-Wagner, C., & Vogeley, K. (2023). Differentiated, rather than shared, strategies for time-coordinated action in social and non-social domains in autistic individuals. *Cortex*, *166*, 207-232. https://doi.org/10.1016/j.cortex.2023.05.008

Personal contribution to the results of the collaboration: CB contributed to the design of the study protocol, wrote the experimental codes to collect and analyze the data, collected and analyzed the data, drafted the manuscript, created figures, and implemented the comments of co-authors and reviewers in the current manuscript version.

Study 3 (*submitted*):

Bloch, **C.**, Tepest, R., Jording, M., Koeroglu, S., Feikes, K., Falter-Wagner, C. M., & Vogeley, K. (2023, PREPRINT). Interacting with autistic virtual characters: Intrapersonal synchrony of nonverbal behavior influences participants' perception. *Open Science Framework*. https://doi.org/10.31219/osf.io/ukh9c

Personal contribution to the results of the collaboration: CB contributed to the design of the study, created virtual characters, animated virtual characters, wrote the experimental codes to collect and analyze the data, conducted the pilot study and analyzed the results from the pilot study, analyzed the data, created the visualizations, drafted the manuscript, and implemented the comments of co-authors in the current manuscript version.

Introduction

Humans are born into a social world. Social interaction is constitutive for the development of cognitive and behavioral repertoires from birth. By adulthood, individuals are equipped with sophisticated social cognitive capacities, characterized by intuitive, rapid, and automatic processes in interpersonal exchange (Fujiwara et al., 2020; Hove & Risen, 2009; Jaques et al., 2016; Langton & Bruce, 2000; Murphy & Hall, 2021; Nguyen & Gatica-Perez, 2015; Pan et al., 2021). For example, when people interact face-to-face, there is a dynamic and rapid exchange of verbal and nonverbal signals. During this exchange, interacting individuals implicitly and rapidly coordinate various signal modalities within themselves, placing them in a temporally coherent relationship with each other. They look at objects and make eye contact, gesture, speak, intonate, smile, etc., and these communicative modalities are expressed in parallel, in a self-synchronized manner. This results in individual time-series of multimodal communication that are the perceptual basis for decoding meaning and planning responses by the interaction partner. Thus, achieving functional self-synchrony may be a crucial basis for social reciprocity.

However, little research has been done on how individuals achieve self-synchrony, or *intra*personal synchrony. With respect to the study of human face-to-face interactions, research has provided significant advances in understanding the mechanisms of social interaction and their developmental trajectories. Besides numerous approaches that highlight *inter*personal synchrony as an essential feature of successful social interaction, the underlying mechanisms that lead to temporally coordinated interactions are not fully understood. The level of *intra*personal synchrony (i.e., temporal coordination within individuals) is a potentially decisive factor that could affect the quality and success of *inter*personal synchrony (i.e., temporal coordination between individuals). Nevertheless, it has been a neglected research topic so far.

Assuming that *intra*personal synchrony is shaped by social interaction from early infancy, is substantially mediated by temporal processing, and is likely to affect *inter*personal coordination, this topic is of importance for the field of autism research. Autism spectrum disorder (ASD) as a developmental disorder is associated with early characteristics in interactional behavior. These are still the main diagnostic criteria for ASD, although lower-level features related to sensory and motor functionality are receiving growing attention for the description of the phenotype. In adulthood, decreased *inter*personal synchrony is a promising objective marker for diagnosis and it provides an empirical approach to dysfunctional reciprocity in ASD. However, in order to understand why *inter*personal coordination fails, it seems imperative to examine the level of *intra*personal synchrony and thus to identify the predisposing individual temporal baselines, which may differ systematically between individuals with and without ASD. Studying *intra*personal synchrony can thereby provide essential insights not only into communicative differences in ASD, but also, independently of the clinical context, help to further develop theories that attribute a special role to temporal factors in communication. Thus, the systematic study of *intra*personal synchrony in adults with and without ASD will be centerpiece of this thesis.

In the first part of this thesis, selected theoretical end empirical approaches to human communication are discussed. In particular, studies are outlined that put a focus on temporal parameters observable in social interactions, also referred to as 'chronemics'. Besides temporal parameters between individuals in interaction, it is argued that temporal coordination of multimodal signals within interacting individuals, i.e., *intra*personal synchrony, is an essential prerequisite for *inter*personal temporal coordination. Findings from studies with infants and children are included illustrating that the development of *intra*personal synchrony emerges already in early childhood interactions. Against this background, ASD is discussed and theoretical considerations are given to the special role of *intra*personal synchrony for ASD. In line with this, the first publication of this thesis (Bloch et al., 2019) introduces a research agenda for the systematic study of *intra*personal synchrony. Starting from the question which behavioral domain is suitable for the investigation of *intra*personal synchrony, studies from the fields of gaze behavior, pointing gestures, and the development of their multimodal coordination in ASD and typical development are reviewed.

In the second part, own empirical studies are presented. To this end, three guiding questions are derived from the theoretical background, which are addressed sequentially in the empirical studies. First, the question of how to measure *intra*personal synchrony during a social interaction in adults with and without ASD is addressed, and the results of Study 1 (Bloch et al., 2022) are presented. Second, the question if an association exists between social and non-social synchronization behavior in adults with and without ASD is the focused study aim in Study 2 (Bloch, Viswanathan, et al., 2023). Third, the target question is what consequences group-specific *intra*personal synchrony production levels have for observers. For this purpose, the results from Study 3 (Bloch, Tepest, et al., 2023) are presented. Finally, the broader scope of this work is discussed leading to an outlook and suggestions for future research.

1. Theoretical background

1.1. Synchronized individuals in synchronized interactions

"*All forms of nonverbal communication messages have their own temporalities, beginnings and endings, startings and stoppings, zeros and ones, befores and afters, faster and slower, and so forth. Verbal messages, too, have major temporal features. We could not possibly communicate without human temporality*. (…) *We are homo temporalis*" (Littlejohn & Foss, 2009, p. 97). This excerpt describes the core idea of communication theories that put a special emphasis on temporal aspects of communication and which are termed **chronemics** (Bruneau, 1980, 2012; Littlejohn & Foss, 2009). While chronemics deal with all conceivable domains in which temporal aspects constitute or influence human communication (e.g., biological rhythms or timing of messages in computer-mediated communication), the focus here will be on behavioral observations of temporality during face-to-face interactions.

Many studies have shown that interacting individuals automatically adjust their behavior to each other in the temporal domain, as a result a shared rhythm in signal transmission becomes observable, a phenomenon called ***inter*personal synchrony** (Bernieri & Rosenthal, 1991; Cacioppo et al., 2014; Delaherche et al., 2012; Dunbar et al., 2022; Fujiwara et al., 2020; Yun et al., 2012). *Inter*personal synchrony has become an intensely studied phenomenon because of its assumed association with positive social consequences like bonding or rapport (Fujiwara et al., 2020; Hove & Risen, 2009; Miles et al., 2009; Tickle-Degnen & Rosenthal, 1990; Vacharkulksemsuk & Fredrickson, 2012; Valdesolo et al., 2010) and its systematic variation in psychopathological conditions (Altmann et al., 2021; Georgescu et al., 2020; Koehler et al., 2021; Kupper et al., 2015; Paulick et al., 2018; Walther et al., 2015). A related phenomenon is mimicry, which is the automatic and simultaneous adaptation of certain forms of interaction (e.g., poses) (Chartrand & Lakin, 2013; Lakin et al., 2008). Nevertheless, Delaherche et al. distinguish *inter*personal synchrony from mimicry in that "*synchrony is dynamic in the sense that the important element is the timing, rather than the nature of the behaviors*" (Delaherche et al., 2012, p. 3). This distinction is important in that synchrony clearly sets a **focus on temporal parameters in interaction** that are shaped by different forms of communication.

An established method for *inter*personal synchrony extraction from video recordings of dyads in interaction is 'Motion Energy Analysis' (MEA). The synchrony measure here is derived from alignments in time-series of motion energy whereby the amount of movement in a defined region of interest may be modulated by different communicative behavior (Ramseyer, 2020; Ramseyer & Tschacher, 2011), for example, leaning forward may result in a similar motion energy as moving an arm upwards. Other methodological operationalization of *inter*personal synchrony exist, yet the basic principle usually lies in the investigation of temporal associations between individual behavioral measurements (Dunbar et al., 2022; Fujiwara et al., 2021).

Thus, the **basis for measuring *inter*personal synchrony lies in the individual time-series**. Individual time-series on the other hand encode temporal parameters associated with each individual, see adaptation in schematic illustration in Figure 1. It can be assumed that the temporal parameters within these individual time-series constitute temporal structures or "gestalts", which are determined by internal synchronization processes. Accordingly, an early theoretical approach from the domain of chronemics emphasizes that endogenous, self-driven rhythmic processes that reside within the interacting individual are the fundamental building blocks of *inter*personal alignment (McGrath & Kelly, 1986). This observational level of ***intra*personal synchrony sets the focus for the individual in the interaction** that essentially constitutes the measurement and presumably also the emergence of *inter*personal synchrony.

Although it is plausible to assume that interactional processes also influences *intra*personal synchrony (i.e., individuals adapt behavior more or less to their interaction partner and to the dyadic rhythm), it is equally conceivable that the individual time-series still contains purely individual parameters. Arguably, such individual temporal baselines are particularly important at the beginning of interactions. More recent approaches even emphasize that the dynamic disruption of *inter*personal synchrony has crucial functions during social interactions, which in turn emphasizes the importance of individual focus (Galbusera et al., 2019; Likens & Wiltshire, 2021; Mayo & Gordon, 2020).

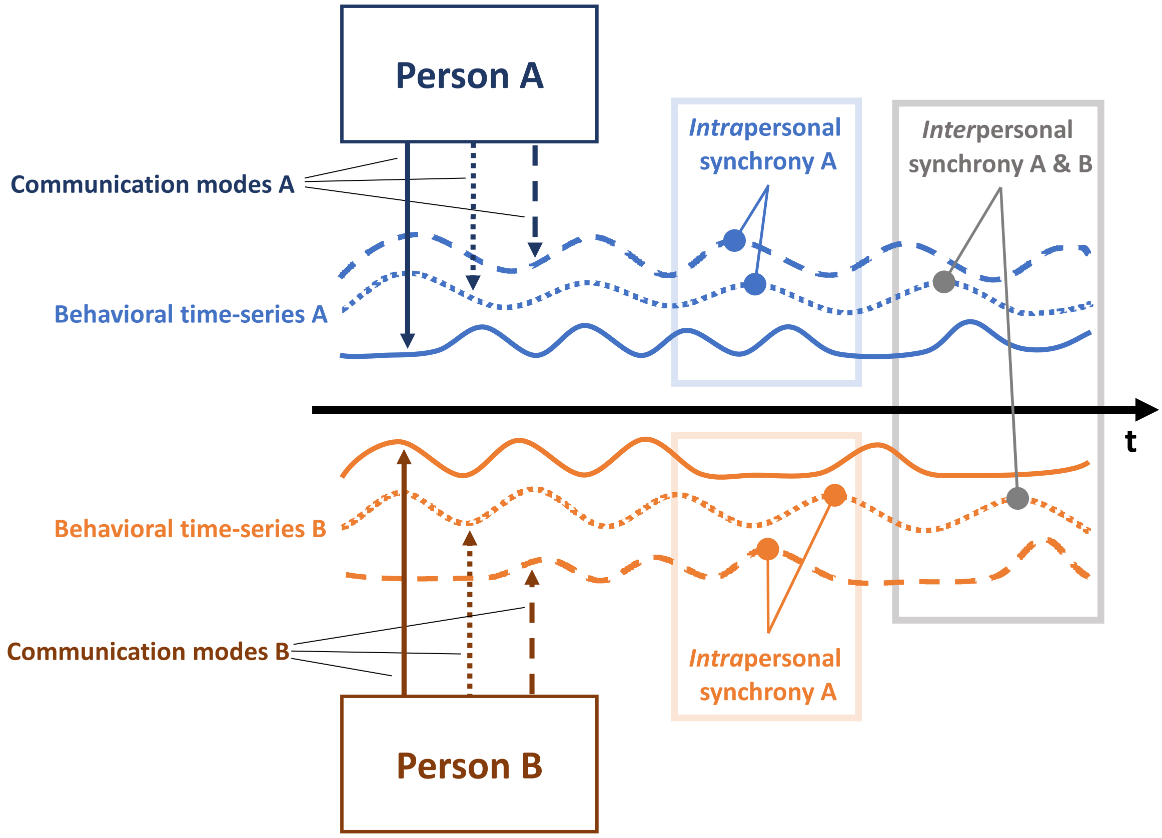

Figure 1. Schematic illustration of two levels of synchrony. Interaction sequence of person A and person B. Each individual communicates via different communication modes that constitute multimodal behavioral time-series per individual (solid, dashed, and dotted curves schematically represent event time-lines of different modes; e.g., speech, gaze, gestures). Temporal relations between these multimodal behavioral time-series within individuals form the level of intrapersonal synchrony. It is assumed that this *intra*personal level of temporal coordination constitutes the measurement of *inter*personal synchrony between A and B.

The elements that require *intra*personal synchronization in a social interaction and thus are to be integrated into a temporal relation are **communication events from different modalities** (e.g., gaze, gestures, speech, etc.). The temporal coupling of such multimodal events could be essential for smooth reciprocal exchange of information. As Streeck puts it: "*Generally we tend to disregard that the construction of messages is a process in time*" (Streeck, 1993, p. 296). As such, the way individuals temporally produce and thereby associate signals from different communication modalities could influence the decoding of meaningful messages by the counterpart and vice versa. Thus, ***intra*personal synchrony could be critical for the production of meaningful signal-units** that segregate the individual communication stream into cohesive bits that can be acted upon. For example, a gaze shift that is temporally coherent with a pointing gesture could constitute a perceived signal-unit that leads the observer to plan and eventually produce a certain response, e.g., to look at what is pointed and to name that object. In addition, a similarity in *intra*personal synchrony production and perception could be beneficial during signal exchange (Koban et al., 2019). Indeed, there is evidence that a matching of individually produced rhythms is predictive of *inter*personal synchrony during joint performance (Alderisio et al., 2017; Bégel et al., 2022; Tranchant et al., 2022; Zamm et al., 2016).

Yet how does *intra*personal synchrony arise in persons who interact with each other? In their social entrainment model, McGrath and Kelly emphasize the implicit character of temporal processes within and between interaction partners (McGrath & Kelly, 1986). Accordingly, it is fair to say that ***intra*personal synchrony comprises implicit processes**, so individuals are not aware of the processes that lead to temporally coordinated multimodal signals within themselves. Instead, observable temporal couplings of multimodal signals are subject to automatized processes that are practiced from an early age onwards. In this context, studies show that already children are capable of both *inter*personal timing (Beebe, 1982; Feldman, 2006, 2007a; Jaffe et al., 2001; Keller et al., 1999; Markova et al., 2019; Rochat et al., 1999; Tricia Striano et al., 2006) and systematic *intra*personal coordination of multimodal signals, such as vocalization/speech, gestures, gaze behavior, facial expressions (Franco, 2005; Iverson, 2010; Parladé & Iverson, 2011; Yale et al., 2003). Thus, ***intra*personal synchronizing mechanisms are likely developed from very early stages in ontogeny on** and likely contribute to the acquisition of an increasingly complex communication repertoire of an adult. As Parladé and Iverson put it: "*When typically-developing (TD) infants communicate, they not only do so through mutual eye gaze, facial expression, gesture, and vocalization, they do so by combining these communicative signals seamlessly into a single, multi-modal act. (…) Indeed, coordinated communication – or the co-production of more than one communicative behavior in time – is a crowning achievement in the early development of social communication*" (Parladé & Iverson, 2015, p. 2219).

As these early multimodal communication acts are directed towards mature and responsive observer (e.g., mother or caregiver), the coordinated or rhythmic self is inevitably socially shaped. This idea of a socially influenced temporal fine-tuning of *intra*personal synchrony processes is consistent with theories that postulate that social cognitive processes can only be understood by taking into account the history of social interaction (Bolis et al., 2023; Han et al., 2013; Schilbach et al., 2012). **In adulthood, *intra*personal synchrony is assumed to be based on mature social-cognitive processes** that have been refined by social interaction since early childhood. This makes *intra*personal synchrony a relevant construct for psychological conditions in which the development of social functioning is atypical from the beginning.

1.2. *Inter*- and *intra*personal synchrony in autism

Autism Spectrum Disorder (**ASD**) is a pervasive developmental disorder with difficulties in communication and social interaction as major diagnostic criteria according to diagnostic manuals (American Psychiatric Association, 2013; World Health Organization, 1993). In addition, there may exist sensory characteristics (Rosen et al., 2021; Tavassoli et al., 2014; Thye et al., 2018), motor features (Fournier et al., 2010; Gowen & Hamilton, 2013; McAuliffe et al., 2017), and co-occurring psychiatric diagnoses (Bloch et al., 2021; Ghaziuddin et al., 2002; Hofvander et al., 2009; Kim et al., 2000), among others, that characterize the ASD phenotype in adulthood, accounting for a highly heterogeneous population (Happé et al., 2006; Mottron & Bzdok, 2020). A recent line of research indicates that *inter*personal synchrony in interactions including individuals with ASD is reduced (Georgescu et al., 2020; Koehler et al., 2021; Noel et al., 2018). Strikingly, these studies report similar movement quantities in groups and no association of *inter*personal synchrony with basic motor coordination (i.e., self-reported dyspraxia) (see Koehler et al., 2021) suggesting that the reduced *inter*personal synchrony is not due to basic motor determinants but must be rooted elsewhere.

ASD is defined as a spectrum disorder, which means that the characteristics vary, but it is imperative to the diagnosis that **signs exist already in early childhood**, even if it is diagnosed not earlier than in adulthood. Numerous research findings point to particular features of social behavior in ASD as early as infancy (Colgan et al., 2006; Elsabbagh et al., 2012; Nyström et al., 2019; Ozonoff et al., 2014; Shumway & Wetherby, 2009; Stone et al., 1997; Trevarthen & Daniel, 2005). In particular, there are longitudinal studies of infants at high-risk for ASD that indicate **atypical development of *intra*personal synchrony**, showing that high-risk infants coordinate signals from different modalities less with each other (Gangi et al., 2014; Ozonoff et al., 2010; Parladé & Iverson, 2015; Winder et al., 2013). In adulthood, such implicit *intra*personal synchronization processes might present differently as a consequence of such early characteristics. Indeed, Feldman refers to time-sensitive periods in which synchrony might be particularly important (Feldman, 2007a). Likewise, Parladé and Iverson point at **sensitive developmental periods in which multimodal communication emerges** and social interaction becomes more complex (Parladé & Iverson, 2015). If characteristics of ASD irritate such sensitive periods, it could lead to cascading effects and it would conceivably be challenging to catch up with the level of temporal refinement of multimodal communication of typically-developed (TD) individuals.

