Temporal synchrony in autism

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REVIEW PAPER

Temporal Synchrony in Autism: a Systematic Review

Mina Murat Baldwin[1] · Zhuoni Xiao[1] · Aja Murray[1]

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Abstract

Temporal synchrony is the alignment of processes in time within or across individuals in social interaction and is observed and studied in various domains using wide-ranging paradigms. Evidence suggesting reduced temporal synchrony in autism (e.g. compared to neurotypicals) has hitherto not been reviewed. To systematically review the magnitude and generalisability of the difference across different tasks and contexts, EBSCO, OVID, Web of Science, and Scopus databases were searched. Thirty-two studies were identified that met our inclusion criteria in audio-visual, audio-motor, visuo-tactile, visuo-motor, social motor, and conversational synchrony domains. Additionally, two intervention studies were included. The findings suggest that autistic participants showed reduced synchrony tendencies in every category of temporal synchrony reviewed. Implications, methodological weaknesses, and evidence gaps are discussed.

Keywords Autism · Temporal synchrony · Sensory processing · Temporal sensory integration

As part of the efforts to better capture the considerable heterogeneity within autism and to provide a more nuanced and detailed picture of the experiences of autistic individuals, investigations are increasingly moving beyond symptoms traditionally viewed as 'core' (Astle & Fletcher-Watson, 2020). A key finding to emerge from these investigations is a potential difference in temporal synchrony tendencies between autistic and neurotypical individuals. Temporal synchrony can be defined as two or more actions integrated in time and/or individuals entrained to each other in social interaction. This can include cross-domain integration within an individual, e.g. audio-visual, audio-motor, visuo-tactile, or visuo-motor integration, or it can refer to interpersonal integration during social interaction, e.g. the alignment of gestures, facial expressions, and language during communication. Thus defined, differences in temporal synchrony tendencies have been proposed to underlie some of the observed differences between typically developing and autistic individuals and to be a promising intervention target (e.g. McNaughton & Redcay, 2020). The goal of the present study is to help evaluate these claims by systematically reviewing the evidence on the nature, extent, and generalisability of temporal synchrony differences between typically developing and autistic individuals, as well as interventions targeting temporal synchrony in autistic individuals.

It has been proposed that during the course of an interaction, individuals become temporally synchronised to each other, meaning that both verbal and non-verbal behaviour during communication align in terms of the phase and frequency or period (McGrath & Kelly, 1986). While there is ample empirical evidence supporting these propositions in neurotypical development (Condon & Sander, 1974; Petitto et al., 2000, 2001), studies on temporal synchrony in autism have identified differences in temporal constructs such the flow and timing of conversations (Wimpory, 2015). The first review study to report on temporal processing and management skills in autistic individuals suggested that there were processing difficulties in various temporal patterns (millisecond, interval, circadian) and difficulties in audio-visual temporal integration (Jurek et al., 2019). Another review study reported inter- and intra-personal asynchrony in autistic individuals, suggesting an altered experience of time and atypical integration of audial, visual, and motor sensory inputs (Bloch et al., 2019). Temporal deviations in various sensory inputs are most likely to influence behaviour related to the ability to establish and maintain synchronous, reciprocal engagement with others, and therefore, may contribute to social-communication differences in autism (McNaughton & Redcay, 2020). Indeed, it has been proposed that diagnostic

✉ Mina Murat Baldwin
mina.muratbaldwin@gmail.com

[1] Department of Psychology, University of Edinburgh, 7 George Square, Edinburgh EH8 9JZ, UK

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practices would benefit from assessing a wider presentation of symptoms associated with autism, and measures of interpersonal alignment could serve as implicit measures aiding diagnosis (Bloch et al., 2019).

While reviews to date have provided important insights and helped provide an expanded focus on autistic symptomatology that goes beyond traditionally ‘core’ symptoms, they have done so only in limited categories of temporal synchrony or using methods that do not involve systematically identifying and evaluating all the primary studies in this area (e.g. Jurek et al., 2019; McNaughton & Redcay, 2020). On the basis of a scoping search, it was found that temporal synchrony has been empirically studied in numerous domains and with a diversity of paradigms. Aspects of temporal synchrony that have been examined in the context of autism to date include audio-visual, audio-motor, visuo-tactile, visuo-motor, social-motor, and conversational synchrony and within these, a variety of paradigms have been employed. For example, studies examining temporal synchrony tendencies across the auditory and visual domains have used preferential looking, illusion susceptibility, and temporal order judgment paradigms, while studies examining conversational synchrony have used methods such as the coding of dyadic interactions for gestural synchrony.