In addition to the outlined developmental factors and other potentially important influences, such as mentalizing processes (David et al., 2008; Frith, 2001; Vogeley, 2017) or attentional characteristics (Happé, 1999; Happé & Frith, 2006; Plaisted, 2001) that could likely affect *intra*personal synchronization in ASD, studies that point to **deviations in basic timing processes in ASD** are particularly relevant to this work. As such, the way individuals perceive temporal intervals, temporally respond to sensory stimuli, or motorically produce time intervals could be associated with temporal parameters of communication behavior in the social domain. Indeed, numerous studies point to population-level differences between ASD and TD in perceptual timing tasks (Allman & Falter, 2015; Allman et al., 2011; Allman & Meck, 2012; Falter et al., 2013; Falter, Elliott, et al., 2012; Falter, Noreika, et al., 2012; Falter & Noreika, 2011), sensorimotor synchronization (SMS) (Morimoto et al., 2018; Vishne et al., 2021), and basic motor timing (Gowen & Hamilton, 2013; Morrison et al., 2018; Price et al., 2012). With regard to a possible relationship of such non-social features with social characteristics, Falter, Elliott, et al. (2012) report an association of atypical visual temporal processing with communication difficulties in adults with ASD. In addition, there are other studies that reported or theorized such **cross-domain relationships between social and non-social processes in ASD** (Hamilton & Pelphrey, 2018; Lense et al., 2021; Murat Baldwin et al., 2021; Thye et al., 2018; van de Cruys et al., 2014; Wimpory et al., 2002). Given the scope of this thesis, differences in basal, non-social timing processing contribute to the suggestion that multimodal communication processes may differ in the temporal domain in adults with ASD.

There is indeed evidence that **differences in *intra*personal synchrony in ASD persist beyond childhood**. In their pioneering study, de Marchena and Eigsti showed that adolescents with ASD produced similar amounts of co-speech gestures, but these were more asynchronous with the respective speech events, which was further related to deteriorated communication quality ratings by TD observers (de Marchena & Eigsti, 2010). Such differences in *intra*personal synchrony suggests itself as a predisposing factor for reduced *inter*personal synchrony. Given the hypothesized relevance of *intra*personal synchrony for social interactions and the evidence for deviations in *intra*personal synchrony in children and adolescents with ASD, it appears imperative to **establish a systematic study of *intra*personal synchrony in adults with ASD**. This may provide a deepened understanding of interactional characteristics, may provide novel objective diagnostic markers, and can potentially inform therapeutic interventions in the future. Noteworthy to mention is that *intra*personal multimodal timing differences are represented in diagnostic items of the ‘Autism Diagnostic Observation Schedule’ (ADOS; Lord et al., 2000). With reference to Figure 1, this level of *intra*personal synchrony should be assumed to constitute the patterns of the individual time-series of multimodal communication and ultimately the quantification of *inter*personal (mis)alignment - a proposition that has specific implications for a research agenda and is addressed in the first publication of this thesis.

1.2.1. Perspective article 1: INTRApersonal synchrony as constituent of INTERpersonal synchrony and its relevance for autism spectrum disorder

In this perspective article, studies supporting *inter*personal synchrony deviations in ASD are reviewed (Bloch et al., 2019). It is argued that temporal differences can also be observed at the *intra*personal level, which should be systematically examined to better understand the mechanisms that lead to *inter*personal (mis-)alignment. Accordingly, *intra*personal synchrony is viewed from a non-social perspective, targeting perceptual and motor timing studies in ASD, as well as from a social perspective, focusing on multimodal communication in individuals with ASD. **A research agenda to the systematic study of *intra*personal synchrony in adults with ASD** is proposed that includes two major branches of investigation, namely the study of *intra*personal synchrony production and perception. For the former, it is suggested to create real-life interaction scenarios and experimentally study self-synchronized time-series data from various communication modalities that compose the endogenous or individual signal streams. By that, for example, multimodal signal onsets can be analyzed what allows for the **quantification of temporal windows of (a-)typical signal coupling**. Furthermore, measures of dispersion and non-social timing measures are identified as important additional parameters to be examined. To study the perception side of *intra*personal synchrony, it is proposed to transfer measured parameters of produced *intra*personal synchrony to virtual characters in order to allow for an experimental investigation of **the effects of different expressions of *intra*personal synchrony on observers** in a standardized and controlled manner.

The outlined significance of *intra*personal synchrony for understanding *inter*personal communication in general and in the clinical context of ASD, as well as the research agenda derived from it, guided the empirical work of this thesis. In what follows, the study of *intra*personal synchrony will be further specified and candidate modalities for investigation are discussed.

1.3. Self-synchronized gaze and pointing gestures

Specifying the study of *intra*personal synchrony, the question arises which communicative modalities and their implicit *intra*personal synchronization are of interest. In this respect, the **special role of gaze in social interactions** should be considered. Gaze has a dual function as it is used not only to gather visual information as a sensory organ but importantly it also has a social function by delivering essential information to others about the current focus of attention (Argyle & Cook, 1976; Cañigueral & Hamilton, 2019; Emery, 2000; Jording et al., 2018). This way, gaze-cueing serves to convey one's perspective and interest in the spatial environment to another person and is one of the earliest means to establish **joint attention (JA)** (Brooks & Meltzoff, 2005; Brooks & Meltzoff, 2008; Farroni et al., 2002; Jording et al., 2018; Mundy & Newell, 2007; Senju & Johnson, 2009). JA includes behaviors that serve as important social cues to direct the partner's attention to a target in the environment (i.e., initiating JA) or responses to such referential cues of the partner (i.e., responding to JA) (Seibert et al., 1982). JA abilities develop around five months of age and continue to mature until around three years of age (Mundy, 2018; Striano & Reid, 2006). JA allows to share experiences and establish a common ground (Vogeley et al., 2001; Vogeley, 2017) and has been widely associated with the development of social cognition (Charman, 2003; Mundy, 2018; Mundy & Crowson, 1997; Mundy & Newell, 2007; Nyström et al., 2019; Tomasello et al., 2005).

Besides gaze as an essential communication modality during JA, **deictic pointing gestures** play a crucial role as referential cues to guide attention (Colonnesi et al., 2010; Diessel, 2006; Franco, 2005; Langton et al., 2000; Langton & Bruce, 2000; Leung & Rheingold, 1981; Liebal et al., 2009; Özçalışkan et al., 2016; Salo et al., 2018). Many studies examined unimodal gaze in JA processes only in standardized laboratory conditions, but gaze can become a rather ambiguous signal in naturalistic and spatially complex scenarios (Yu & Smith, 2017). In naturalistic scenarios, pointing gestures act as salient and robust cues; more specifically, the **coordination of pointing gestures with gaze** determined JA in infants and their parents (Yu & Smith, 2013, 2017, 2015). In line with that, Franco report a developmental timeline of gaze and pointing coordination from nine – 18 month of age (Franco, 2005), see Figure 2. In this, the author describes the emergence of gaze-pointing coordination from unimodal gaze-cueing to the strategic temporal coupling of gaze and pointing in order to achieve JA, suggesting that *intra*personal synchronization mechanisms of deictic gaze and pointing gestures are already acquired through social interactions in early childhood.

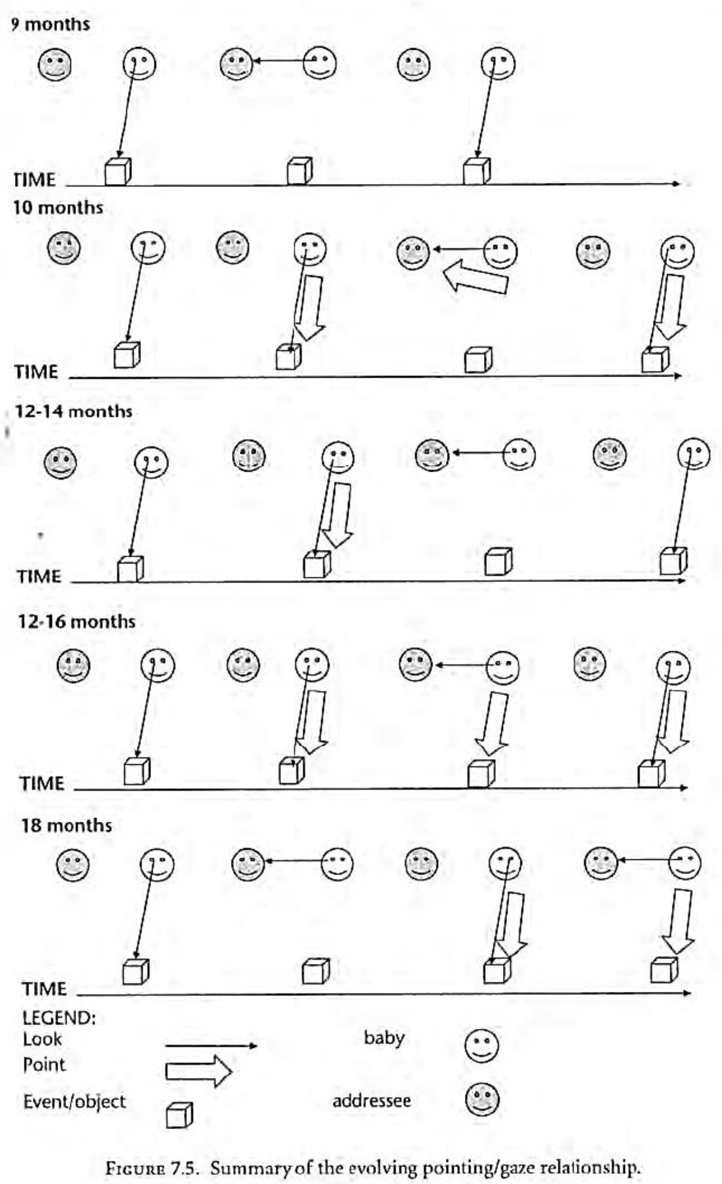

Figure 2. Development of gaze and pointing coordination from Franco (2005, p. 143). The schematic illustration is based on reports of behavioral observations of infants at different ages in interaction with adults across different studies. (Reproduced with the permission of The Licensor through PSLclear.)

Studies in adult samples show that gaze and pointing cues are automatically integrated (Caruana et al., 2021; Langton & Bruce, 2000), both can serve as triggers for attentional shifts possibly through common neural correlates (Sato et al., 2009), and motor studies show a strong functional coupling of the two modalities (Ballard et al., 1997; de Brouwer et al., 2021; Jana et al., 2017a, 2017b). Accordingly, it can be assumed that the production and perception of ***intra*personally synchronized gaze and pointing gestures in adulthood** result in implicit and automatized behavior.

1.3.1. *Intra*personally synchronized gaze and pointing gestures in autism

A large body of studies indicate **JA behavior as an early indicator of ASD** (Billeci et al., 2016; Bruinsma et al., 2004; Charman, 2003; Dawson et al., 2004; Nyström et al., 2019; Presmanes et al., 2007; Stallworthy et al., 2022; Sullivan et al., 2007). There is further evidence for persistent differences in JA in adults with ASD (Caruana et al., 2018; Redcay et al., 2013). Considering gaze as a referential signal, studies indicate intact gaze-following behavior while the subsequent processing of the information delivered by gaze seems to be atypical in infants with ASD (Bedford et al., 2012; Chawarska et al., 2003; Frischen et al., 2007; Senju et al., 2004; Thorup et al., 2022). Regarding deictic pointing, Stone et al. (1997) reported decreased frequencies of deictic pointing in young children with ASD, which is in line with findings of numerous other studies showing specific differences in the production and perception of declarative pointing gestures in ASD (Baron-Cohen, 1989; Camaioni et al., 2003; LeBarton & Iverson, 2016; Maes et al., 2021; Manwaring et al., 2018; Mastrogiuseppe et al., 2015; Mishra et al., 2021; Mundy et al., 1990; Ramos-Cabo et al., 2019; Sansavini et al., 2019; Shumway & Wetherby, 2009). Importantly, **children with ASD showed less complex multimodal combinations of communicative behavior** (Stone et al., 1997) and presented with differences in the functional integration of gaze and gestures (Buitelaar et al., 1991). These findings are further supported by a study that shows that children with ASD produced less multimodal combinations (i.e., gaze, gestures, and vocalization) and that specifically combinations of gaze with other modalities (e.g., with gestures) occurred less in the ASD group (Murillo et al., 2021). Based on this evidence, it can be inferred that **synchronization strategies for gaze and pointing gestures follow atypical developmental trajectories in individuals with ASD** and that differences potentially persist into adulthood, because major developmental periods may pass atypically (Parladé & Iverson, 2015).

Considering that *intra*personal synchronization of deictic gaze and pointing gestures is acquired early in TD individuals during JA processes and is subject to implicit, automatized processes in adulthood and, in contrast, is potentially subject to atypical developmental trajectories and deviations in temporal processing in ASD, *intra*personal synchrony was operationalized as the temporal coordination of gaze and pointing gestures in the empirical work of this thesis.

2. Open questions and research framework

Based on the theoretical background outlined above, open questions arise. Although studies suggest that *intra*personal multimodal communication develops differently in ASD and may further be altered through distinctive features in non-social domains (here specifically temporal processing deviations), it is still unclear whether *intra*personal synchrony is indeed persistently divergent into adulthood. Even though the pioneering study by de Marchena and Eigsti (2010) pointed to an asynchrony in multimodal signal coupling (i.e., increased temporal intervals between semantic aspects of speech and co-speech gestures) in adolescents with ASD, they did not measure communication behavior in an interactive scenario but in a narrative task without reciprocal nature. Thus, an ecologically valid and likewise standardized assessment of *intra*personal synchrony in adults with and without ASD during a social interaction is lacking. Furthermore, there is still a gap of knowledge about the relationship of social-communicative features with non-social features of the ASD phenotype. The assumption that there is a relationship between *intra*personal synchrony differences in the social domain and a particular temporal coordination mode in the non-social domain remains to be explored. In addition, further basic research is required to understand the perceptual processes involved in multimodal *inter*personal communication. In particular, open questions are how *intra*personal synchrony contributes to the perception of multimodal information and thereby how it affects observers' response behavior and impression formation.

In the following, three studies are summarized that constitute the empirical work of this thesis. The studies follow three successive guiding research questions, that will be targeted in the respective study in order to address the research desiderates presented before:

I. How can *intra*personal synchrony be measured in adults with and without ASD during a social interaction?

II. Does an association exist between synchronization in the social and non-social domains in adults with and without ASD?

III. What are the perceptual consequences of group-specific *intra*personal synchrony for observers with and without ASD?

All studies were clinically preregistered at the German register for clinical trials (https://drks.de/search/de/trial/DRKS00011271). Study 3 was additionally preregistered at the Open Science Framework (OSF) (https://doi.org/10.17605/OSF.IO/DT6VH). Code that was generated for the acquisition and analysis of data was made publicly available on OSF (see references in Appendences 2 - 4). All study procedures were approved by the ethics committee of the medical faculty of the University of Cologne (Reference number: 16-126). Recruitment of individuals with ASD for all studies was conducted via the specialized outpatient clinic for autism in adulthood at the University Hospital of Cologne. As such, all diagnoses were established in adulthood by specialized therapists based on standardized and manualized consensus diagnostic procedures based on the German S3 guidelines (Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften, 2016).

Besides publications in peer-reviewed journals, parts of the research have been presented at national and international conferences. Preliminary results of Study 1 were presented as a penal talks at the DGPPN (‘Deutsche Gesellschaft für Psychiatrie und Psychotherapie, Psychosomatik und Nervenheilkunde‘) 2020 and at the INFAR (‘International Society for Autism Research’) Annual Meeting 2021. Results from Study 1, Study 2, and Study 3 have been presented as scientific posters at the WTAS (‘Wissenschaftliche Tagung Autismus Spektrum’) in 2020, 2022, and 2023. The poster for Study 3 was awarded the 1st poster prize at WTAS 2023. Additionally, results from Study 3 will be presented as a poster at the INFAR Annual Meeting 2023.

2.1. Study 1: Intrapersonal synchrony analysis reveals a weaker temporal coherence between gaze and gestures in adults with autism spectrum disorder

With evidence from the literature suggesting that *intra*personal multimodal temporal coordination deviates in ASD, this study addressed the question: How can *intra*personal synchrony be measured in adults with and without ASD during a social interaction?

In this study (Bloch et al., 2022), an approach to this question is introduced in which *intra*personal synchrony was operationalized as the temporal coordination of deictic gaze and pointing gestures in an interaction task with a trained interaction partner (see Figure 3). Importantly, the measurement took place in a structured, but real social face-to-face interaction scenario, which should recruit realistic social-cognitive processes (Redcay & Schilbach, 2020; Schilbach et al., 2012). Additionally, the interaction task allowed a standardized measurement and ensured comparability between individuals due to the simple and repetitive implementation. In a repeated-measures design, participants had to indicate the appearance of a target stimulus to their interaction partner using only gaze and pointing gestures. No verbal communication was involved. Using eye-tracking technology and customized experimental software to record pointing events as a synchronized data-stream to gaze events, this setup enabled the acquisition of ecologically valid temporal parameters of *intra*personal synchrony with high precision.

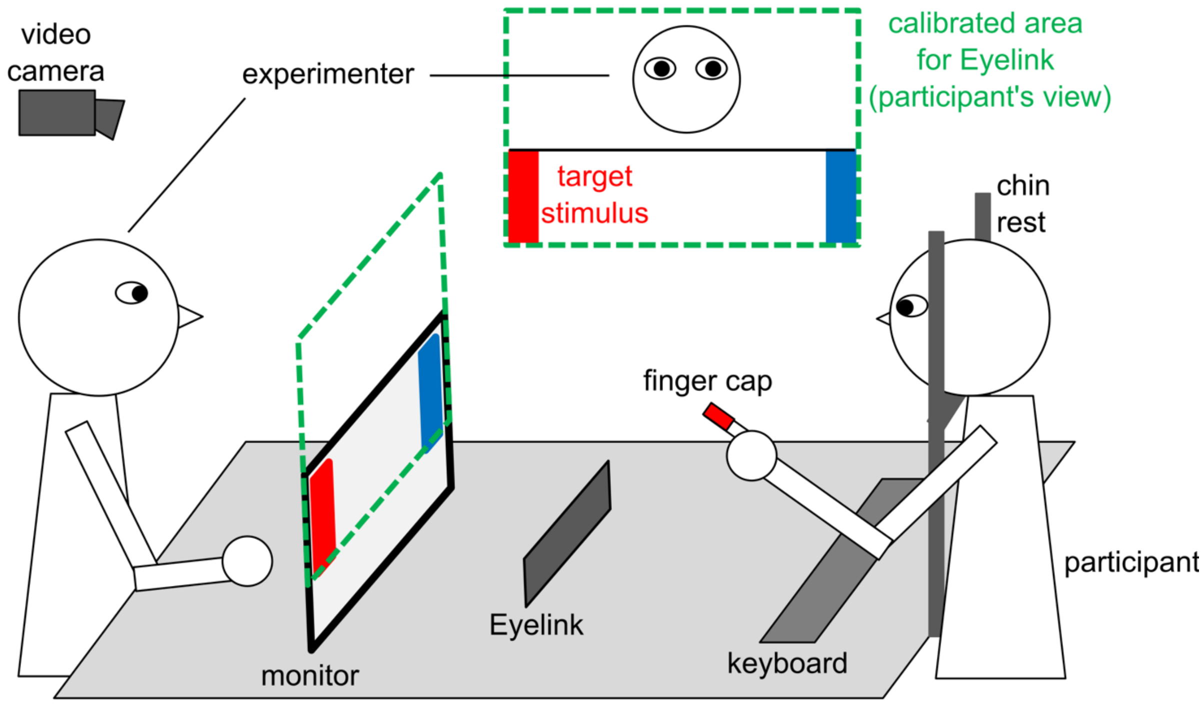

Figure 3. Study setup for *intra*personal synchrony assessment. The experimenter was the designated interaction partner during the task and sat opposite to the participants. A monitor facing the participants displayed the stimuli. An Eyelink 1000 Plus System (SR Research Ltd.) recorded participants' eye movements in 1000 Hz resolution. The calibrated area included the interaction partner's face area and the visual stimuli. A video camera recorded participants during all trials. (From Bloch et al., 2022)

A group of 24 adults with ASD (F84.5, according to ICD-10; World Health Organization, 1993) was compared to a group of 24 adults without any psychiatric or neurological diagnosis. Groups were matched with respect to age, gender identity, and handedness, and did not differ to a significant extent with regard to attention, and IQ.

Gaze data were preselected with a selection algorithm to assure that in all trials the gaze shift a) started with eye-contact between interaction partners, b) was not interrupted by more than one intermittent fixation, c) ended with a fixation of the target, d) was not affected by preceding blinks, and e) its onset preceded the pointing onset. Selected gaze shifts were ascribed a communicative quality in that they started with partner-oriented gaze according to the 'social gaze space' (Jording et al., 2018) and re-directed the partner's attention via relocating the gaze to the target of interest. Having the pointing gesture onset precisely synchronized to the gaze data, gaze-gesture delays in millisecond resolution as well as their *intra*personal stability (indicated by dispersion within individuals) could be compared between groups. In addition, video recordings were used as input to a frame-differencing algorithm that inferred the spatial position of the index finger per video frame. Thus, spatio-temporal properties of the pointing gestures were derived and analyzed as control measures.

According to the a priori hypothesis derived from the multimodal asynchrony between sematic aspects of speech and co-speech gestures reported by de Marchena and Eigsti (2010), results revealed enlarged gaze-gesture delays in adults with ASD. Deploying adequate statistical procedures to account for individual variance (i.e., multilevel modelling), this group difference was identified as significant beyond chance level (Figure 4).

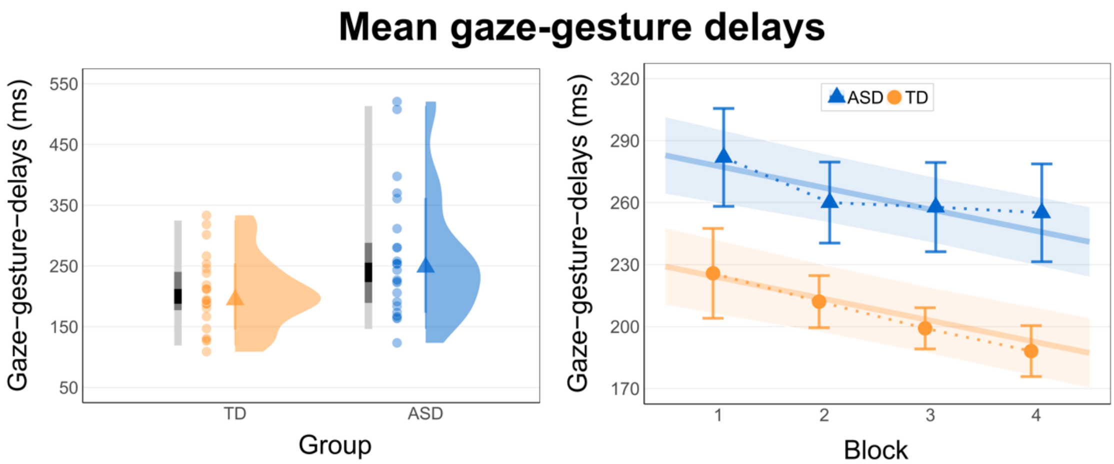

Figure 4. Gaze-gesture delays in groups and experimental blocks. Left panel: Subject-wise gaze-gesture delays, averaged for target sides (dots) in groups with vertical density plots and 95% colored confidence intervals (light grey = 95%; dark grey = 50%; black = 25%). Right panel: Group-wise aggregated gaze-gesture delays per block with standard errors of the means as error bars in both groups with linear regression lines and confidence bands. (From Bloch et al., 2022)

Further analyses revealed that enlarged gaze-gesture delays correlated with larger *intra*personal variability of delays. An extraction of movement trajectories showed that groups did not differ above chance level in the spatio-temporal properties of pointing gestures (i.e., gesture amplitudes and velocities). Likewise, there was no indication for significant group differences in the spontaneous usage of communication modalities in an unconstrained version of the interaction task that was conducted prior to the nonverbal (gaze and pointing) task version.

Essentially, this study introduces a paradigm that allows to study *intra*personal synchrony of nonverbal communication signals in a real *inter*personal scenario in a precise and at the same time ecologically valid way. Furthermore, results provide important evidence for enlarged and more variable temporal couplings of gaze and pointing gestures in adults with ASD. This is consistent with previous findings (de Marchena & Eigsti, 2010). Based on the results, *intra*personal synchrony in ASD was characterized as a weaker temporal coherence between conjoined multimodal signals. Having identified distinctive *intra*personal synchrony baselines between groups, a crucial ensuing question targets potential factors that are associated with the shift in temporal baselines between groups.

2.2. Study 2: Differentiated, rather than shared, strategies for time-coordinated action in social and non-social domains in autistic individuals

Having demonstrated hypothesis-compliant disparities in *intra*personal synchrony between individuals with and without ASD in Study 1, in this subsequent study the search for explanatory factors is pursued, addressing the question: Does an association exist between synchronization in the social and non-social domains in adults with and without ASD?

Besides synchronization deviations in social domains (Bloch, Tepest, et al., 2022; Fitzpatrick et al., 2016; Georgescu et al., 2020; Koehler et al., 2021; McNaughton & Redcay, 2020), synchronization differences in ASD were also reported in non-social domains (Morimoto et al., 2018; Vishne et al., 2021), however, the relationship of time-coordinated behavior in social and non-social domains is unresolved. Domain-general theories propose ASD-specific features that could affect social as well as non-social behavior (Hamilton & Pelphrey, 2018; Lense et al., 2021; Murat Baldwin et al., 2021; Thye et al., 2018; van de Cruys et al., 2014; Wimpory et al., 2002). In accordance and specific to this study, an ASD-specific general synchronization style was examined as a plausible correlate of atypical *intra*personal synchrony in adults with ASD. To approach this, a multivariate analysis procedure was conducted in Study 2 (Bloch, Viswanathan, et al., 2023).

Data from the sample of Study 1 (Bloch et al., 2022) was used in addition to data from two non-social timing tasks that were not reported in Study 1. These tasks included a self-paced motor timing task with no sensory input, and a sensorimotor synchronization (SMS) task that was conducted in two different sensory modalities and their combination (i.e., visual, auditory, audiovisual) and four sub- and supra-second inter-onset-intervals (IOI; i.e., 700; 900; 1200; 1800 ms), see Figure 5.

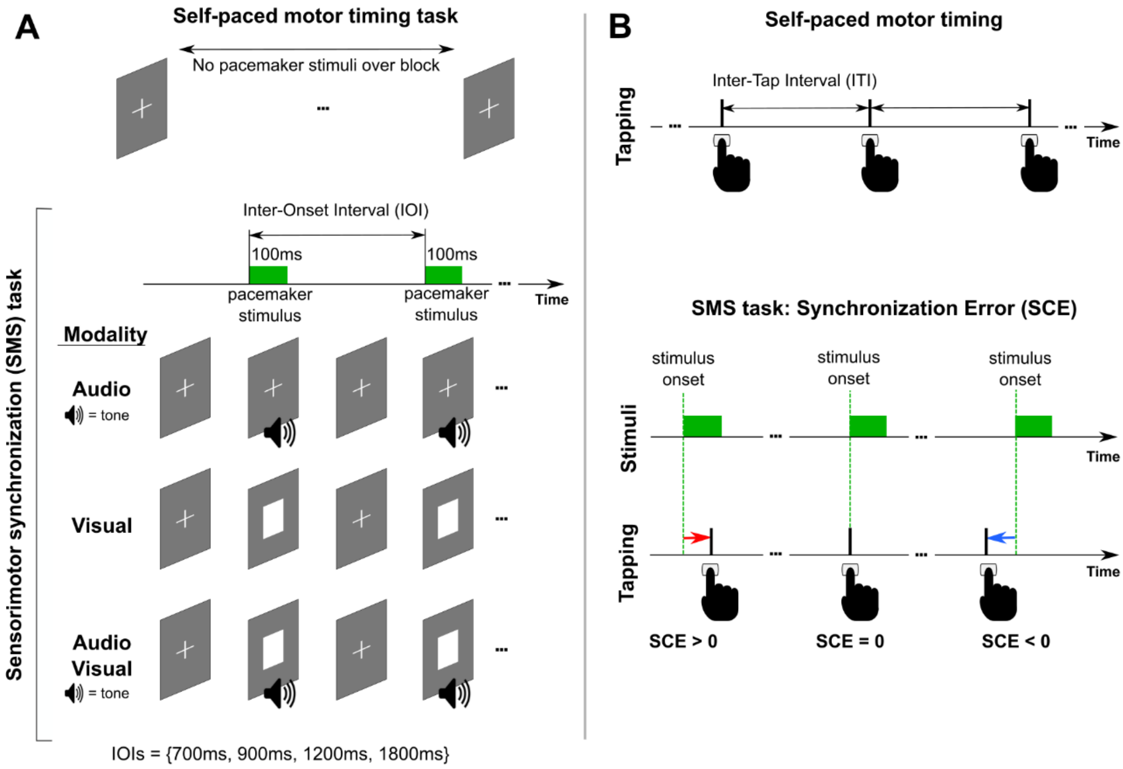

Figure 5. Stimuli and data from non-social timing tasks. The self-paced motor timing task (**A** and **B**, upper row) required participants to produce a steady pace of finger taps in a chosen pace. The data derived from that task were the inter-tap-intervals (ITI) and their *intra*personal variability. The SMS task (**A** and **B**, lower row) was conducted in two sensory modalities and their combination (auditory, visual, audiovisual), each presented in four different inter-onset-intervals (IOI). Participants were required to produce a finger tap in synchrony with each stimulus onset. The temporal deviation from stimulus onset and response (i.e., the synchronization error (SCE)) and its *intra*personal variability were calculated and analyzed as dependent variables. (From Bloch, Viswanathan, et al., 2022)

In addition to the timing parameters from the non-social tasks, further temporal parameters were extracted from the social pointing (SP) task that was used to quantify *intra*personal synchrony in Study 1 (Figure 3). This allowed to investigate the temporal structure of the full social-motor procedure, including the initiation and termination of multimodal events (Figure 6).

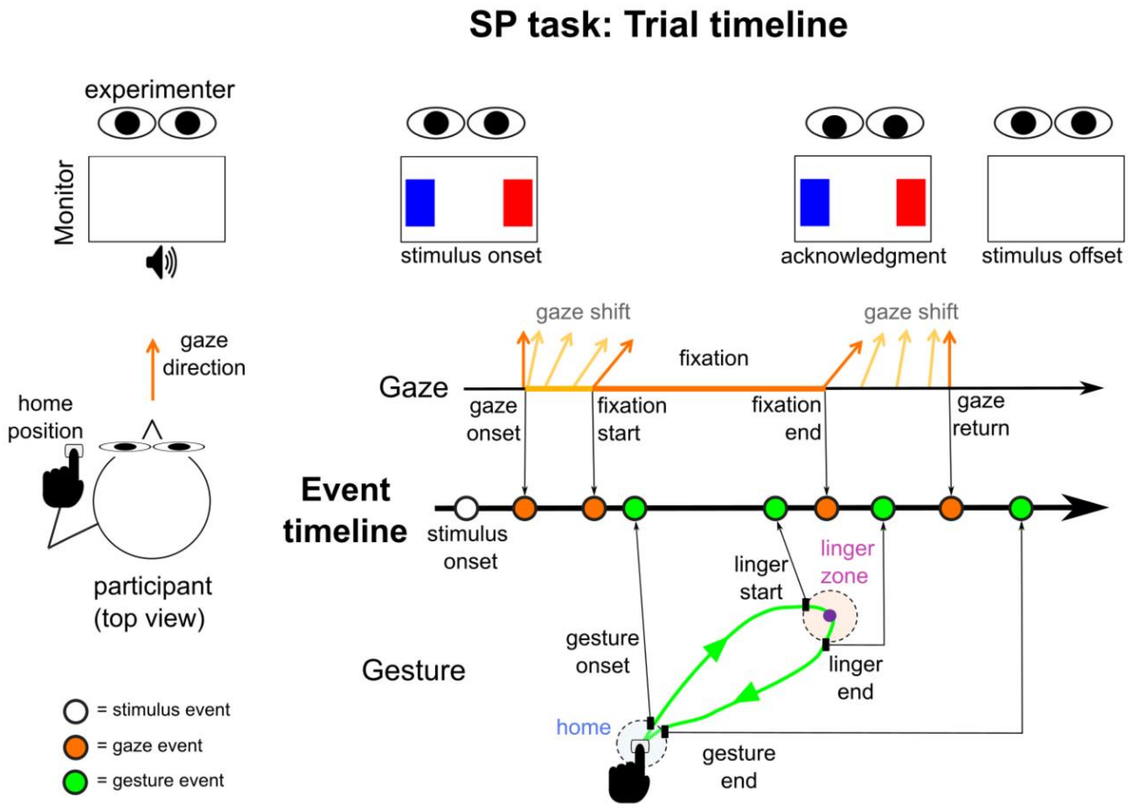

Figure 6. Trial procedure of the social pointing (SP) task. Stimulus timeline: After a tone participants established eye-contact with the experimenter who then initiated the stimulus presentation and acknowledged the nonverbal response by participants. Gaze event timeline: After eye-contact and stimulus onset, a gaze shift was conducted after which the target was fixated for a variable amount of time. Afterwards, the fixation was terminated and participants relocated their gaze somewhere else (e.g., back to interaction partner). Pointing gesture timeline: Some time after the gaze onset the gesture was initiated and the index finger was relocated in a pointing position, which was held for a variable amount of time (i.e., linger time in a spatial linger zone). After a self-chosen delay, the pointing gesture was terminated and the index finger was relocated to the home position. Event timeline: Multimodal events that were read out per trial. (From Bloch, Viswanathan, et al., 2022)

The analysis strategy was to first analyze population-level differences within the social and non-social domains separately. In order to infer the existence of group-specific synchronization styles, multivariate analysis at the individual-level (i.e., principal component analysis (PCA)) was conducted across parameters that accounted for the population-level differences in both domains.

Results in the non-social domain revealed no group differences in the self-paced motor timing task and in the variability of synchronization errors (SCE) derived from the SMS task. However, examination of mean SCE revealed that individuals with and without ASD adjusted their synchronized responses to different modalities and timescales distinctively, especially synchronization in the audiovisual condition showed substantial differences between groups.

Results in the social domain revealed distinctive coordination strategies during initiation and termination of multimodal signals between diagnostic groups: A parallel execution strategy in the TD group contrasted with a serial strategy in ASD during initiation. During termination, TD individuals terminated the target fixation coherently either shortly before or shortly after the termination of the pointing gesture; this pattern was less pronounced in the ASD group.

Importantly, considering cross-domain structural associations of synchronization strategies, PCA across parameters from both domains revealed cross-domain relationships for individuals in the TD group, indicative of a general synchronization style, while these were strikingly absent for individuals from the ASD group, see Figure 7.