Given the volume and diversity of research in this area, and the potential implications for illuminating autistic experiences and informing interventions, a systematic review would thus be beneficial to provide an overview of the evidence concerning various types of temporal synchrony, and to assess the quality of the available data. Another advantage of a systematic review of this topic is that it can identify common methodological weaknesses and evidence gaps that can provide the basis for recommendations to help strengthen knowledge in this field. It can also identify the generalisability and the limits of the findings of asynchrony in autism and define the domains and tasks in which it is in evidence.

Therefore, the present information gap will be filled by reviewing different aspects of temporal synchrony in autism with the aim of answering whether, and in which contexts, the research findings indicate atypical temporal synchrony in autism.

Methods

A systematic review protocol was developed following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis Protocols (PRISMA-P) recommendations (Moher et al., 2015) prior to beginning the review. The only deviations from the original protocol were that data on participant sex/gender was not mentioned in the data extraction section of the protocol, and neural temporal synchrony studies were excluded from the review.

Search Strategy

Two main search methods were used: (a) database search and (b) examination of reference lists.

a) The database search involved key concepts of the study defined as ‘autism’, ‘temporal’, and ‘synchrony’. To identify relevant studies, synonyms were used in search terms (Table 1). Boolean operators (‘AND’, ‘OR’, and ‘NOT’) were used to manage search strings and to combine key concepts. The operators were tailored to the syntax of each of the databases used: EBSCO (which combines MEDLINE, Child Development and Adolescent Studies, and CINAHL), OVID (which combines PsycINFO, PsycArticles and EMBASE), Web of Science, and Scopus.

   An example of the search string used and adapted to other databases was (Autism OR Asperger OR autistic disorder OR Autism spectrum disorder OR autistic syndrome disorder OR ASD OR pervasive developmental disorder) AND (temporal OR time OR timing OR chrono* OR pattern) AND (synchron* OR dyssynchron* OR asynchron* OR desynchron* OR entrain* OR align*).
b) Reference lists of both the relevant papers included in the review and literature reviews identified through database searches were screened to identify additional pertinent works.

Table 1 Example search terms

Population	Temporal synchrony
Autism	Temporal
Asperger	Time
Autistic disorder	Timing
Autism spectrum disorder	Synchron*
Autistic syndrome disorder	Dyssonchron*
ASD	Assynchron*
Pervasive developmental disorder	Chrono*
	Entrain*
	Pattern
	Align*