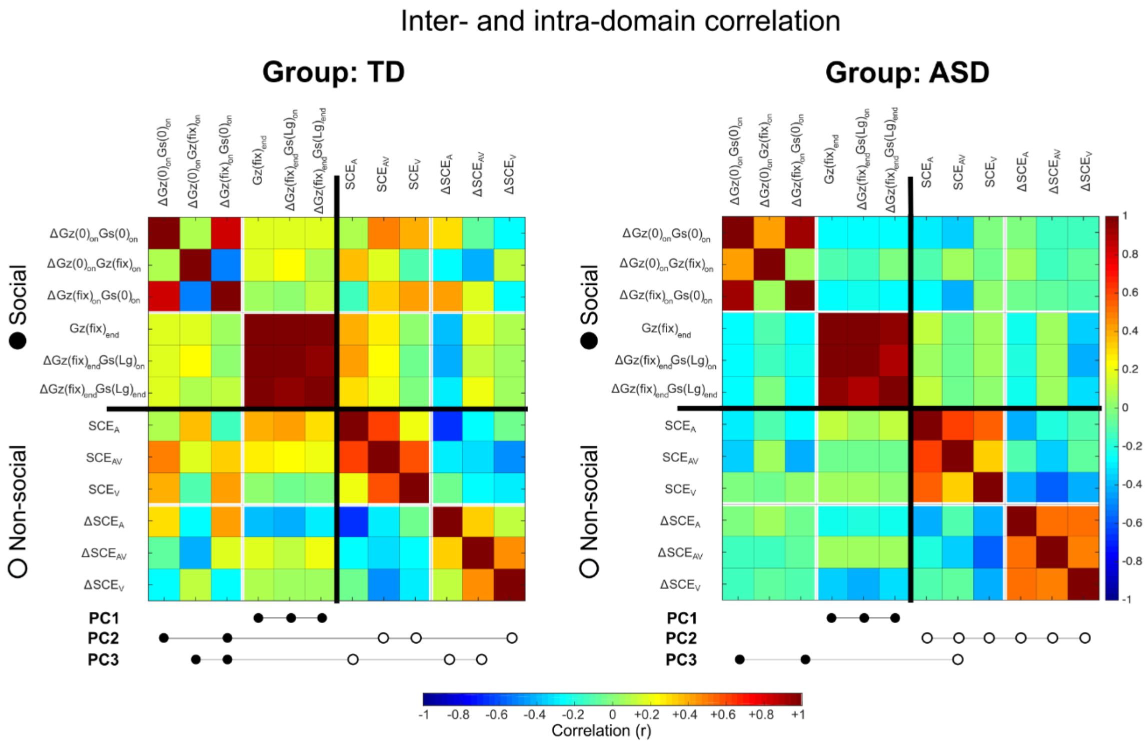

Figure 7. Cross-domain associations of social and non-social synchronization parameters. Correlograms are displayed separately for both groups, TD group left and ASD group right. Correlograms depict size and direction of bivariate Pearson correlation coefficients across different parameters. Upper left and lower right quarters show intra-domain correlations. Lower left and upper right quarters depict cross-domain correlations. Below the correlograms the compositions of principal components (PC) derived from Principal Component Analysis (PCA) with subsequent dimension reduction and Varimax rotation are shown. (From Bloch, Viswanathan, et al., 2022)

These results contradict a specific synchronization style in ASD, in which case we would have expected multivariate cross-domain relationships. Results rather indicate a divergence of and specialization within social and non-social synchronization behavior in ASD. Importantly, with regard to the lack of basic performance differences between groups (i.e., individuals with and without ASD were equally able to perform the tasks), the question arises how domain-general theories of ASD are to be proven with regard to the developmental heterogeneity and the acquisition of individualized alternative strategies to accomplish tasks. By pursuing this question, this study further provides a framework for individual-centered analyses that are in accordance with recent endeavors of precision medicine and neurodiversity in research (Fernandes et al., 2017; Monk et al., 2022) (see also section **3.4. Heterogeneity and cross-domain factors in ASD**).

Having measured *intra*personal synchrony and quantified group differences between adults with and without ASD in Study 1, and further analyzed potential associations with non-social synchronization behavior in Study 2, a subsequent question is what consequences such group-specific expressions of gaze-gesture synchronization entail for observers.

2.3. Study 3: Creating a virtual character from nonverbal behavior in autism: Effects on observers with and without autism

In this follow-up study, the research perspective is shifted from the production side to the perception side of temporal parameters of multimodal communication and the question is pursued: What are the perceptual consequences of group-specific *intra*personal synchrony for observers with and without ASD?

Consistent with the idea that *intra*personal synchrony processes serve the production of temporally coherent multimodal messages (i.e., signal-units), group-specific expressions of gaze-gesture delays, as identified in Study 1 (Bloch et al., 2022), may entail distinctive communicative effects on observers. Furthermore, *intra*personal synchrony differences are a potential candidate to explain unfavorable judgements of behavioral displays of individuals with ASD by TD observers (Edey et al., 2016; Grossman, 2015; Sasson et al., 2017). To test this, a virtual paradigm was developed in Study 3 that allowed a standardized examination of the perception of *intra*personal synchrony in a cross-design, testing observers with and without ASD (Bloch, Tepest, et al., 2023).

For the virtual task, spatial parameters from the participant setup in Study 1 and Study 2 (see Figure 3) were artificially reconstructed in a virtual room. Two virtual characters were created and preselected from 10 possible characters by a pilot study. These two characters were then animated by using real-life measurements from Study 1. As such, a controlled manipulation of *intra*personal synchrony was realized through two distinctive behavioral sets that only differed in the temporal coupling of the avatars' gaze and pointing signal onsets, while all other parameters were kept constant (see trial procedure in Figure 8). The two behavioral sets (red annotations of duration in Figure 8) were aligned to group-specific expressions of *intra*personal synchrony, so the ASD set ($IaPS_{ASD}$) differed from the TD set ($IaPS_{TD}$) in that it entailed enlarged gaze-gesture delays with a greater *intra*personal dispersion. All constant temporal parameters (eye contact duration, saccade latency, gaze shift duration, gesture duration) were approximated to averaged measurements from Study 1.

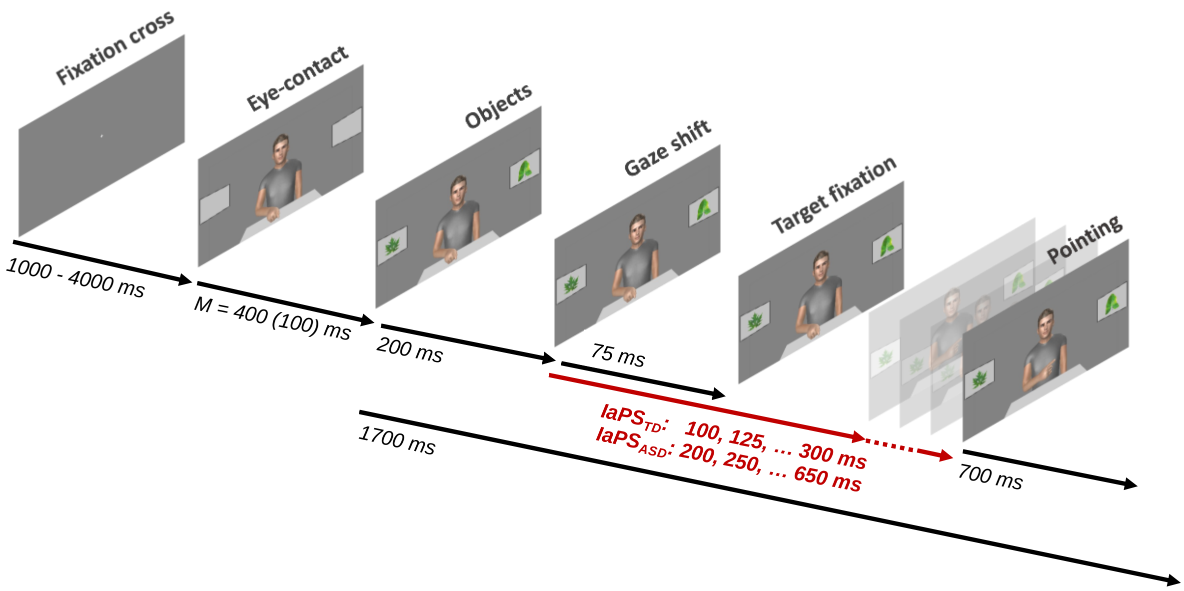

Figure 8. Trial procedure of the virtual interaction task. Each trial started with a fixation cross presented for a variable amount of time. Then the avatar appeared, gazing at participants for a variable amount of time. The variability in these initial trial phases should bring a natural dynamic to the interaction sequences. Next, the objects appeared, located left and right of the avatar on two virtual screens. After a short latency, the avatar shifted its gaze to one of the two objects. Then the avatar gazed at the object for a variable amount of time before the pointing gesture started. This gaze-gesture delay was specific to the respective behavioral sets ($IaPS_{TD}$ versus $IaPS_{ASD}$, see red annotations). After the pointing gesture reached its final linger position, the trial ended after a certain amount of time, depending on the gaze-gesture delay. The duration from object onset until trial end was fixed as well as the gesture duration from onset to linger position. (From Bloch, Tepest, et al., 2023)

During a virtual interaction task, participants were sequentially engaged with both characters, each displaying one of the two behavioral sets, either resembling the ASD or the TD behavioral pattern (i.e., $IaPS_{ASD}$ or $IaPS_{TD}$). In each trial, they were asked to select one of two objects via keypress, which were indicated nonverbally by their virtual partners. While doing so, gaze behavior, response times, as well as post-hoc impression formation were recorded. A group of 34 adult observers with ASD (F84.5, according to ICD-10; World Health Organization, 1993) was compared to a group of 34 TD observers. Groups were matched on age and gender identity, and did not differ with regard to verbal IQ, and attention.

Results revealed that interactions with the virtual character resembling ASD-like behavior ($IaPS_{ASD}$) led to overall extended decoding times – especially in observers with ASD. Linear mixed effects models showed that these effects were beyond chance level. Response times across the delay conditions further showed a linear increase in decoding times in both groups. This contradicts the assumption that the primary gaze signal was sufficient for making a decision (in which case we would have expected a flatlining of decoding times across IaPS levels). However, this linear increase was not linked to specific gesture events, further contradicting a specific gesture anchor for decisions (e.g., responses at pointing peak). In contrast to these possible unimodal strategies, on the group-level results rather indicate an integration of gaze with subsequent pointing by observers with and without ASD.

However, observers from both groups seemingly used different strategies to achieve an integration of multimodal signals and generating adequate responses. A classification of the gaze behavior of the observers allowed to examine such strategies during decoding in more detail, see Figure 9. This exploratory analysis showed that TD observers very consistently paid overt attention to the region of the characters' eyes, i.e., they used a common gaze-focused decoding strategy that was associated with efficient and fast responses. In contrast, observers with ASD deployed strikingly variable decoding strategies that were no longer systematically related to the characters eye region.

There were no effects of *intra*personal synchrony conditions on post-hoc impression formation in observers with and without ASD.

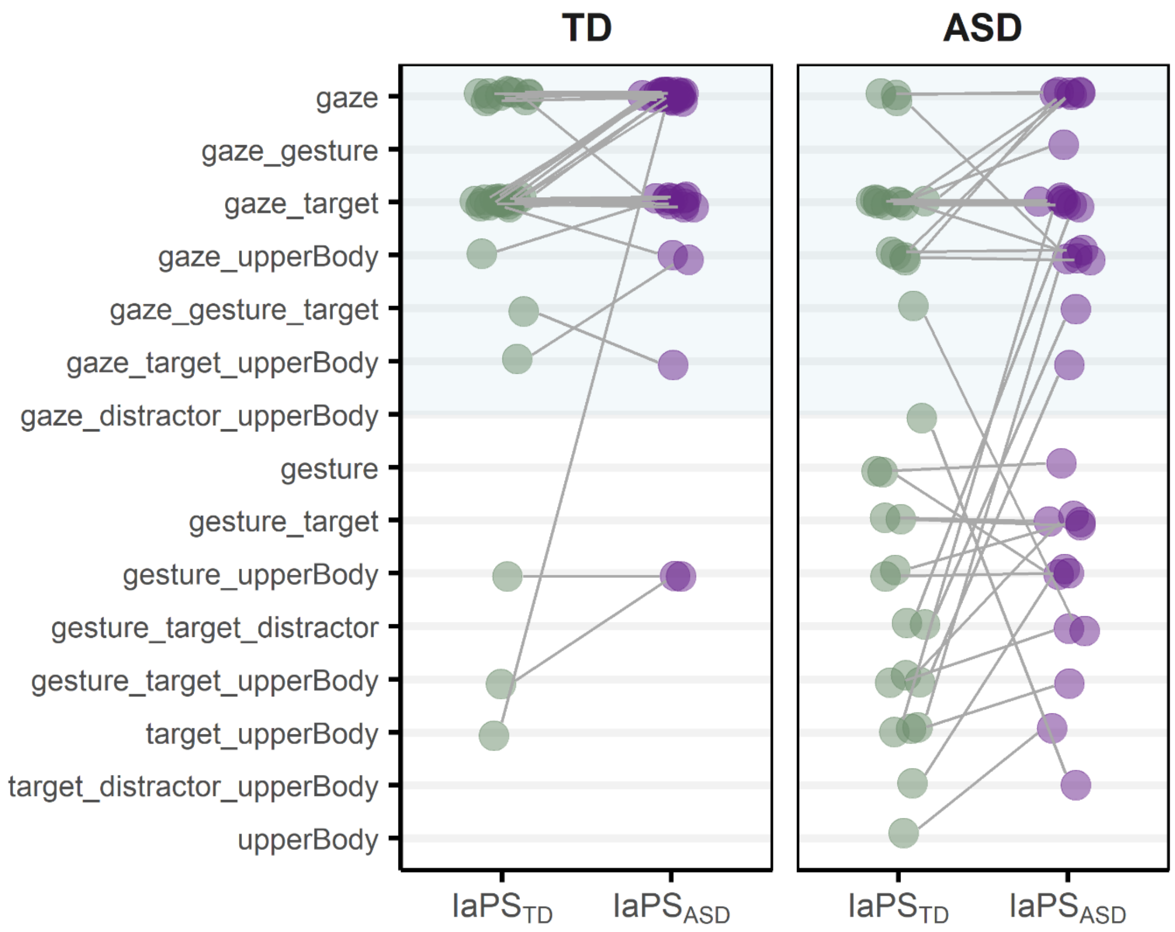

Figure 9. Gaze types in two different *intra*personal synchrony conditions. Gaze types displayed on y-axis. Dots display gaze types for each subject in *intra*personal synchrony conditions (IaPS$_{TD}$ left; IaPS$_{ASD}$ right) in both observer groups (TD left panel; ASD right panel). Two dots per participant are connected with grey lines. Horizontally aligned grey lines show individuals whose gaze type did not vary across conditions; vertical lines show individuals whose gaze type varied with *intra*personal synchrony condition. Light blue area marks gaze types that include the eyes region of the virtual characters. (From Bloch, Tepest, et al., 2023)

This study provides insights into the effects of group-specific expressions of *intra*personal synchrony in a crossed-design, investigating observers with and without ASD. Essentially the results show that group-specific production levels of *intra*personal synchrony are accompanied not only by an effect on communication efficiency (i.e., slower responses to ASD-like behavior) but also by group-specific timing of responses to these multimodal acts. This shifts the focus of reduced reciprocity in ASD from individual to the temporal dynamics in the interaction and suggests a bidirectional discrepancy of multimodal communication timing (see also section **3.5. *Intra*personal synchrony as factor for *inter*personal processes**).

3. General discussion

The temporal coordination of multimodal signals within interacting individuals, or *intra*personal synchrony, is assumed to constitute predisposing temporal baselines in social interactions. This hitherto little studied level of *intra*personal synchrony and its expressions in adults with and without ASD was the subject of research in this thesis. *Intra*personal synchrony was operationalized as the produced temporal coordination between gaze and pointing gestures. The pre-established research agenda comprised various methodological approaches to the study of *intra*personal synchrony and allowed to explore the construct from different perspectives. Major findings from this work provide evidence that i) *intra*personal synchrony systematically differs between adults with and without ASD, ii) synchronized or time-coordinated behavior yielded cross-domain associations in TD adults but was rather differentiated in social and non-social domains in individuals with ASD, and, iii) group-specific expressions of *intra*personal synchrony affected TD and ASD observers' decoding and response processes in distinctive ways.

3.1. Brief discussion of main results

In alignment to considerations from the perspective article (Bloch et al., 2019), Study 1 (Bloch et al., 2022) provided hypothesis-compliant empirical evidence that multimodal temporal coordination of nonverbal signals in adults with ASD differed systematically from the mode of production in TD individuals. These results replicate and extend existing findings (de Marchena & Eigsti, 2010) and suggest that temporal parameters of multimodal communication in adults with and without ASD should be target of future studies. For example, it would be of great interest to investigate *intra*personal synchrony in different task contexts (De Jonge-Hoekstra et al., 2021) and extend the findings to other modes of communication (e.g., gaze and speech). Here, *intra*personal synchrony provides a framework for quantitatively characterizing characteristics of nonverbal communication that are, on the one hand, a main diagnostic feature of ASD, while, on the other hand, a precise description of what is characteristic is still incomplete (see also section **3.3. *Intra*personal synchrony as an ASD-specific marker?**).

In Study 2 (Bloch, Viswanathan, et al., 2023), we were able to show that *intra*personal synchronization in the social domain was associated with synchronized behavior in the non-social domain in TD individuals, whereas behavioral features across domains were highly differentiated in individuals with ASD. This exploratory approach not only provides important insights into the relationships between behavior in social and non-social domains in ASD, but also offers a theoretical underpinning for further research addressing cross-domain factors in ASD. Moreover, the results suggest that in TD adults, synchronized behavior is subject to shared principles, whereas individuals with ASD present as a rather heterogeneous group (see also section **3.6. Optimized behavior in TD**). Given the results of this study, it appears that *intra*personal synchrony in ASD, in contrast to TD, is conditioned by domain-specific and possibly highly individualized synchronization strategies (see also section **3.4. Heterogeneity and cross-domain factors in ASD**).

In Study 3 (Bloch, Tepest, et al., 2023) the focus was shifted to the perspective of the observer of group-specific *intra*personal synchrony. In this study, the advantage of virtual technologies was used to present group-specific expressions of multimodal temporal coordination of gaze and pointing gestures in a standardized and controlled manner, thus allowing to mask other influencing factors that occur in real-life interactions. *Intra*personal synchrony was shown to affect observers response behavior in terms of decoding time and gaze behavior, and to do so in distinctive ways for observers with and without ASD. These results suggest a bidirectional discrepancy of multimodal communication timing between individuals with and without ASD that could constitute a factor for *inter*personal dys-synchrony (see also section **3.5. *Intra*personal synchrony as a factor for *inter*personal processes**).

General discussion points of the broader scope of this line of research are outlined below. In doing so, the most important results of the studies will be taken up again sporadically and in some cases put into a common context. For discussions of specific study findings, please refer to Bloch et al., 2022, Bloch, Viswanathan, et al., 2023, and Bloch, Tepest, et al., 2023.

3.2. No performance disparity between TD and ASD

The investigations of *intra*personal synchrony presented here provide new insights into the phenomenology of ASD in adulthood. Overall, it should be emphasized that individuals with and without ASD did not differ in their basic performance on a population-level in the presented studies. Thus, individuals with ASD did not substantially differ in their ability to communicate or generally produce adequate behavior, but by measurable differences in the temporal production of and response to multimodal communication. In this sense, this work is consistent with the assumption that communication differences in adults with ASD are not necessarily rooted in amounts or types of communicative elements but in their mode of expression, here specifically in their *intra*personal temporal coordination (see also Georgescu et al., 2020; Noel et al., 2018; de Marchena & Eigsti, 2010).

In alignment to that, there was no indication of reduced motor skills that could have caused the observed synchrony differences in the presented studies. In Study 1 and Study 2 motor parameters were investigated, namely spatio-temporal aspects of the pointing gestures (Bloch et al., 2022) and pace and stability during self-paced and externally-paced motor timing (Bloch, Viswanathan, et al., 2023). In none of these measures did individuals with ASD significantly differ from TD individuals. These results suggest that the differences in self-synchronizing gaze and gesture events and in the timed response to non-social stimuli were not due to observable differences in low-level motor timing skill in the ASD group.

3.3. *Intra*personal synchrony as an ASD-specific marker?

Although adults with ASD were essentially able to perform the communicative task, they markedly differed from the TD adults in terms of the temporal coupling of gaze and pointing gestures (Bloch et al., 2022). A subsequent and crucial question is if atypical *intra*personal synchrony could represent an ASD-specific marker in adulthood. This assumption is supported by the report of increased intervals between semantic aspects of language and associated co-speech gestures in adolescents with ASD that align with the enlarged temporal delays between gaze and pointing events that we report in Study 1 (Bloch et al., 2022; de Marchena & Eigsti, 2010). Thus, it could be assumed that there is a common underlying mechanism in multimodal signal production in ASD that could be generalized across modalities and that could behaviorally present as increased temporal coupling windows between communicative signals. A possible explanation could be that what has been described as multimodal signal-units (see section **1.1. Synchronized individuals in synchronized interactions**) may operate less in an integrated but rather in a detached fashion in persons with ASD. A weak central coherence in cognitive processing (Happé, 1999; Happé & Frith, 2006) or a general temporal binding deficit (Brock et al., 2002), both possibly associated with a functional underconnectivity (Belmonte et al., 2004; Cherkassky et al., 2006), would be in accordance with the observation of extended temporal binding windows during the production of multimodal communication in ASD. In the concrete example, gaze and gesture processes might operate less coupled and more as separate systems due to such characteristics. A stronger segregation of modalities is further in accordance with the findings in Study 2 (Bloch, Viswanathan, et al., 2023) that show that i) gaze and gesture onsets tended to be triggered by a serial execution mechanism in ASD, rather than a parallel mechanism that was found in TD, and ii) that the termination of gaze and gesture events in the ASD group was rather unstructured and not systematically coordinated as in TD group.

That multimodal communication behavior in ASD may indeed be based on a general cross-modality mechanism is further supported by studies of eye-hand coordination in ASD. These show that group differences between TD and ASD do not occur unimodally, but occur multimodally in tasks that require a coupling of the two effectors (Crippa et al., 2013; Glazebrook et al., 2009). This is assumed to be caused by a reduced connectivity between specific brain regions (here between the ocular system and the manual system) (Belmonte et al., 2004; Glazebrook et al., 2009). The same principle could be applied to the coupling of communication modalities in the social domain and could even be related to findings that have shown a tendency for less complex, more unimodal communication behavior in children with ASD (Buitelaar et al., 1991; Murillo et al., 2021; Stone et al., 1997).

What should be noted here, however, is that the increased intervals between gaze and gesture onsets were associated with increased *intra*personal variability in Study 1 (Bloch et al., 2022). Thus, it is not the case that *intra*personal synchrony in ASD was characterized by a general temporal shift in the average coupling windows, but rather by an additional and associated increase in the instability of event coupling. Unfortunately, de Marchena and Eigsti (2010) do not report on the *intra*personal dispersion of speech-gesture couplings, so there is no indication if this increased variability of signal coupling could be generalized to other modalities. Whether there is indeed a generalizable and ASD-specific principle in multimodal communication in adulthood cannot be answered unequivocally by the research outlined but is a valuable direction for future studies. If *intra*personal synchrony differences can be generalized in hypothesis-driven studies and specified by comparison with other diagnostic groups, this would not only help to better understand and describe the phenotype of ASD in adulthood but may also provide an objective diagnostic marker.

3.4. Heterogeneity and cross-domain factors in ASD

Finding objective behavioral markers for diagnosis is difficult due to the marked heterogeneity of the ASD population in adulthood. In addition to the characteristics in the social domains, there are other features in non-social domains that have been recently incorporated in the diagnostic spectrum (Rosen et al., 2021). It is not clear if and how these non-social, sensory differences are related to the core aspects of ASD in the social domain (Hamilton & Pelphrey, 2018; Thye et al., 2018). It would undoubtedly be valuable if there were evidence for common, cross-domain factors that could explain behavior in ASD across behavioral domains, reducing the observed complexity. However, it is still an open debate whether the ASD phenotype can indeed be explained by generalized, cross-domain factors (e.g., by sensory integration characteristics (Murat Baldwin et al., 2021) or by deviations in temporal processing (Brock et al., 2002; Falter & Noreika, 2014; Wimpory et al., 2002)).

Study 2 (Bloch, Viswanathan, et al., 2023) specifically addressed this and examined whether it is plausible to assume a general cross-domain factor that constitutes associations between features in social (here, temporal coordination of multimodal communication events) and non-social (here, temporal coordination of non-social stimuli and responses) domains. Strikingly, cross-domain associations were present in the TD group whereas there was a clear differentiation of domains in the ASD group that seemingly contradicts a common factor across domains. In the discussion of results of Study 2, an explanatory model is outlined that sets a focus on individual developmental pathways in ASD that could result in individualized cognitive strategies (in this case synchronization strategies) that enable the performance of tasks, see Figure 10. Let's assume, for example, that ASD is characterized by a general difference in temporal binding (Brock et al., 2002) which comprehensively affects social and non-social behavior, representing here exemplary a potential cross-domain factor of ASD. With respect to the social domain and sensitive developmental periods in which multimodal communication skills are acquired and refined (Feldman, 2007b; Parladé & Iverson, 2015), passing such periods atypically due to temporal binding differences may entail cascading effects on social-cognitive processing strategies acquired in these situations. Similarly, in the non-social domain, temporal binding differences could trigger the development of individual processing strategies for accomplishing everyday tasks, under the given differences in temporal processing. However, as these non-social situations pose substantially different demands compared to social situations, developing domain-distinctive and specialized strategies appear as a suitable approach. It should be noted here that in many cases ASD is associated with typical or even increased levels of cognitive functioning, which enable individuals to develop effective alternative strategies to cope with daily demands (see also *camouflaging* literature, e.g., Cook et al., 2021). Indeed, investigating individuals to which the ASD diagnosis was mostly not given until adulthood, as in the present studies, underlines the idea that those individuals must somehow have developed their own adaption to the world. As such, even if there was indeed a common factor across domains (here exemplary a difference in temporal binding), the question is how it could be verified in adulthood, given individual and assumable domain-specific developmental pathways.

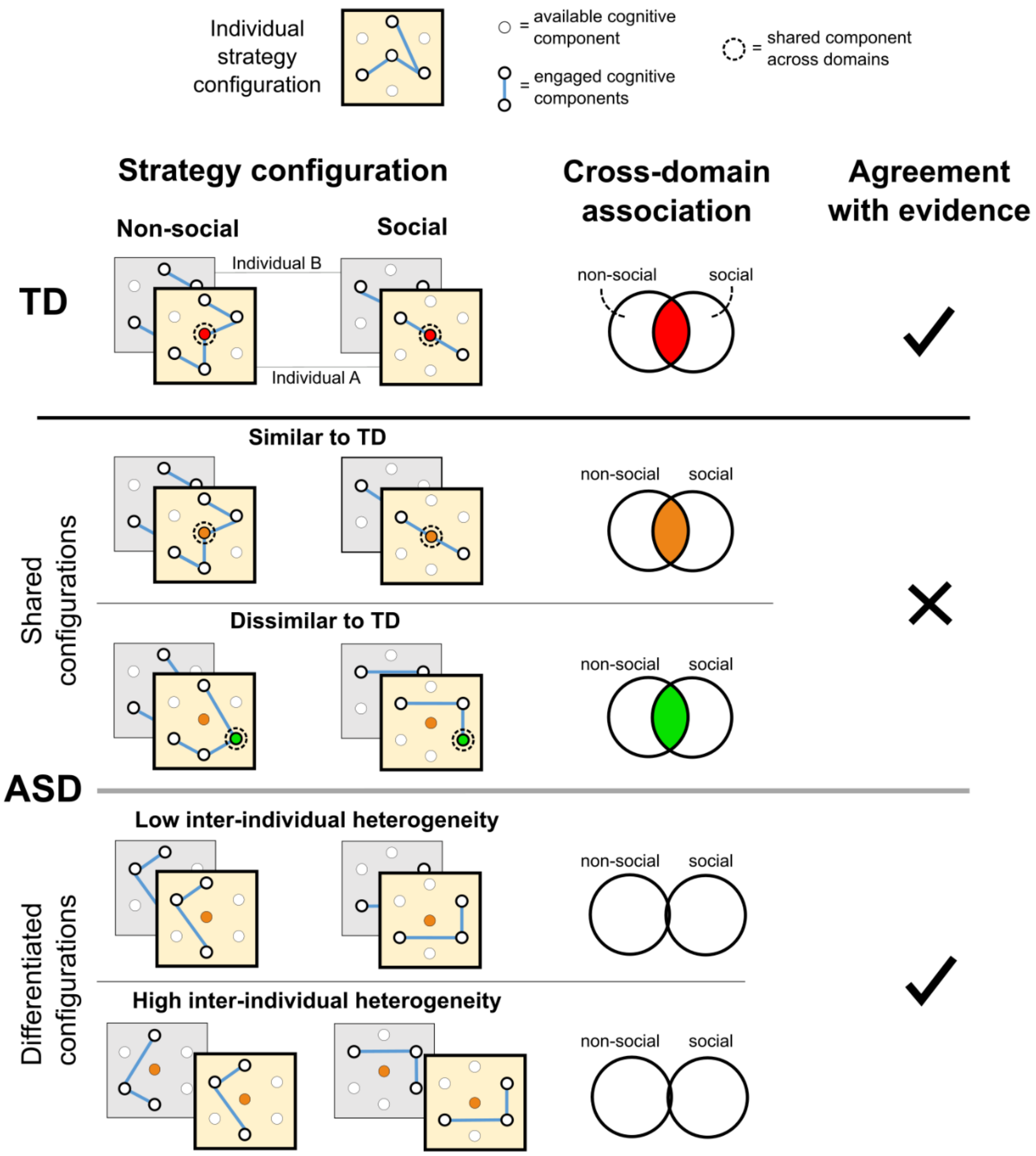

Figure 10. A simplistic model of individual strategies and cross-domain relationships. Yellow and grey squares depict different individuals. Nodes within squares represent cognitive components that may be engaged in a task. The blue edges connecting the nodes represent different strategy configurations. If similar cognitive components are engaged in social and non-social strategies, a cross-domain association is depicted as overlapping circles in the Venn-diagram, with the overlap area colored by the color of the component that caused the intersection. For all ASD scenarios (rows 2-5) the orange node represents an ASD-specific component that may yield shared configurations (rows 2 & 3) or differentiated configurations of components (rows 4 & 5). The right column depicts which scenarios are supported by our data (i.e., the TD scenario and the differentiated configurations scenarios for ASD). (From Bloch, Viswanathan, et al., 2023)

Recognizing that adults with ASD may have developed certain behavioral repertoire later in life (e.g., due to missed developmental periods), but may also have developed unique and domain-specific strategies to accomplish task demands, underscores the need to recognize the given behavioral heterogeneity in the adult ASD population. This also requires research to develop methods and approaches that can accommodate and even embrace this heterogeneity. As Hobson and Petty so aptly put it: "*with the frustrations that come with the heterogeneity of autism, (…) we should not sacrifice validity for the sake of simplicity*" (Hobson & Petty, 2021, p. 2). The suggested model (Figure 10) could help to disentangle latent processes within individuals that could underlie observed behavior and allows for a differentiated and individual-focused perspective on cross-domain associations in ASD. Our study arguably relates to a very specific context of time-coordinated behavior and covers only a small part of the autism spectrum in adulthood. However, the model is theoretically applicable to other contexts. More research on cross-domain associations is certainly needed to clarify whether and how social and non-social aspects are related in individuals with ASD. Our study may help to guide future endeavors in this direction.

3.5. ***Intra*personal synchrony as a factor for *inter*personal processes**

The systematic reduction of *inter*personal synchrony in interactions with a person with ASD is a promising marker for diagnosis in adulthood (Georgescu et al., 2019, 2020; Koehler et al., 2021; Koehler & Falter-Wagner, 2023). Currently there is little information on the factors that determine this reduction. According to Koban et al. the fact that people synchronize their behavior could be explained by an optimization principle in the sense of a Bayesian Brain (Friston, 2012; Parr & Friston, 2019) and accordingly prediction errors (i.e., free energy) are reduced by a matching of produced and perceived behavior (Koban et al., 2019). Even though the presented studies do not provide data about gradual dyadic adjustments of *intra*personal synchrony levels throughout an interaction, deviant entry levels of *intra*personal synchrony (as presented in Bloch et al., 2022 and Bloch, Viswanathan, et al., 2023) could increase the probability for mutual prediction errors that potentially irritate *inter*personal synchronization. In this context Study 3 (Bloch, Tepest, et al., 2023) provides further evidence for a mutual mismatch of timed behavior during social interactions in the form of timed responses to multimodal signals. In this sense, similar behaviors in the production of (Study 1 and Study 2) and responses to (Study 3) multimodal communication behavior, as shown in the TD groups, could reduce prediction errors and thus ultimately foster the emergence of *inter*personal synchrony. In contrast, divergence was present between individuals with and without ASD at both levels of observation (production and perception), which could increase prediction errors and even disrupt corrective mechanisms (e.g., adjusting one's own multimodal coordination mode to others). Thus, both parties enter the interaction with different multimodal temporal baselines and different approaches of decoding and responding to them. The interaction process in mixed dyads (i.e., consisting of individuals with ASD and TD individuals) should be considered under the aspect of this potential bidirectional discrepancy of multimodal communication timing.

In line with the 'Double Empathy Hypothesis' (Milton, 2012), one could expect individuals with ASD to benefit from interactions with other individuals from the spectrum. While this is certainly the case in different contexts (Crompton et al., 2020; Mitchell et al., 2021), the results of Study 3 do not suggest that there is an in-group advantage, i.e., that individuals with ASD interact more beneficial due to fine-tuning the timing of multimodal communication of a virtual partner to match the group production mode. That there are no communicative advantages (in this case an increased communication efficiency) due to group-adjusted multimodal temporal coordination is in line with evidence that there is still a reduction of *inter*personal synchrony in interactions between two individuals with ASD (Georgescu et al., 2020). In this context, the variability that has been shown both, on the production side (i.e., variability of gaze-gesture delays in Study 1, individualized synchronization strategies in Study 2), and on the perception side (i.e., gaze types in ASD group in Study 3) should be considered. Such a group-inherent heterogeneity in the temporal coordination of multimodal communication and its perception could provide a possible explanation as to why there is no improved temporal adjustment within ASD dyads. Here, *intra*personal synchrony as a predisposing factor for *inter*personal synchrony is a promising direction for further basic research.

3.6. Optimized behavior in TD

Beyond implications for ASD, this research informs about principles of communication in non-autistic adults. It is striking how homogeneous the TD group appeared in the results, especially in contrast to the ASD group. Relatively homogeneous intra-group patterns were revealed both, in the production of gaze-gesture coordination (Study 1 and Study 2), and in their decoding (Study 3) in TD individuals. It is plausible to assume that this observed consistency within the TD group stems from implicit communication automatisms that are learned and refined from an early age in a shared social-interactive environment by individuals capable of similar (social-)cognitive functions. During communicative encounters, TD adults 'simply do it', implicitly and intuitively, and they achieve high processing efficiency. This is probably due to a shared temporal baseline that constitutes a fundamental basis for reciprocity. There may be an optimization principle here at the behavioral level, which is also supported by the generalization of gaze and gesture event synchronization to sensorimotor processes (Bloch, Viswanathan, et al., 2023). This group-inherent consistency contrasts sharply with the heterogeneity within the ASD group. The tension between homogeneous in-group behavior and ASD deviations from it could provide an explanation why people with ASD are conspicuous in their behavior as judged by non-autistic observers (Grossman, 2015; Sasson et al., 2017). Ascribing attributes such as 'weird' or 'strange' however presupposes that a deviation from a subjective and familiar spectrum of expression is recognized. The results presented here provide examples of behavioral expressions that could shape subjective and familiar spectrums of expressions in TD individuals.

In Study 3 (Bloch, Tepest, et al., 2023) it was investigated if ASD-specific expressions of *intra*personal synchrony (in contrast to a probably more familiar TD expression mode) would yield poorer subjective ratings. Arguably, the type of manipulation in Study 3 was highly reduced (i.e., important channels for impression judgements thus disengaged) and the avatars were probably too similar to each other to elicit systematic differences in impression judgements. However, although we did not find any effects of deviant *intra*personal synchrony on impression formation in Study 3, it is possible that in naturalistic scenarios the likelihood of ASD behavior being judged as 'odd', i.e., noticeably deviating from the range of TD behavior, is increased. Here, it is inevitable to consider both sides of a social interaction, as a behavioral (mis-)match or reduced reciprocity can only arise as a result of the encounter between two parties. *Intra*personal synchrony here provides a framework for individual-centered investigations of both sides of an interaction and thus quantitative constrains for mutual matching at the implicit behavioral level.

4. Conclusion and future directions

With apparent ease, people interact with each other, producing and decoding time-sensitive communication codes that are the basis for *inter*personal alignment. In this work, the focus was set on this fundamental micro-level of multimodal signal coordination within interacting individuals, i.e., *intra*personal synchrony. Adults with and without ASD were compared on the basis of informed considerations that *intra*personal synchrony might differ systematically between these groups.