Note. *Wildcard

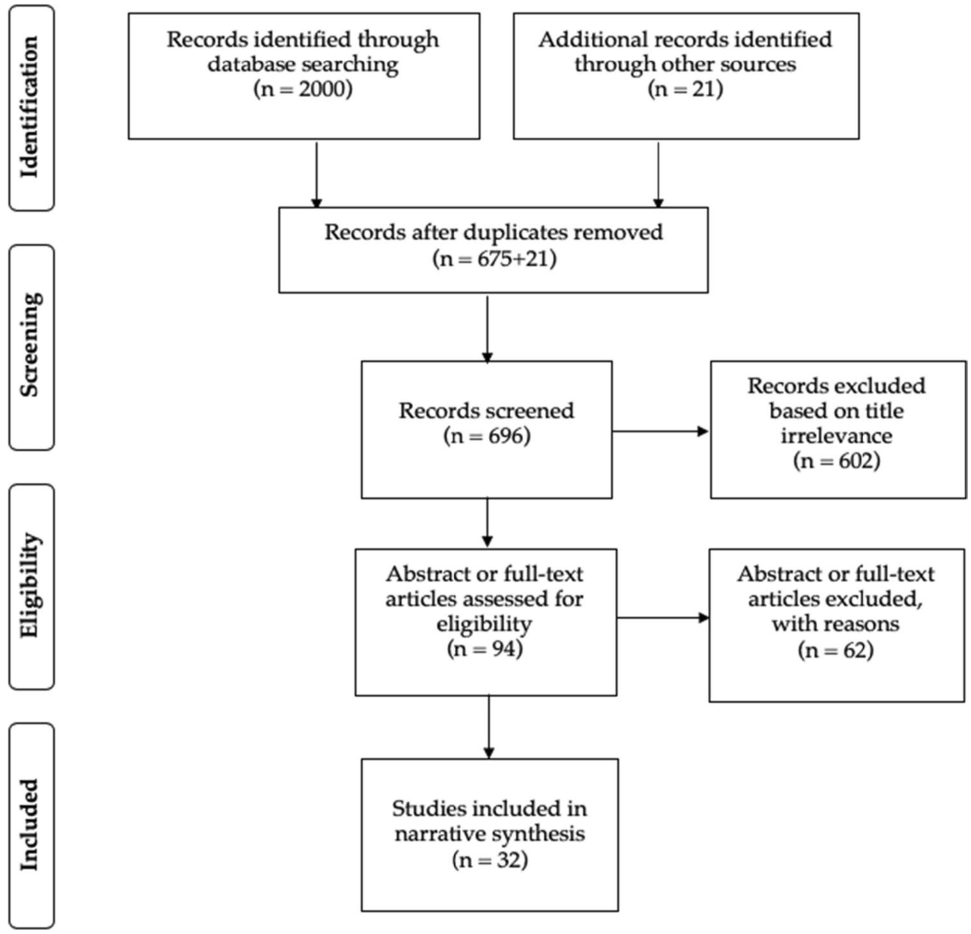

Fig. 1 Flow Chart of the Systematic Review Based on PRISMA Guidelines

Data Extraction

The bibliographic software programme Zotero was used to manage and store relevant studies. Duplicate records were removed using the same software. Search results were independently evaluated for eligibility by two reviewers based on the study title, abstract, and full text.

Studies were selected according to the criteria below:

i. Participants with a diagnosis of autism based on either *Diagnostic and Statistical Manual of Mental Health Disorders* (*DSM*) or *International Classification of Diseases* (*ICD*) criteria and/or individuals who met the research and/or clinical cut-off points of a validated screening tool.
ii. Participants from all age groups
iii. Studies that were reported in English
iv. Temporal synchrony investigated in various contexts to be discussed later in coherent groups
v. Both randomised and non-randomised studies including intervention studies
vi. There was no restriction on the publication year

Studies were excluded according to the criteria below:

i. Animal studies
ii. Grey literature identified as dissertations/theses, abstracts, unpublished reports and ongoing trials
iii. Cohort studies and other non-experimental designs
iv. Non-empirical articles, including case reports, book chapters, letters, editorials, and opinion pieces
v. Studies investigating neural temporal synchrony
vi. Studies for which it was not possible to obtain the full text

The selection process was completed when an agreement was reached between the first author and the second reviewer. In the case of a difference of opinion, the issue was resolved by involving a third reviewer. The final decision on the inclusion or exclusion of studies (along with reasons for exclusion) was documented for each study. The initial literature search returned 2000 records[1] at the time of

[1] This number of results was returned after an initial automatic deduplication by EBSCO database.