This line of research aimed to provide a detailed view on how *intra*personal synchrony manifests in adults with and without ASD in a social interaction scenarios. Importantly, while focusing on the individual, this line of research still acknowledges the dyad as the fundamental unit of analysis. Having established a first foundation for the systematic study of *intra*personal synchrony, this approach leads to important follow-up research questions and suggests a testbed for investigations in future research. The most essential ones are to establish a link of *intra*personal synchrony as baseline measures with *inter*personal synchrony in naturalistic real-life interactions. Additionally, from a methodological viewpoint, it would be of great value to implement the study of *intra*personal synchrony in the context of Human-Computer-Interactions or Human-Robot-Interactions and possibly apply temporal parameters of multimodal communication to interactive agents or artificial humans. This would for example allow to study the effects of multimodal timing incrementally before applying measures in highly complex naturalistic scenarios. On the other hand, these *intra*personal parameters could provide information for behavioral computation in artificial behavior algorithms. In addition, in order to derive potential diagnostic markers, it is essential to replicate results in further samples and investigate the specificity of the demonstrated effects in comparison with other psychiatric and neurodevelopmental diagnoses. Testing whether the effects generalize to other communication modalities, other diagnostic groups (e.g., schizophrenia), different cultural contexts, and to the broader autism spectrum would be of great interest. Furthermore, in order to better understand the underlying mechanisms of self-synchronization during communicative encounters, more studies are needed that target the relation with non-social characteristics in ASD. In this context, longitudinal studies are essential in order to investigate the potentially dynamic relationship of social and non-social behavior over ontogeny.

Literature

Alderisio, F., Fiore, G., Salesse, R. N., Bardy, B. G., & Bernardo, M. Di. (2017). Interaction patterns and individual dynamics shape the way we move in synchrony. *Scientific Reports*, *7*(1), 1–10. https://doi.org/10.1038/s41598-017-06559-4

Allman, M., & Falter, C. (2015). Abnormal timing and time perception in autism spectrum disorder? A review of the evidence. In A. Vatakis & M. J. Allman (Eds.), *Time distortions in mind--temporal processing in clinical populations* (pp. 37–56). Brill.

Allman, M. J., DeLeon, I. G., & Wearden, J. H. (2011). Psychophysical assessment of timing in individuals with autism. *American Journal on Intellectual and Developmental Disabilities*, *116*(2), 165–178. https://doi.org/10.1352/1944-7558-116.2.165

Allman, M. J., & Meck, W. H. (2012). Pathophysiological distortions in time perception and timed performance. *Brain*, *135*(3), 656–677. https://doi.org/10.1093/brain/awr210

Altmann, U., Brümmel, M., Meier, J., & Strauss, B. (2021). Movement Synchrony and Facial Synchrony as Diagnostic Features of Depression. *Journal of Nervous & Mental Disease*, *209*(2), 128–136. https://doi.org/10.1097/nmd.0000000000001268

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). https://doi.org/10.1176/appi.books.9780890425596

Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften. (2016). Autismus-Spektrum-Störungen im Kindes-, Jugend- und Erwachsenenalter - Teil 1: Diagnostik - Interdisziplinäre S3-Leitlinie der DGKJP und der DGPPN sowie der beteiligten Fachgesellschaften, Berufsverbände und Patientenorganisationen Langversion. In *AWMF online*. https://doi.org/10.1055/b-0037-146934

Argyle, M., & Cook, M. (1976). *Gaze and mutual gaze*. Cambridge U Press.

Ballard, D. H., Hayhoe, M. M., Pook, P. K., & Rao, R. P. N. (1997). Deictic codes for the embodiment of cognition. *Behavioral and Brain Sciences*, *20*(4), 723–767. https://doi.org/10.1017/S0140525X97001611

Baron-Cohen, S. (1989). Perceptual role taking and protodeclarative pointing in autism. *British Journal of Developmental Psychology*, *7*(2), 113–127. https://doi.org/10.1111/j.2044-835X.1989.tb00793.x

Bedford, R., Elsabbagh, M., Gliga, T., Pickles, A., Senju, A., Charman, T., & Johnson, M. H. (2012). Precursors to social and communication difficulties in infants at-risk for autism: gaze following and attentional engagement. *Journal of Autism and Developmental Disorders*, *42*, 2208–2218. https://doi.org/10.1007/s10803-012-1450-y

Beebe, B. (1982). Micro-timing in mother-infant communication. *Nonverbal Communication Today: Current Research*, 169–195.

Bégel, V., Demos, A. P., Wang, M., & Palmer, C. (2022). Social Interaction and Rate Effects in Models of Musical Synchronization. *Frontiers in Psychology*, *13*. https://doi.org/10.3389/fpsyg.2022.865536

Belmonte, M. K., Allen, G., Beckel-Mitchener, A., Boulanger, L. M., Carper, R. A., & Webb, S. J. (2004). Autism and abnormal development of brain connectivity. *Journal of Neuroscience*, *24*(42), 9228–9231. https://doi.org/10.1523/JNEUROSCI.3340-04.2004

Bernieri, F., & Rosenthal, R. (1991). Interpersonal coordination: Behavior matching and interactional synchrony. In R. Feldman & B. Rimé (Eds.), *Fundamentals of nonverbal behavior* (pp. 401–432). Cambridge University Press.

Billeci, L., Narzisi, A., Campatelli, G., Crifaci, G., Calderoni, S., Gagliano, A., Calzone, C., Colombi, C., Pioggia, G., Muratori, F., Raso, R., Ruta, L., Rossi, I., Ballarani, A., Fulceri, F., Darini, A., Maroscia, E., Lattarulo, C., Tortorella, G., … Comminiello, V. (2016). Disentangling the initiation from the response in joint attention: An eye-tracking study in toddlers with autism spectrum disorders. *Translational Psychiatry*, *6*(5), 1–8. https://doi.org/10.1038/tp.2016.75

Bloch, C., Burghof, L., Lehnhardt, F.-G., Vogeley, K., & Falter-Wagner, C. M. (2021). Alexithymia traits outweigh autism traits in the explanation of depression in adults with autism. *Scientific Reports*, *11*(2258), 1–7. https://doi.org/10.1038/s41598-021-81696-5

Bloch, C., Tepest, R., Jording, M., Vogeley, K., & Falter-Wagner, C. M. (2022). Intrapersonal synchrony analysis reveals a weaker temporal coherence between gaze and gestures in adults with autism spectrum disorder. *Scientific Reports*, *12*(20417), 1–12. https://doi.org/10.1038/s41598-022-24605-8

Bloch, C., Tepest, R., Koeroglu, S., Feikes, K., Jording, M., Vogeley, K., & Falter-Wagner, C. M. (2023). PREPRINT: Interacting with autistic virtual characters: Intrapersonal synchrony of nonverbal behavior influences participants' perception. *Open Science Framework*. https://doi.org/10.31219/osf.io/ukh9c

Bloch, C., Viswanathan, S., Tepest, R., Jording, M., Falter-Wagner, C. M., & Vogeley, K. (2023). Differentiated, rather than shared, strategies for time-coordinated action in social and non-social domains in individuals with autism. *Cortex, 166,* 207-232. https://doi.org/10.1016/j.cortex.2023.05.008

Bloch, C., Vogeley, K., Georgescu, A. L., & Falter-Wagner, C. M. (2019). INTRApersonal Synchrony as Constituent of INTERpersonal Synchrony and Its Relevance for Autism

Spectrum Disorder. *Frontiers in Robotics and AI*, *6*(73), 1–8. https://doi.org/10.3389/frobt.2019.00073

Bolis, D., Dumas, G., & Schilbach, L. (2023). Interpersonal attunement in social interactions: from collective psychophysiology to inter-personalized psychiatry and beyond. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *378*(20210365), 1–13. https://doi.org/10.1098/rstb.2021.0365

Brock, J., Brown, C. C., Boucher, J., & Rippon, G. (2002). The temporal binding deficit hypothesis of autism. *Development and Psychopathology*, *14*(2), 209–224. https://doi.org/10.1017/s0954579402002018

Brooks, R., & Meltzoff, A. N. (2005). The development of gaze following and its relation to language. *Developmental Science, 8*(6), 535–543. https://doi.org/10.1111/j.1467-7687.2005.00445.x

Brooks, R., & Meltzoff, A. N. (2008). Infant gaze following and pointing predict accelerated vocabulary growth through two years of age: A longitudinal, growth curve modeling study. *Journal of Child Language*, *35*(1), 207–220.

Bruinsma, Y., Koegel, R. L., & Koegel, L. K. (2004). Joint attention and children with autism: A review of the literature. *Mental Retardation and Developmental Disabilities Research Reviews*, *10*(3), 169–175. https://doi.org/10.1002/mrdd.20036

Bruneau, T. (1980). Chronemics and the verbal-nonverbal interface. In M. R. Key (Ed.), *The relationship of verbal and nonverbal communication* (pp. 101–118). Mouton Publishers.

Bruneau, T. (2012). Chronemics: Time-binding and the construction of personal time. *ETC: A Review of General Semantics*, *69*(1), 72–92. http://www.jstor.org/stable/42579170

Buijsman, R., Begeer, S., & Scheeren, A. M. (2022). 'Autistic person' or 'person with autism'? Person-first language preference in Dutch adults with autism and parents. *Autism*, *27*(3), 788–795. https://doi.org/10.1177/13623613221117914

Buitelaar, J. K., van Engeland, H., de Kogel, K. H., Vries, H. de, & van Hooff, J. A. R. A. M. (1991). Differences in the Structure of Social Behaviour of Autistic Children and Non-Autistic Retarded Controls. *Journal of Child Psychology and Psychiatry*, *32*(6), 995–1015. https://doi.org/10.1111/j.1469-7610.1991.tb01925.x

Bury, S. M., Jellett, R., Haschek, A., Wenzel, M., Hedley, D., & Spoor, J. R. (2022). Understanding language preference: Autism knowledge, experience of stigma and autism identity. *Autism*, *0*(0), 1–13. https://doi.org/10.1177/13623613221142383

Cacioppo, S., Zhou, H., Monteleone, G., Majka, E. A., Quinn, K. A., Ball, A. B., Norman, G. J., Semin, G. R., & Cacioppo, J. T. (2014). You are in sync with me: Neural correlates of interpersonal synchrony with a partner. *Neuroscience*, *277*, 842–858. https://doi.org/10.1016/j.neuroscience.2014.07.051

Camaioni, L., Perucchini, P., Muratori, F., Parrini, B., & Cesari, A. (2003). The communicative use of pointing in autism: Developmental profile and factors related to change. *European Psychiatry*, *18*(1), 6–12. https://doi.org/10.1016/S0924-9338(02)00013-5

Cañigueral, R., & Hamilton, A. F. de C. (2019). The role of eye gaze during natural social interactions in typical and autistic people. *Frontiers in Psychology*, *10*, 1–18. https://doi.org/10.3389/fpsyg.2019.00560

Caruana, N., Inkley, C., Nalepka, P., Kaplan, D. M., & Richardson, M. J. (2021). Gaze facilitates responsivity during hand coordinated joint attention. *Scientific Reports*, *11*(1), 1–11. https://doi.org/10.1038/s41598-021-00476-3

Caruana, N., Stieglitz Ham, H., Brock, J., Woolgar, A., Kloth, N., Palermo, R., & McArthur, G. (2018). Joint attention difficulties in autistic adults: an interactive eye-tracking study. *Autism*, *22*(4), 502–512. https://doi.org/10.1177/1362361316676204

Charman, T. (2003). Why is joint attention a pivotal skill in autism?. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *358*(1430), 315–324. https://doi.org/10.1098/rstb.2002.1199

Chartrand, T. L., & Lakin, J. L. (2013). The Antecedents and Consequences of Human Behavioral Mimicry. *Annual Review of Psychology*, *64*(1), 285–308. https://doi.org/10.1146/annurev-psych-113011-143754

Chawarska, K., Klin, A., & Volkmar, F. (2003). Automatic Attention Cueing Through Eye Movement in 2-Year-Old Children with Autism. *Child Development*, *74*(4), 1108–1122. https://doi.org/10.1111/1467-8624.00595

Cherkassky, V. L., Kana, R. K., Keller, T. A., & Just, M. A. (2006). Functional connectivity in a baseline resting-state network in autism. *NeuroReport*, *17*(16), 1687–1690. https://doi.org/10.1097/01.wnr.0000239956.45448.4c

Colgan, S. E., Lanter, E., McComish, C., Watson, L. R., Crais, E. R., & Baranek, G. T. (2006). Analysis of social interaction gestures in infants with autism. *Child Neuropsychology*, *12*(4–5), 307–319. https://doi.org/10.1080/09297040600701360

Colonnesi, C., Stams, G. J. J. M., Koster, I., & Noom, M. J. (2010). The relation between pointing and language development: A meta-analysis. *Developmental Review*, *30*(4), 352–366. https://doi.org/10.1016/j.dr.2010.10.001

Cook, J., Hull, L., Crane, L., & Mandy, W. (2021). Camouflaging in autism: A systematic review. *Clinical Psychology Review, 89*, 102080. https://doi.org/10.1016/j.cpr.2021.102080

Crippa, A., Forti, S., Perego, P., & Molteni, M. (2013). Eye-hand coordination in children with high functioning autism and Asperger's disorder using a gap-overlap paradigm. *Journal of Autism and Developmental Disorders*, *43*(4), 841–850. https://doi.org/10.1007/s10803-012-1623-8

Crompton, C. J., Ropar, D., Evans-Williams, C. V. M., Flynn, E. G., & Fletcher-Watson, S. (2020). Autistic peer-to-peer information transfer is highly effective. *Autism*, *24*(7), 1704–1712. https://doi.org/10.1177/1362361320919286

David, N., Aumann, C., Santos, N. S., Bewernick, B. H., Eickhoff, S. B., Newen, A., Shah, N. J., Fink, G. R., & Vogeley, K. (2008). Differential involvement of the posterior temporal cortex in mentalizing but not perspective taking. *Social Cognitive and Affective Neuroscience*, *3*(3), 279–289. https://doi.org/10.1093/scan/nsn023

Dawson, G., Toth, K., Abbott, R., Osterling, J., Munson, J., Estes, A., & Liaw, J. (2004). Early Social Attention Impairments in Autism: Social Orienting, Joint Attention, and Attention to Distress. *Developmental Psychology*, *40*(2), 271–283. https://doi.org/10.1037/0012-1649.40.2.271

de Brouwer, A. J., Flanagan, J. R., & Spering, M. (2021). Functional Use of Eye Movements for an Acting System. *Trends in Cognitive Sciences*, *25*(3), 252–263. https://doi.org/10.1016/j.tics.2020.12.006

De Jonge-Hoekstra, L., Cox, R. F. A., Van der Steen, S., & Dixon, J. A. (2021). Easier Said Than Done? Task Difficulty's Influence on Temporal Alignment, Semantic Similarity, and Complexity Matching Between Gestures and Speech. *Cognitive Science*, *45*(6), 1–35. https://doi.org/10.1111/cogs.12989

de Marchena, A., & Eigsti, I. M. (2010). Conversational gestures in autism spectrum disorders: Asynchrony but not decreased frequency. *Autism Research*, *3*(6), 311–322. https://doi.org/10.1002/aur.159

Delaherche, E., Chetouani, M., Mahdhaoui, A., Saint-Georges, C., Viaux, S., & Cohen, D. (2012). Interpersonal synchrony: A survey of evaluation methods across disciplines. *IEEE Transactions on Affective Computing*, *3*(3), 349–365. https://doi.org/10.1109/T-AFFC.2012.12

Diessel, H. (2006). Demonstratives, joint attention, and the emergence of grammar. *Cognitive Linguistics*, *17*(4), 463–489. https://doi.org/10.1515/COG.2006.015

Dunbar, N. E., Burgoon, K., & Fujiwara, K. (2022). Automated Methods to Examine Nonverbal Synchrony in Dyads. *Proceedings of Machine Learning Research*, *173*, 204–217.

Edey, R., Cook, J., Brewer, R., Johnson, M. H., Bird, G., & Press, C. (2016). Interaction takes two: Typical adults exhibit mind-blindness towards those with autism spectrum disorder. *Journal of Abnormal Psychology*, *125*(7), 879. https://doi.org/10.1037/abn0000199

Elsabbagh, M., Mercure, E., Hudry, K., Chandler, S., Pasco, G., Charman, T., Pickles, A., Baron-Cohen, S., Bolton, P., & Johnson, M. H. (2012). Infant neural sensitivity to dynamic eye gaze is associated with later emerging autism. *Current Biology*, *22*(4), 338–342. https://doi.org/10.1016/j.cub.2011.12.056

Emery, N. J. (2000). The eyes have it: the neuroethology, function and evolution of social gaze. *Neuroscience & Biobehavioral Reviews*, *24*(6), 581–604. https://doi.org/10.1016/S0149-7634(00)00025-7

Falter, C. M., Braeutigam, S., Nathan, R., Carrington, S., & Bailey, A. J. (2013). Enhanced access to early visual processing of perceptual simultaneity in autism spectrum disorders. *Journal of Autism and Developmental Disorders*, *43*(8), 1857–1866. https://doi.org/10.1007/s10803-012-1735-1

Falter, C. M., Elliott, M. A., & Bailey, A. J. (2012). Enhanced visual temporal resolution in autism spectrum disorders. *PLoS ONE*, *7*(3), 1–6. https://doi.org/10.1371/journal.pone.0032774

Falter, C. M., & Noreika, V. (2011). Interval Timing Deficits and Abnormal Cognitive Development. *Frontiers in Integrative Neuroscience*, *5*, 1–2. https://doi.org/10.3389/fnint.2011.00026

Falter, C. M., & Noreika, V. (2014). Time processing in developmental disorders: A comparative view. In V. Arstila & D. Lloyd (Eds.), *Subjective time: The philosophy, psychology, and neuroscience of temporality* (pp. 557–597). Boston Review.

Falter, C. M., Noreika, V., Wearden, J. H., & Bailey, A. J. (2012). More consistent, yet less sensitive: Interval timing in autism spectrum disorders. *Quarterly Journal of Experimental Psychology*, *65*(11), 2093–2107. https://doi.org/10.1080/17470218.2012.690770

Farroni, T., Csibra, G., Simion, F., & Johnson, M. H. (2002). Eye contact detection in humans from birth. *Proceedings of the National Academy of Sciences of the United States of America*, *99*(14), 9602–9605. https://doi.org/10.1073/pnas.152159999

Feldman, R. (2006). From biological rhythms to social rhythms: Physiological precursors of mother-infant synchrony. *Developmental Psychology*, *42*(1), 175–188. https://doi.org/10.1037/0012-1649.42.1.175

Feldman, R. (2007a). Parent--infant synchrony and the construction of shared timing; physiological precursors, developmental outcomes, and risk conditions. *Journal of Child Psychology and Psychiatry*, *48*(3–4), 329–354. https://doi.org/10.1111/j.1469-7610.2006.01701.x

Feldman, R. (2007b). Parent--infant synchrony: Biological foundations and developmental outcomes. *Current Directions in Psychological Science*, *16*(6), 340–345.