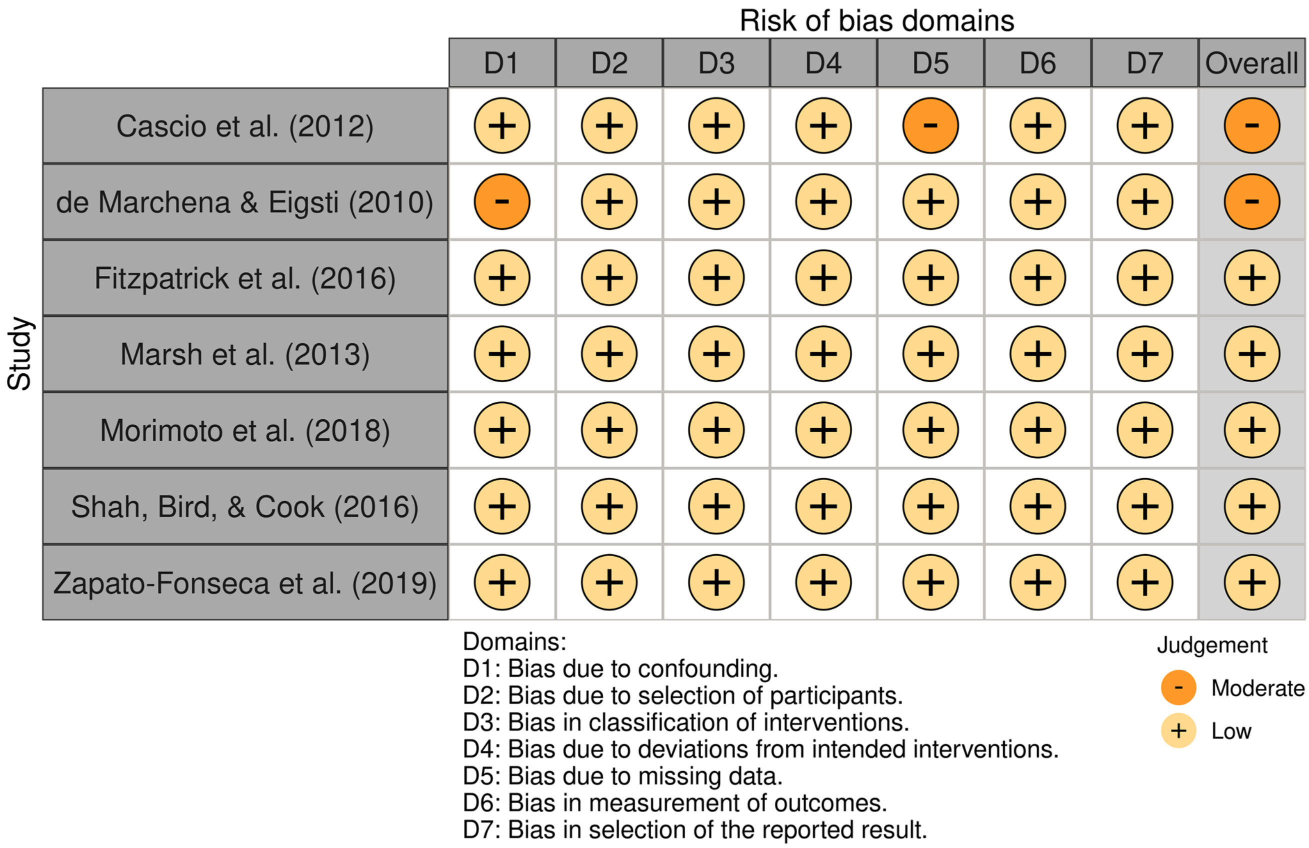

Fig. 2 Risk of Bias Assessment of Non-randomised Controlled Studies

search, which was reduced to 675 after manually excluding duplicates. An additional 21 records were identified through reference lists of relevant papers. Following the preliminary screening of the titles and the eligibility criteria, 602 records were excluded; a further 94 records were excluded after screening the abstracts and/or full-texts based on the relevance of data to the current study (Fig. 1). Three studies were excluded after the data extraction: Feldstein et al. (1982) owing to the lack of a control group; Massaro and Bosseler (2002) for not reporting the autism assessment method; and Tavano et al. (2014) for not reporting the results of the paradigm relevant to the review.

Data from each selected study was extracted both by the author and the second reviewer using a piloted extraction form. The extracted data are presented in two tables per category of temporal synchrony. The 'study characteristics' tables include information regarding study names and locations, sample sizes, study designs, autism assessment, comparator groups, temporal synchrony assessment, study paradigms, results, findings, and finally, the group main effects were reported in partial eta squares (n_p^2) when available. The 'participant characteristics' tables include information regarding participants' mean age and mean IQ, level of functioning (high vs. low).

Each selected study was evaluated regarding the risk of bias and the evaluation was made by two reviewers using an assessment tool selected according to each study design. The quality of the selected randomised controlled studies was assessed by the 'Risk of Bias' (RoB 2) tool (Sterne et al., 2019). The tool has five domains assessing bias arising from the randomisation process, due to deviations from intended interventions/exposure, missing outcome data, measurement of the outcome and finally, selection of the reported results. The selected non-randomised controlled studies were assessed by the 'Risk of Bias in Non-randomised Studies – of Interventions' (ROBINS-I) tool (Sterne et al., 2016). The assessment was based on pre-intervention, at intervention and post-intervention domains where bias might occur. In order to summarise the quality assessment, risk of bias plots (Figs. 2 and 3) were created using the 'Risk of Bias Visualisation' (robvis) web application (McGuinness & Higgins, 2020).

Fig. 3 Risk of Bias Assessment of Randomised Controlled Studies

Table 2 Studies on audio-visual synchrony and autism

Study	Location	Sample size	Design	Autism assessment	Comparator	Paradigm	Results	Findings	Effect size in n_p^2
Bebko et al. (2006)	Canada	ASC = 16, DD = 15, NH = 16	RCT	DSM-IV	DD and NH	A preferential looking paradigm: participants viewed non-linguistic, simple linguistic or complex linguistic events on 2 screens displaying identical video tracks, but with 1 offset from the other by 3 s and with the single audio track matched to only 1 of the displays	ASC < DD/NH	Autistic group showed reduced chance level of responding to linguistic stimuli. Both comparator groups showed significant non-random preferential looking to temporal synchrony violations with and without linguistic stimuli	.21
de Boer et al., (2013)	The Netherlands	ASC = 16, TD = 16	RCT	DSM-IV	TD	Temporal order judgment task[a]	ASC < TD	Autistic group was generally less sensitive in judgments of audio-visual temporal order. There was no significant difference with social stimuli	.13
Foss-Feig et al. (2010)	USA	ASC = 29, TD = 17	RCT	ADOS	TD	Temporal order judgment task	ASC < TD	Autistic group reported the flash-beep illusion over an extended range of stimulus onset asynchronies relative to TD group	N/I
Grossman et al., (2009)	USA	ASC = 25, TD = 25	RCT	DSM-IV	TD	Participants were shown video clips in random order and asked to indicate whether each clip was in-synch or not	ASC = TD	No differences between autistic and TD groups in the accuracy of onset asynchrony detection at any "slip rate."	0

Table 2 (continued)

Study	Location	Sample size	Design	Autism assessment	Comparator	Paradigm	Results	Findings	Effect size in n_p^2
Grossman et al. (2015)	USA	ASC = 30, TD = 30	RCT	Expert clinical impression confirmed by ADOS	TD	A split-screen video of 2 identical individuals speaking side by side, while only 1 of the speakers was in synchrony with the corresponding audio track. Participants were asked to watch the video without instructions (implicit condition) or to specifically watch the in-synch speaker (explicit condition)	ASC < TD	Autistic group looked at the in-synch video less than TD group and did not increase their gaze time as much as TD group in the explicit task	.22
Iarocci et al. (2010)	Canada	ASC = 12, TD = 12	RCT	Clinical diagnosis confirmed by ADI-R	TD	A computer task in which only the mouth area of the face was displayed, and participants reported what they heard or saw when presented with consonant–vowel sounds in unimodal visual condition, and a bimodal condition	ASC < TD	Autistic group showed less visual influence and more auditory influence on the bimodal speech perception compared to TD group—largely due to significantly poorer performance in the unimodal visual condition (lip-reading)	0
Kwakye et al. (2011)	USA	ASC = 35, TD = 27	RCT	Clinical diagnosis	TD	Temporal order judgment task	ASC < TD	Autistic group thresholds were higher in the auditory task. No differences in thresholds were observed on the visual task	N/I

Table 2 (continued)

Study	Location	Sample size	Design	Autism assessment	Comparator	Paradigm	Results	Findings	Effect size in n_p^2
Magnee et al. (2008)	The Netherlands	PDD = 12; TD = 13	RCT	DSM-IV	TD	Auditory and visual stimulus of a woman's face producing similar utterances. Incongruency between auditory and visual stimuli became noticeable after visual onset	PDD < TD	PDD group had poorer performance on complex phonological processes in audio-visual interactions. Their performance was intact for pre-phonological audio-visual interactions	0
Mongillo et al. (2008)	USA	ASC = 15; TD = 21	RCT	DSM-IV	TD	Perceptual tasks: a purely visual male/female face classification, and audio-visual tasks such as the McGurk task, and the gender, vowel, ball size and ball composition match/mismatch tasks	ASC < TD on human faces and voice stimuli, ASC = TD on non-human stimuli	Autistic group performed poorer on audio-visual tasks involving human faces and voices. They scored similarly to TD group on audio-visual tasks involving nonhuman stimuli (bouncing balls)	N/I
Righi et al. (2018)	USA	ASC = 45, TD = 32	RCT	Clinical diagnosis confirmed by ADOS	TD	A speech processing task	ASC < TD	Autistic group were less sensitive to asynchronies of 0.3 s, 0.6 s, or 1.0 s between a video of a woman speaking and the corresponding audio track. TD group was sensitive to both 0.6 s and 1.0 s asynchronies	0
Stevenson et al. (2014)	USA	ASC = 32, TD = 32	RCT	Clinical diagnosis confirmed by ADOS	TD	Audio-visual simultaneity judgment task, a McGurk task, and auditory and visual temporal-order judgment tasks	ASC < TD	Autistic group showed a speech-specific asynchronous tendency in multisensory temporal processing	.05
van der Smagt et al., (2007)	The Netherlands	ASC = 15, TD = 15	RCT	DSM-IV	TD	Temporal order judgment task	ASC = TD	No difference found between groups	0

Table 2 (continued)

Study	Location	Sample size	Design	Autism assessment	Comparator	Paradigm	Results	Findings	Effect size in η_p^2
Woynaroski et al. (2013)	USA	ASC = 18, TD = 18	RCT	Clinical diagnosis confirmed by ADOS	TD	Participants were presented consonant vowel syllables in visual only, auditory only and mismatched audio-visual conditions	ASC < TD	Autistic group performed poorer in visual-only and matched audio-visual speech perception. Autistic group also reported a visual influence on heard speech in response to mismatched audio-visual syllables	.25