Fernandes, B. S., Williams, L. M., Steiner, J., Leboyer, M., Carvalho, A. F., & Berk, M. (2017). The new field of “precision psychiatry.” *BMC Medicine*, *15*(1), 1–7. https://doi.org/10.1186/s12916-017-0849-x

Fitzpatrick, P., Frazier, J. A., Cochran, D. M., Mitchell, T., Coleman, C., & Schmidt, R. C. (2016). Impairments of social motor synchrony evident in autism spectrum disorder. *Frontiers in Psychology*, *7*, 1–13. https://doi.org/10.3389/fpsyg.2016.01323

Fournier, K. A., Hass, C. J., Naik, S. K., Lodha, N., & Cauraugh, J. H. (2010). Motor coordination in autism spectrum disorders: a synthesis and meta-analysis. *Journal of Autism and Developmental Disorders*, *40*(10), 1227–1240. https://doi.org/10.1007/s10803-010-0981-3

Franco, F. (2005). Infant pointing: Harlequin, Servant of two masters. In N. Eilan, C. Hoerl, T. McCormack, & J. Roessler (Eds.), *Joint attention: Communication and other minds* (pp. 129–164). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199245635.001.0001

Frischen, A., Bayliss, A. P., & Tipper, S. P. (2007). Gaze Cueing of Attention: Visual Attention, Social Cognition, and Individual Differences. *Psychological Bulletin*, *133*(4), 694–724. https://doi.org/10.1037/0033-2909.133.4.694

Friston, K. (2012). The history of the future of the Bayesian brain. *NeuroImage*, *62*(2), 1230–1233. https://doi.org/10.1016/j.neuroimage.2011.10.004

Frith, U. (2001). Mind blindness and the brain in autism. *Neuron*, *32*(6), 969–979. https://doi.org/10.1016/S0896-6273(01)00552-9

Fujiwara, K., Bernhold, Q. S., Dunbar, N. E., Otmar, C. D., & Hansia, M. (2021). Comparing Manual and Automated Coding Methods of Nonverbal Synchrony. *Communication Methods and Measures*, *15*(2), 103–120. https://doi.org/10.1080/19312458.2020.1846695

Fujiwara, K., Kimura, M., & Daibo, I. (2020). Rhythmic Features of Movement Synchrony for Bonding Individuals in Dyadic Interaction. *Journal of Nonverbal Behavior*, *44*(1), 173–193. https://doi.org/10.1007/s10919-019-00315-0

Galbusera, L., Finn, M. T. M., Tschacher, W., & Kyselo, M. (2019). Interpersonal synchrony feels good but impedes self-regulation of affect. *Scientific Reports*, *9*(1), 1–12. https://doi.org/10.1038/s41598-019-50960-0

Gangi, D. N., Ibañez, L. V., & Messinger, D. S. (2014). Joint Attention Initiation With and Without Positive Affect: Risk Group Differences and Associations with ASD Symptoms. *Journal of Autism and Developmental Disorder*, *44*, 1414–1424. https://doi.org/10.1007/s10803-013-2002-9

Georgescu, A. L., Koehler, J. C., Weiske, J., Vogeley, K., Koutsouleris, N., & Falter-Wagner, C. M. (2019). Machine learning approaches to study social interaction difficulties in ASD. *Frontiers in Robotics and AI*, *6*(132), 1–7. https://doi.org/10.3389/frobt.2019.00132

Georgescu, A. L., Koeroglu, S., Hamilton, A., Vogeley, K., Falter-Wagner, C. M., & Tschacher, W. (2020). Reduced nonverbal interpersonal synchrony in autism spectrum disorder independent of partner diagnosis: a motion energy study. *Molecular Autism*, *11*(1), 1–15. https://doi.org/10.1186/s13229-019-0305-1

Ghaziuddin, M., Ghaziuddin, N., & Greden, J. (2002). Depression in Persons with Autism: Implications for Research and Clinical Care. *Journal of Autism and Developmental Disorders*, *32*(4), 299–306. https://doi.org/10.1023/A:1016330802348

Glazebrook, C., Gonzalez, D., Hansen, S., & Elliott, D. (2009). The role of vision for online control of manual aiming movements in persons with autism spectrum disorders. *Autism*, *13*(4), 411–433. https://doi.org/10.1177/1362361309105659

Gowen, E., & Hamilton, A. (2013). Motor abilities in autism: A review using a computational context. *Journal of Autism and Developmental Disorders*, *43*(2), 323–344. https://doi.org/10.1007/s10803-012-1574-0

Grossman, R. B. (2015). Judgments of social awkwardness from brief exposure to children with and without high-functioning autism. *Autism*, *19*(5), 580–587. https://doi.org/10.1177/1362361314536937

Hamilton, A., & Pelphrey, K. (2018). Sensory and social features of autism – can they be integrated? *Developmental Cognitive Neuroscience*, *29*, 1–3. https://doi.org/10.1016/j.dcn.2018.02.009

Han, S., Northoff, G., Vogeley, K., Wexler, B. E., Kitayama, S., & Varnum, M. E. W. (2013). A cultural neuroscience approach to the biosocial nature of the human brain. *Annual Review of Psychology*, *64*(1), 335–359. https://doi.org/10.1146/annurev-psych-071112-054629

Happé, F. (1999). Autism: cognitive deficit or cognitive style? *Trends in Cognitive Sciences*, *3*(6), 216–222. https://doi.org/10.1016/S1364-6613(99)01318-2

Happé, F., & Frith, U. (2006). The weak coherence account: Detail-focused cognitive style in autism spectrum disorders. *Journal of Autism and Developmental Disorders*, *36*(1), 5–25. https://doi.org/10.1007/s10803-005-0039-0

Happé, F., Ronald, A., & Plomin, R. (2006). Time to give up on a single explanation for autism. *Nature Neuroscience*, *9*(10), 1218–1220. https://doi.org/10.1038/nn1770

Hobson, H., & Petty, S. (2021). Moving forwards not backwards: heterogeneity in autism spectrum disorders. *Molecular Psychiatry*, *26*(12), 7100–7101. https://doi.org/10.1038/s41380-021-01226-7

Hofvander, B., Delorme, R., Chaste, P., Nydén, A., Wentz, E., Ståhlberg, O., Herbrecht, E., Stopin, A., Anckarsäter, H., Gillberg, C., Råstam, M., & Leboyer, M. (2009). Psychiatric and psychosocial problems in adults with normal-intelligence autism spectrum disorders. *BMC Psychiatry*, *9*, 1–9. https://doi.org/10.1186/1471-244X-9-35

Hove, M. J., & Risen, J. L. (2009). It's all in the timing: Interpersonal synchrony increases affiliation. *Social Cognition*, *27*(6), 949–960. https://doi.org/10.1521/soco.2009.27.6.949

Iverson, J. M. (2010). Iverson J. M. (2010). Developing language in a developing body: the relationship between motor development and language development. J, 37(2), 229–261. https://doi.org/. *Journal of Child Language*, *37*(2), 229–261. https://doi.org/10.1017/S0305000909990432

Jaffe, J., Beebe, B., Feldstein, S., Crown, C., Jasnow, M., Rochat, P., & Stern, D. (2001). Rhythms of Dialogue in Infancy: Coordinated Timing in Development. *Monographs of the Society for Research in Child Development*, *66*(2), 1–149.

Jana, S., Gopal, A., & Murthy, A. (2017a). A Computational Framework for Understanding Eye–Hand Coordination. *Journal of the Indian Institute of Science*, *97*(4), 543–554. https://doi.org/10.1007/s41745-017-0054-0

Jana, S., Gopal, A., & Murthy, A. (2017b). Evidence of common and separate eye and hand accumulators underlying flexible eye-hand coordination. *Journal of Neurophysiology*, *117*(1), 348–364. https://doi.org/10.1152/jn.00688.2016

Jaques, N., McDuff, D., Kim, Y. L., & Picard, R. (2016). Understanding and predicting bonding in conversations using thin slices of facial expressions and body language. In D. Traum, W. Swartout, Khooshabeh, S. P., Kopp, S. Scherer, & A. Leuski (Eds.), *Lecture Notes in Computer Science: Intelligent Virtual Agents (IVA 2016): Vol. 10011 LNAI* (pp. 64–74). Springer. https://doi.org/10.1007/978-3-319-47665-0_6

Jording, M., Hartz, A., Bente, G., Schulte-Rüther, M., & Vogeley, K. (2018). The "Social Gaze Space": A taxonomy for gaze-based communication in triadic interactions. *Frontiers in Psychology*, *9*(FEB), 1–8. https://doi.org/10.3389/fpsyg.2018.00226

Keating, C. T., Hickman, L., Leung, J., Monk, R., Montgomery, A., Heath, H., & Sowden, S. (2022). Autism-related language preferences of English-speaking individuals across the globe: A mixed methods investigation. *Autism Research*, *16*(2), 406–428. https://doi.org/10.1002/aur.2864

Keller, H., Lohaus, A., Völker, S., Cappenberg, M., & Chasiotis, A. (1999). Temporal contingency as an independent component of parenting behavior. *Child Development*, *70*(2), 474–485. https://doi.org/10.1111/1467-8624.00034

Kenny, L., Hattersley, C., Molins, B., Buckley, C., Povey, C., & Pellicano, E. (2016). Which terms should be used to describe autism? Perspectives from the UK autism community. *Autism*, *20*(4), 442–462. https://doi.org/10.1177/1362361315588200

Kim, J. A., Szatmari, P., Bryson, S. E., Streiner, D. L., & Wilson, F. J. (2000). The prevalence of anxiety and mood problems among children with autism and Asperger syndrome. *Autism*, *4*(2), 117–132. https://doi.org/10.1177/1362361300004002002

Koban, L., Ramamoorthy, A., & Konvalinka, I. (2019). Why do we fall into sync with others? Interpersonal synchronization and the brain's optimization principle. *Social Neuroscience*, *14*(1), 1–9. https://doi.org/10.1080/17470919.2017.1400463

Koehler, J. C., & Falter-Wagner, C. M. (2023). Digitally assisted diagnostics of autism spectrum disorder. *Frontiers in Psychiatry*, *14*, 1–6. https://doi.org/10.3389/fpsyt.2023.1066284

Koehler, J., Georgescu, A. L., Weiske, J., Spangemacher, M., Burghof, L., Falkai, P., Koutsouleris, N., Tschacher, W., Vogeley, K., & Falter-Wagner, C. (2021). Brief Report: Specificity of Interpersonal Synchrony Deficits to Autism Spectrum Disorder and Its Potential for Digitally Assisted Diagnostics. *Journal of Autism and Developmental Disorders*, *52*, 3718–3726. https://doi.org/10.1007/s10803-021-05194-3

Kupper, Z., Ramseyer, F., Hoffmann, H., & Tschacher, W. (2015). Nonverbal synchrony in social interactions of patients with schizophrenia indicates socio-communicative deficits. *PLoS ONE*, *10*(12), 1–18. https://doi.org/10.1371/journal.pone.0145882

Lakin, J. L., Chartrand, T. L., & Arkin, R. M. (2008). I am too just like you: Nonconscious mimicry as an automatic behavioral response to social exclusion. *Psychological Science*, *19*(8), 816–822. https://doi.org/10.1111/j.1467-9280.2008.02162.x

Langton, S. R. H., & Bruce, V. (2000). You must see the point: Automatic processing of cues to the direction of social attention. *Journal of Experimental Psychology: Human Perception and Performance*, *26*(2), 747–757. https://doi.org/10.1037/0096-1523.26.2.747

Langton, S. R. H., Watt, R. J., & Bruce, V. (2000). Do the eyes have it? Cues to the direction of social attention. *Trends in Cognitive Sciences*, *4*(2), 50–59. https://doi.org/10.1016/S1364-6613(99)01436-9

LeBarton, E. S., & Iverson, J. M. (2016). Gesture development in toddlers with an older sibling with autism. *International Journal of Language & Communication Disorders*, *51*(1), 18–30. https://doi.org/10.1111/1460- 6984.12180

Lense, M. D., Ladányi, E., Rabinowitch, T. C., Trainor, L., & Gordon, R. (2021). Rhythm and timing as vulnerabilities in neurodevelopmental disorders. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *376*(1835), 1–13. https://doi.org/10.1098/rstb.2020.0327

Leung, E. H., & Rheingold, H. L. (1981). Development of pointing as a social gesture. *Developmental Psychology*, *17*(2), 215–220. https://doi.org/10.1037/0012-1649.17.2.215

Liebal, K., Behne, T., Carpenter, M., & Tomasello, M. (2009). Infants use shared experience to interpret pointing gestures. *Developmental Science*, *12*(2), 264–271. https://doi.org/10.1111/j.1467-7687.2008.00758.x

Likens, A. D., & Wiltshire, T. J. (2021). Windowed multiscale synchrony: Modeling time-varying and scale-localized interpersonal coordination dynamics. *Social Cognitive and Affective Neuroscience*, *16*(1–2), 232–245. https://doi.org/10.1093/scan/nsaa130

Littlejohn, S. W., & Foss, K. A. (2009). *Encyclopedia of communication theory.* (1st ed.). SAGE Publications Inc. https://doi.org/10.4135/9781412959384

Lord, C., Risi, S., Lambrecht, L., Cook, E. H., Leventhal, B. L., DiLavore, P. C., Pickles, A., & Rutter, M. (2000). The Autism Diagnostic Observation Schedule—Generic: A standard measure of social and communication deficits associated with the spectrum of autism. *Journal of Autism and Developmental Disorders*, *30*(3), 205–223. https://doi.org/10.1023/A:1005592401947

Maes, P., Stercq, F., & Kissine, M. (2021). Attention to intentional versus incidental pointing gestures in young autistic children: An eye-tracking study. *Journal of Experimental Child Psychology*, *210*, 1–15. https://doi.org/10.1016/j.jecp.2021.105205

Manwaring, S. S., Stevens, A. L., Mowdood, A., & Lackey, M. (2018). A scoping review of deictic gesture use in toddlers with or at-risk for autism spectrum disorder. *Autism & Developmental Language Impairments*, *3*, 1–27. https://doi.org/10.1177/2396941517751891

Markova, G., Nguyen, T., & Hoehl, S. (2019). Neurobehavioral Interpersonal Synchrony in Early Development: The Role of Interactional Rhythms. *Frontiers in Psychology*, *10*(2078), 1–6. https://doi.org/10.3389/fpsyg.2019.02078

Mastrogiuseppe, M., Capirci, O., Cuva, S., & Venuti, P. (2015). Gestural communication in children with autism spectrum disorders during mother–child interaction. *Autism*, *19*(4), 469–481. https://doi.org/10.1177/136236131452839

Mayo, O., & Gordon, I. (2020). In and out of synchrony—Behavioral and physiological dynamics of dyadic interpersonal coordination. *Psychophysiology*, *57*(6), 1–15. https://doi.org/10.1111/psyp.13574

McAuliffe, D., Pillai, A. S., Tiedemann, A., Mostofsky, S. H., & Ewen, J. B. (2017). Dyspraxia in ASD: Impaired coordination of movement elements. *Autism Research*, *10*(4), 648–652. https://doi.org/10.1002/aur.1693

McGrath, J. E., & Kelly, J. R. (1986). *Time and human interaction: Toward a social psychology of time.* Guilford Press. https://psycnet.apa.org/record/1986-98714-000

McNaughton, K. A., & Redcay, E. (2020). Interpersonal Synchrony in Autism. *Current Psychiatry Reports*, *22*(3), 1–11. https://doi.org/10.1007/s11920-020-1135-8

Miles, L. K., Nind, L. K., & Macrae, C. N. (2009). The rhythm of rapport: Interpersonal synchrony and social perception. *Journal of Experimental Social Psychology*, *45*(3), 585–589. https://doi.org/10.1016/j.jesp.2009.02.002

Milton, D. E. M. (2012). On the ontological status of autism: The “double empathy problem.” *Disability and Society*, *27*(6), 883–887. https://doi.org/10.1080/09687599.2012.710008

Mishra, A., Ceballos, V., Himmelwright, K., McCabe, S., & Scott, L. (2021). Gesture Production in Toddlers with Autism Spectrum Disorder. *Journal of Autism and Developmental Disorders*, *51*(5), 1658–1667. https://doi.org/10.1007/s10803-020-04647-5

Mitchell, P., Sheppard, E., & Cassidy, S. (2021). Autism and the double empathy problem: Implications for development and mental health. *British Journal of Developmental Psychology*, *39*(1), 1–18. https://doi.org/10.1111/bjdp.12350

Monk, R., Whitehouse, A. J. O., & Waddington, H. (2022). The use of language in autism research. *Trends in Neurosciences*, *45*(11), 791–793. https://doi.org/10.1016/j.tins.2022.08.009

Morimoto, C., Hida, E., Shima, K., & Okamura, H. (2018). Temporal Processing Instability with Millisecond Accuracy is a Cardinal Feature of Sensorimotor Impairments in Autism Spectrum Disorder: Analysis Using the Synchronized Finger-Tapping Task. *Journal of Autism and Developmental Disorders*, *48*(2), 351–360. https://doi.org/10.1007/s10803-017-3334-7

Morrison, S., Armitano, C. N., Raffaele, C. T., Deutsch, S. I., Neumann, S. A., Caracci, H., & Urbano, M. R. (2018). Neuromotor and cognitive responses of adults with autism spectrum disorder compared to neurotypical adults. *Experimental Brain Research*, *236*(8), 2321–2332. https://doi.org/10.1007/s00221-018-5300-9

Mottron, L., & Bzdok, D. (2020). Autism spectrum heterogeneity: fact or artifact? *Molecular Psychiatry*, *25*(12), 3178–3185. https://doi.org/10.1038/s41380-020-0748-y

Mundy, P. (2018). A review of joint attention and social-cognitive brain systems in typical development and autism spectrum disorder. *European Journal of Neuroscience*, *47*(6), 497–514. https://doi.org/10.1111/ejn.13720

Mundy, P., & Crowson, M. (1997). Joint attention and early social communication: Implications for research on intervention with autism. *Journal of Autism and Developmental Disorders*, *27*(6), 653–676. https://doi.org/10.1023/A:1025802832021

Mundy, P., & Newell, L. (2007). Attention, joint attention, and social cognition. *Current Directions in Psychological Science*, *16*(5), 269–274. https://doi.org/10.1111/j.1467-8721.2007.00518.x

Mundy, P., Sigman, M., & Kasari, C. (1990). A longitudinal study of joint attention and language development in autistic children. *Journal of Autism and Developmental Disorders*, *20*(1), 115–128. https://doi.org/10.1007/BF02206861

Murat Baldwin, M., Xiao, Z., & Murray, A. (2021). Temporal Synchrony in Autism: a Systematic Review. *Review Journal of Autism and Developmental Disorders*, *9*, 596–617. https://doi.org/10.1007/s40489-021-00276-5

Murillo, E., Camacho, L., & Montero, I. (2021). Multimodal Communication in Children with Autism Spectrum Disorder and Different Linguistic Development. *Journal of Autism and*

Developmental Disorders, *51*(5), 1528–1539. https://doi.org/10.1007/s10803-020-04637-7

Murphy, N. A., & Hall, J. A. (2021). Capturing Behavior in Small Doses: A Review of Comparative Research in Evaluating Thin Slices for Behavioral Measurement. *Frontiers in Psychology*, *12*, 1–13. https://doi.org/10.3389/fpsyg.2021.667326

Nguyen, L. S., & Gatica-Perez, D. (2015). I would hire you in a minute: Thin slices of nonverbal behavior in job interviews. In *ICMI 2015 - Proceedings of the 2015 ACM International Conference on Multimodal Interaction* (pp. 51–58). https://doi.org/10.1145/2818346.2820760

Noel, J.-P., De Niear, M. A., Lazzara, N. S., & Wallace, M. T. (2018). Uncoupling Between Multisensory Temporal Function and Nonverbal Turn-Taking in Autism Spectrum Disorder. *IEEE Transactions on Cognitive and Developmental Systems*, *10*(4), 973–982. https://doi.org/10.1109/TCDS.2017.2778141.