Note: Abbreviations: *ADI-R*, Autism Diagnostic Interview-Revised; *ADOS*, Autism Diagnostic Observation Schedule; *ASC*, autism spectrum condition; *DD*, developmental disorders; *DSM*, Diagnostic and Statistical Manual of Mental Disorders; *NH*, non-handicapped; *PDD*, pervasive developmental disorders; *RCT*, randomised-controlled studies; *TD*, typically developed; *USA*, United States of America

[a]Temporal order judgment tasks are paradigms investigating processing times of information in different modalities—in this case, audial and visual information

Data Analysis

Meta-analysis was not conducted due to heterogeneity in autism diagnostic assessment, participant age groups, experimental paradigms, and, thus, measurements of outcome. Given these differences between studies, it was judged that it would not be valid to pool effect sizes across studies. Instead, a narrative synthesis approach was used to combine results across studies.

Results

The systematic review of the literature returned 32 articles concerning audio-visual ($n = 13$), audio-motor ($n = 3$), visuo-tactile ($n = 3$), visuo-motor ($n = 3$), social motor ($n = 3$), and conversational synchronies ($n = 5$). Intervention studies ($n = 2$) on temporal synchrony were also included. Studies confirmed the diagnostic assessment of autism according to one of the following: clinical diagnosis; DSM-III-R; DSM-IV; DSM-V (American Psychiatric Association (1987), 1994, 2013); Autism Diagnostic Observation Schedule (ADOS) (Gotham et al., 2006); Autism Diagnostic Interview-Revised (ADI-R) (Kim et al., 2013); or International Classification of Diseases (ICD)-10 (World Health Organization, 2004). While a majority of the studies focused on autism diagnosis, one of the studies (Magnée et al., 2008) included a Pervasive Developmental Disorders (PDD) experimental group.

An autism sample size of 15 or more was present in 23 studies (71.8%) while an autism sample size less than 15 was present in 8 studies (25%). Half of the studies ($n = 16$) reported high functioning autism groups and the rest did not report the level of functioning of the participants.

According to the risk of bias assessment of non-randomised (Fig. 2) and randomised (Fig. 3) controlled studies, the overall quality of the included studies was low ($n = 25$) to moderate ($n = 6$). Only one study (Kwakye et al., 2011) presented a high risk of bias in three domains (D2; D4; D5).

Audio-visual Synchrony in Autistic Individuals

A majority of empirical studies on temporal synchrony investigated audio-visual synchrony, with thirteen studies in this category meeting inclusion criteria (Tables 2 and 3). The first study using a preferential looking paradigm reported poorer performance of autistic individuals in response to linguistic stimuli (Bebko et al., 2006). Similar results were found in other studies where autistic individuals showed lower scores in audio-visual synchrony tasks that were mainly speech-specific (Righi et al., 2018; Stevenson et al., 2014; Woynaroski et al., 2013). Iarocci et al. (2010)

Table 3 Participant characteristics of studies on audio-visual synchrony and autism

Study	Mean age	Mean IQ	Level of functioning
Bebko et al. (2006)	ASC = 5.49, DD = 4.88, NH = 2.36	N/I	N/I
de Boer et al. (2013)	ASC = 19.2, TD = 19.6	ASC = 106.2, TD = 106.6	High
Foss-Feig et al. (2010)	N/I	N/I	High
Grossman et al. (2009)	ASC = 14.5, TD = 13.7	Verbal ASC = 109.24, TD = 116.9; non-verbal ASC = 113.20, TD = 113.60	High
Grossman et al. (2015)	ASC = 11.10, TD = 12.5	ASC = 104, TD = 109	High
Iarocci et al. (2010)	ASC and TD = 12	N/I	N/I
Kwakye et al. (2011)	N/I	N/I	High
Magnee et al. (2008)	PDD = 21.1; TD = 23.0	PDD = 119.4; TD = 127	High
Mongillo et al. (2008)	ASC = 13.73; TD = 13.44	ASC = 96.13; TD = 101.11	High
Righi et al. (2018)	ASC = 5.12, TD = 3.04	N/I	N/I
Stevenson et al. (2014)	N/I	N/I	High
van der Smagt et al. (2007)	ASC = 20.5, TD = 20.7	ASC = 122, TD = 119	High
Woynaroski et al. (2013)	ASC = 12.4, TD = 11.5	ASC = 111.2, TD = 111.0	High

Note. Abbreviations: *ASC*, autism spectrum condition; *DD*, developmental disorders; *NH*, non-handicapped; *N/I*, not indicated; *PDD*, pervasive developmental disorders; *TD*, typically developed

also reported that an autistic participant group showed less visual and more auditory influence on speech perception, providing evidence of the linguistic stimuli impact on audio-visual synchrony in autistic individuals. Another study investigating a preferential looking paradigm with a split-screen video of two identical individuals speaking found that the autistic individuals looked at the synchronous video less than the typically developing group (Grossman et al., 2015).

While the findings indicate speech- and linguistically influenced performance in audio-visual synchrony in autistic groups, there seems to be evidence for temporal processing differences between autistic participants and comparator groups from studies where temporal order judgment tasks were adapted. It was found that autistic individuals tended to show less sensitivity in judgments of audio-visual temporal order (de Boer-Schellekens et al., 2013), reported the flash-beep illusion effect over an extended range of stimulus onset asynchronies (Foss-Feig et al., 2010), and had higher thresholds on the auditory task relative to typically developed groups, evidencing reduced synchronous tendencies in auditory temporal processing (Kwakye et al., 2011). Such tendencies of a PDD group on complex phonological processes in audio-visual interactions were also reported (Magnée et al., 2008). However, van der Smagt et al., (2007) did not find such differences on temporal order judgment tasks between autistic and typically developed groups.

Furthermore, another autistic group was reported to have preferences that are less synchronous when audio-visual tasks involve human faces and voices (as opposed to non-human stimuli, such as bouncing balls; Mongillo et al., 2008). Grossman et al., (2009) found no differences between autistic and typically developed groups in the accuracy of onset asynchrony detection in video clips of human faces and speech.

In summary, the evidence suggests that autistic individuals' performance in various audio-visual tasks are different and less synchronous when compared to typically developed individuals. The majority of the evidence seems to suggest that audio-visual synchrony was affected by speech and linguistic related tasks resulting in a poorer performance of autistic individuals.

Audio-motor Synchrony in Autistic Individuals

Three studies evaluated audio-motor synchrony in autistic individuals (Tables 4 and 5). There was agreement between the three studies that the autistic groups' performance was poorer in audio-motor synchrony tasks (Morimoto et al., 2018; Whyatt & Craig, 2013; Zapata-Fonseca et al., 2019). It was suggested that the autistic group showed more variability in temporal processing parameters than neurotypical individuals, and that temporal processing instability was related to altered motor performance (Morimoto et al., 2018). Autistic individuals were also found to perform poorer than both receptive-language and non-verbal control groups (Whyatt & Craig, 2013), and to be less inclined to sustain mutual interaction in general (Zapata-Fonseca et al., 2019). Empirical evidence on audio-motor synchrony thus suggests that autistic individuals showed poorer performance on audio-motor synchrony tasks when compared with typically developed individuals.

Table 4 Studies on audio-motor synchrony and autism

Study	Location	Sample size	Design	Autism assessment	Comparator	Paradigm	Results	Findings	Effect size in n_p^2
Morimoto et al. (2018)	Japan	ASC = 59, TD = 58	nRCT	Clinical diagnosis (DSM-V)	TD	Finger-tapping task: participants were instructed to repeat index-thumb tapping in synchronisation with onset times of periodic pulse auditory stimuli	ASC < TD	Autistic group showed more variability in temporal processing parameters than TD group. Temporal processing instability was related to altered motor performance	0
Whyatt and Craig (2013)	UK	ASC = 9, VAM = 9, CAM = 9	RCT	Clinical diagnosis (DSM-IV)	TD	Participants were asked to catch a ball as it rolled down a fixed ramp. 2 ramp heights provided 2 levels of task difficulty while the sensory information provided (audio, visual, audio-visual) was varied	ASC < VAM, CAM	Autistic group performed poorer than both the receptive language and non-verbal control groups in terms of total number of balls caught	.32
Zapata-Fonseca et al. (2019)	Mexico	ASC = 10, TD = 10	nRCT	Clinical diagnosis (ICD-10)	TD	Movement patterns exhibited during computer-mediated real-time sensorimotor interaction in 10 dyads of participants, each consisting of 1 control individual and 1 HFA individual	ASC < TD	Autistic group appeared less inclined to sustain mutual interaction and instead explored the virtual environment more generally. Multi- scale coordination between participants was present. Despite the dyadic alignment, individuals' movements differed in style	0

Note: Abbreviations: *ASC*, autism spectrum condition; *CAM*, chronological age matched; *DSM*, Diagnostic and Statistical Manual of Mental Disorders; *HFA*, high-functioning autism; *ICD*, International Classification of Diseases; *nRCT*, non-randomised controlled studies; *RCT*, randomised-controlled studies; *TD*, typically developed; *UK*, United Kingdom; *VAM*, verbal age matched