Nyström, P., Thorup, E., Bölte, S., & Falck-Ytter, T. (2019). Joint Attention in Infancy and the Emergence of Autism. *Biological Psychiatry*, *86*(8), 631–638. https://doi.org/10.1016/j.biopsych.2019.05.006

Özçalışkan, Ş., Adamson, L. B., & Dimitrova, N. (2016). Early deictic but not other gestures predict later vocabulary in both typical development and autism. *Autism*, *20*(6), 754–763. https://doi.org/10.1177/1362361315605921

Ozonoff, S., Iosif, A. M., Baguio, F., Cook, I. C., Hill, M. M., Hutman, T., Rogers, S. J., Rozga, A., Sangha, S., Sigman, M., Steinfeld, M. B., & Young, G. S. (2010). A prospective study of the emergence of early behavioral signs of autism. *Journal of the American Academy of Child and Adolescent Psychiatry*, *49*(3), 256–266. https://doi.org/10.1016/j.jaac.2009.11.009

Ozonoff, S., Young, G. S., Belding, A., Hill, M., Hill, A., Hutman, T., Johnson, S., Miller, M., Rogers, S. J., Schwichtenberg, A. J., Steinfeld, M., & Iosif, A. M. (2014). The broader autism phenotype in infancy: When does it emerge? *Journal of the American Academy of Child and Adolescent Psychiatry*, *53*(4), 398–407. https://doi.org/10.1016/j.jaac.2013.12.020

Pan, Y., Novembre, G., Song, B., Zhu, Y., & Hu, Y. (2021). Dual brain stimulation enhances interpersonal learning through spontaneous movement synchrony. *Social Cognitive and Affective Neuroscience*, *16*(1–2), 210–221. https://doi.org/10.1093/scan/nsaa080

Parladé, M. V., & Iverson, J. M. (2011). The interplay between language, gestures, and affect during communicative transition: A dynamic systems approach. *Developmental Psychology*, *47*(3), 820–833. https://doi.org/10.1037/a0021811

Parladé, M. V., & Iverson, J. M. (2015). The Development of Coordinated Communication in Infants at Heightened Risk for Autism Spectrum Disorder. *Journal of Autism and Developmental Disorder*, *45*(7), 2218–2234. https://doi.org/10.1007/s10803-015-2391-z

Parr, T., & Friston, K. J. (2019). Generalised free energy and active inference. *Biological Cybernetics*, *113*(5–6), 495–513. https://doi.org/10.1007/s00422-019-00805-w

Paulick, J., Rubel, J. A., Deisenhofer, A. K., Schwartz, B., Thielemann, D., Altmann, U., Boyle, K., Strauß, B., & Lutz, W. (2018). Diagnostic Features of Nonverbal Synchrony in Psychotherapy: Comparing Depression and Anxiety. *Cognitive Therapy and Research*, *42*(5). https://doi.org/10.1007/s10608-018-9914-9

Plaisted, K. C. (2001). Reduced Generalization in Autism: An Alternative to Weak Central Coherence. In J. A. Burack, A. Charman, N. Yirmiya, & N. Zelazo (Eds.), *Development and autism: Perspectives from theory and research* (pp. 149–169). Lawrence Erlbaum Associates. https://doi.org/10.4324/9781410600196-15

Presmanes, A. G., Walden, T. A., Stone, W. L., & Yoder, P. J. (2007). Effects of different attentional cues on responding to joint attention in younger siblings of children with autism spectrum disorders. *Journal of Autism and Developmental Disorders*, *37*(1), 133–144. https://doi.org/10.1007/s10803-006-0338-0

Price, K. J., Edgell, D., & Kerns, K. A. (2012). Timing deficits are implicated in motor dysfunction in Asperger's syndrome. *Research in Autism Spectrum Disorders*, *6*(2), 857–860. https://doi.org/10.1016/j.rasd.2011.11.007

Ramos-Cabo, S., Vulchanov, V., & Vulchanova, M. (2019). Gesture and language trajectories in early development: An overview from the autism spectrum disorder perspective. *Frontiers in Psychology*, *10*, 1–9. https://doi.org/10.3389/fpsyg.2019.01211

Ramseyer, F. T. (2020). Motion energy analysis (MEA): A primer on the assessment of motion from video. *Journal of Counseling Psychology*, *67*(4), 536–549. https://doi.org/10.1037/cou0000407

Ramseyer, F., & Tschacher, W. (2011). Nonverbal synchrony in psychotherapy: coordinated body movement reflects relationship quality and outcome. *Journal of Consulting and Clinical Psychology*, *79*(3), 284–295. https://doi.org/10.1037/a0023419

Redcay, E., Dodell-Feder, D., Mavros, P. L., Kleiner, M., Pearrow, M. J., Triantafyllou, C., Gabrieli, J. D., & Saxe, R. (2013). Atypical brain activation patterns during a face-to-face joint attention game in adults with autism spectrum disorder. *Human Brain Mapping*, *34*(10), 2511–2523. https://doi.org/10.1002/hbm.22086

Redcay, E., & Schilbach, L. (2020). Using second-person neuroscience to elucidate the mechanisms of social interaction. *Nature Reviews Neuroscience*, *20*(8), 495–505. https://doi.org/10.1038/s41583-019-0179-4.Using

Rochat, P., Querido, J. G., & Striano, T. (1999). Emerging sensitivity to the timing and structure of protoconversation in early infancy. *Developmental Psychology*, *35*(4), 950–957.

Rosen, N. E., Lord, C., & Volkmar, F. R. (2021). The Diagnosis of Autism: From Kanner to DSM-III to DSM-5 and Beyond. *Journal of Autism and Developmental Disorders*, *51*(12), 4253–4270. https://doi.org/10.1007/s10803-021-04904-1

Salo, V. C., Rowe, M. L., & Reeb-Sutherland, B. (2018). Exploring Infant Gesture and Joint Attention as Related Constructs and as Predictors of Later Language. *Infancy*, *23*(3), 432–452. https://doi.org/10.1111/infa.12229

Sansavini, A., Guarini, A., Zuccarini, M., Lee, J. Z., Faldella, G., & Iverson, J. M. (2019). Low Rates of Pointing in 18-Month-Olds at Risk for Autism Spectrum Disorder and Extremely Preterm Infants: A Common Index of Language Delay? *Frontiers in Psychology*, *10*, 1–12. https://doi.org/10.3389/fpsyg.2019.02131

Sasson, N. J., Faso, D. J., Nugent, J., Lovell, S., Kennedy, D. P., & Grossman, R. B. (2017). Neurotypical peers are less willing to interact with those with autism based on thin slice judgments. *Scientific Reports*, *7*(40700), 40700. https://doi.org/10.1038/srep40700

Sato, W., Kochiyama, T., Uono, S., & Yoshikawa, S. (2009). Commonalities in the neural mechanisms underlying automatic attentional shifts by gaze, gestures, and symbols. *NeuroImage*, *45*(3), 984–992. https://doi.org/10.1016/j.neuroimage.2008.12.052

Schilbach, L., Timmermans, B., Reddy, V., Costall, A., Kai, G. B., Schlicht, T., & Vogeley, K. (2012). Toward a second-person neuroscience. *Behavioral and Brain Sciences*, *36*(4), 393–414. https://doi.org/10.1017/S0140525X12000660

Seibert, J. M., Hogan, A. E., & Mundy, P. C. (1982). Assessing interactional competencies: The early social-communication scales. *Infant Mental Health Journal*, *3*(4), 244–258. https://doi.org/10.1002/1097-0355(198224)3:4<244::AID-IMHJ2280030406>3.0.CO;2-R

Senju, A., & Johnson, M. H. (2009). The eye contact effect: mechanisms and development. *Trends in Cognitive Sciences*, *13*(3), 127–134. https://doi.org/10.1016/j.tics.2008.11.009

Senju, A., Tojo, Y., Dairoku, H., & Hasegawa, T. (2004). Reflexive orienting in response to eye gaze and an arrow in children with and without autism. In *Journal of Child Psychology and Psychiatry and Allied Disciplines* (Vol. 45, Issue 3, pp. 445–458). https://doi.org/10.1111/j.1469-7610.2004.00236.x

Shumway, S., & Wetherby, A. M. (2009). Communicative Acts of Children With Autism Spectrum Disorders in the Second Year of Life. *Journal of Speech and Language Hearing Research*, *52*(5), 1139–1156. https://doi.org/110.1044/1092-4388(2009/07-0280)

Stallworthy, I. C., Lasch, C., Berry, D., Wolff, J. J., Pruett, J. R., Marrus, N., Swanson, M. R., Botteron, K. N., Dager, S. R., Estes, A. M., Hazlett, H. C., Schultz, R. T., Zwaigenbaum, L., Piven, J., & Elison, J. T. (2022). Variability in Responding to Joint Attention Cues in the First Year is Associated With Autism Outcome. *Journal of the American Academy of Child and Adolescent Psychiatry*, *61*(3), 413–422. https://doi.org/10.1016/j.jaac.2021.03.023

Stone, W. L., Ousley, O. Y., Yoder, P. J., Hogan, K. L., & Hepburn, S. L. (1997). Nonverbal Communication in Two- and Three-Year-Old Children with Autism. *Journal of Autism and Developmental Disorder*, *27*, 677–696. https://doi.org/10.1023/A:1025854816091

Streeck, J. (1993). Gesture as communication I: Its coordination with gaze and speech. *Communications Monographs*, *60*(4), 275–299.

Striano, T., Henning, A., & Stahl, D. (2006). Sensitivity to interpersonal timing at 3 and 6 months of age. *Interaction Studies. Social Behaviour and Communication in Biological and Artificial Systems*, *7*(2), 251–271. https://doi.org/10.1075/is.7.2.08str

Striano, T., & Reid, V. M. (2006). Social cognition in the first year. *Trends in Cognitive Sciences*, *10*(10), 471-476. https://doi.org/10.1016/j.tics.2006.08.006

Sullivan, M., Finelli, J., Marvin, A., Garrett-Mayer, E., Bauman, M., & Landa, R. (2007). Response to Joint Attention in Toddlers at Risk for Autism Spectrum Disorder: A Prospective Study. *Journal of Autism and Developmental Disorder*, *37*, 37–48. https://doi.org/10.1007/s10803-006-0335-3

Tavassoli, T., Hoekstra, R. A., & Baron-Cohen, S. (2014). The Sensory Perception Quotient (SPQ): Development and validation of a new sensory questionnaire for adults with and without autism. *Molecular Autism*, *5*(1), 1–10. https://doi.org/10.1186/2040-2392-5-29

Tepest, R. (2021). The Meaning of Diagnosis for Different Designations in Talking About Autism. *Journal of Autism and Developmental Disorders*, *51*(2), 760–761. https://doi.org/10.1007/s10803-020-04584-3

Thorup, E., Nyström, P., Bölte, S., & Falck-Ytter, T. (2022). What are you looking at? Gaze following with and without target objects in ASD and typical development. *Autism*, *26*(7), 1668–1680. https://doi.org/10.1177/13623613211061940

Thye, M. D., Bednarz, H. M., Herringshaw, A. J., Sartin, E. B., & Kana, R. K. (2018). The impact of atypical sensory processing on social impairments in autism spectrum disorder. *Developmental Cognitive Neuroscience*, *29*, 151–167. https://doi.org/10.1016/j.dcn.2017.04.010

Tickle-Degnen, L., & Rosenthal, R. (1990). The nature of rapport and its nonverbal correlates. *Psychological Inquiry*, *1*(4), 285–293. https://doi.org/10.1207/s15327965pli0104_1

Tomasello, M., Carpenter, M., Call, J., Behne, T., & Moll, H. (2005). Understanding and sharing intentions: The origins of cultural cognition. *Behavioral and Brain Sciences*, *28*(5), 675–691. https://doi.org/10.1017/S0140525X05000129

Tranchant, P., Scholler, E., & Palmer, C. (2022). Endogenous rhythms influence musicians' and non-musicians' interpersonal synchrony. *Scientific Reports*, *12*(1), 1–14. https://doi.org/10.1038/s41598-022-16686-2

Trevarthen, C., & Daniel, S. (2005). Disorganized rhythm and synchrony: Early signs of autism and Rett syndrome. *Brain and Development*, *27*(1), 25–34. https://doi.org/10.1016/j.braindev.2005.03.016

Vacharkulksemsuk, T., & Fredrickson, B. L. (2012). Strangers in sync: Achieving embodied rapport through shared movements. *Journal of Experimental Social Psychology*, *48*(1), 399–402. https://doi.org/10.1016/j.jesp.2011.07.015

Valdesolo, P., Ouyang, J., & DeSteno, D. (2010). The rhythm of joint action: Synchrony promotes cooperative ability. *Journal of Experimental Social Psychology*, *46*(4), 693–695. https://doi.org/10.1016/j.jesp.2010.03.004

van de Cruys, S., Evers, K., van der Hallen, R., van Eylen, L., Boets, B., de-Wit, L., & Wagemans, J. (2014). Precise minds in uncertain worlds: Predictive coding in autism. *Psychological Review*, *121*(4), 649–675. https://doi.org/10.1037/a0037665

Vishne, G., Jacoby, N., Malinovitch, T., Epstein, T., Frenkel, O., & Ahissar, M. (2021). Slow update of internal representations impedes synchronization in autism. *Nature Communications*, *12*(1), 1–15. https://doi.org/10.1038/s41467-021-25740-y

Vogeley, K. (2017). Two social brains: Neural mechanisms of intersubjectivity. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *372*(1727), 1–11. https://doi.org/10.1098/rstb.2016.0245

Vogeley, K., Bussfeld, P., Newen, A., Herrmann, S., Happé, F., Falkai, P., Maier, W., Shah, N. J., Fink, G. R., & Zilles, K. (2001). Mind reading: neural mechanisms of theory of mind and self-perspective. *Neuroimage*, *14*(1), 170–181. https://doi.org/10.1006/nimg.2001.0789

Walther, S., Stegmayer, K., Sulzbacher, J., Vanbellingen, T., Müri, R., Strik, W., & Bohlhalter, S. (2015). Nonverbal social communication and gesture control in schizophrenia. *Schizophrenia Bulletin*, *41*(2), 338–345. https://doi.org/10.1093/schbul/sbu222

Wimpory, D., Nicholas, B., & Nash, S. (2002). Social timing, clock genes and autism: A new hypothesis. *Journal of Intellectual Disability Research*, *46*(4), 352–358. https://doi.org/10.1046/j.1365-2788.2002.00423.x

Winder, B. M., Wozniak, R. H., Parladé, M. V., & Iverson, J. M. (2013). Spontaneous initiation of communication in infants at low and heightened risk for autism spectrum disorders. *Developmental Psychology*, *49*(10), 1931–1942. https://doi.org/10.1037/a0031061

World Health Organization. (1993). *The ICD-10 classification of mental and behavioural disorders : diagnostic criteria for research*. World Health Organization. https://apps.who.int/iris/handle/10665/37108 %0A

Yale, M. E., Messinger, D. S., Cobo-Lewis, A. B., & Delgado, C. F. (2003). The Temporal Coordination of Early Infant Communication. *Developmental Psychology*, *39*(5), 815–824. https://doi.org/10.1037/0012-1649.39.5.815

Yu, C., & Smith, L. B. (2013). Joint attention without gaze following: Human infants and their parents coordinate visual attention to objects through eye-hand coordination. *PLoS ONE*, *8*(11), 1–10. https://doi.org/10.1371/journal.pone.0079659

Yu, C., & Smith, L. B. (2015). Linking Joint Attention with Hand-Eye Coordination - A Sensorimotor Approach to Understanding Child-Parent Social Interaction. *CogSci - Annual Conference of the Cognitive Science Society*, 2763–2768. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5722468/

Yu, C., & Smith, L. B. (2017). Hand–Eye Coordination Predicts Joint Attention. *Child Development*, *88*(6), 2060–2078. https://doi.org/10.1111/cdev.12730

Yun, K., Watanabe, K., & Shimojo, S. (2012). Interpersonal body and neural synchronization as a marker of implicit social interaction. *Scientific Reports*, *2*(959), 1–8. https://doi.org/10.1038/srep00959

Zamm, A., Wellman, C., & Palmer, C. (2016). Endogenous rhythms influence interpersonal synchrony. *Journal of Experimental Psychology: Human Perception and Performance*, *42*(5), 611–616. https://doi.org/10.1037/xhp0000201