Table 5 Participant characteristics of studies on audio-motor synchrony and autism

Study	Mean age	Mean IQ	Level of functioning
Morimoto et al. (2018)	ASC = 14.7, TD = 14.7	N/I	N/I
Whyatt et al. (2013)	ASC = 10.16	N/I	N/I
Zapata-Fonseca et al. (2019)	ASC = 42.32	N/I	High

Note. Abbreviations: *ASC*, autism spectrum condition; *N/I*, not indicated; *TD*, typically developed

Visuo-tactile Synchrony in Autistic Individuals

Three studies evaluated visuo-tactile synchrony in autistic individuals (Tables 6 and 7). All three studies used a rubber hand illusion paradigm and reported similar outcomes: autistic individuals' performance was poorer when compared to neurotypical individuals (Cascio et al., 2012; Greenfield et al., 2015; Ropar et al., 2018). When compared with chronological age-matched controls, autistic individuals showed similar performance to younger mental-age controls: reduced embodiment of the spatially incongruent, but temporally congruent, hand at shorter temporal delays (Ropar et al., 2018). Thus, the available evidence on visuo-tactile synchrony suggests poorer task performance in autistic participant groups, indicating delayed visuo-tactile integration.

Visuo-motor Synchrony in Autistic Individuals

Visuo-motor synchrony in autism was evaluated by three studies (Tables 8 and 9; Edey et al., 2019; Kawasaki et al., 2017; Marsh et al., 2013). These studies used different paradigms to assess synchrony in autistic individuals but two reported similar results. During tasks in which participants were expected to show temporally synchronous motor behaviour with given visual stimuli, autistic individuals showed greater difficulty (Kawasaki et al., 2017) and less tendency to cooperate simultaneously and synchronously (Marsh et al., 2013), compared to neurotypical individuals. However, Edey et al. (2019) reported that autistic participants exhibited fewer temporal errors relative to their neurotypical counterparts in the visuo-motor synchrony task. Thus overall, these studies suggested less synchronous performance in autistic individuals.

Social Motor Synchrony in Autistic Individuals

Three studies investigated social motor synchrony in autistic individuals in comparison to neurotypicals using different experimental conditions (Tables 10 and 11). Autistic individuals demonstrated less synchronisation in both spontaneous and intentional interpersonal coordination when they were asked to swing pendulums with others (Fitzpatrick et al., 2016). They also exhibited fewer stable patterns of social synchronisation ability, while their performance of motor movements was slower in both spacing and timing (Fitzpatrick et al., 2017). However, in another study no difference between autistic and neurotypical individuals was found when participants were asked to perform movements that had been introduced earlier in synchrony with the experimenter (Fitzpatrick et al., 2013).

In summary, one study on social motor synchrony found no difference between autism and typically developed group performances, but two suggested reduced temporal synchrony in the social motor performance of autistic individuals.

Conversational Synchrony in Autistic Individuals

Five studies investigated conversational synchrony in autistic individuals compared to neurotypical subjects (Tables 12 and 13). It was reported that autistic individuals synchronised gestures less closely with co-occurring speech (de Marchena & Eigsti, 2010), and interpersonal synchrony was more observable in neurotypical individuals (Georgescu et al., 2020). Furthermore, spontaneous verbal and non-verbal gestures were also reported to be less likely in autistic individuals (Hobson & Lee, 1998). However, two studies did not find any difference in performance between autistic and neurotypical participants. Autistic and typically developed groups were found to be equally able to detect physical differences on two given faces when temporally desynchronised (Shah et al., 2016). The tendency to align on a pragmatically conditional aspect of language was also found to be similar between autistic and typically developed groups (Branigan et al., 2016). In summary, a majority of the studies reported a reduced synchronous tendency in gesture performance and interpersonal synchrony in autism.

Table 6 Studies on visuo-tactile synchrony and autism

Study	Location	Sample size	Design	Autism assessment	Comparator	Paradigm	Results	Findings	Effect size in n_p^2
Cascio et al. (2012)	USA	ASC = 21, TD = 28	nRCT	ADOS	TD	Rubber hand illusion[a]	ASC < TD	Autistic group was initially less susceptible to the illusion than TD group but showed the effects of the illusion after 6 min	.04
Greenfield et al. (2015)	UK	ASC = 31. VAM = 29. CAM = 29	RCT	Clinical diagnosis (ADOS/ADI-R)	TD	Rubber hand illusion	ASC < TD	Visuo-tactile synchrony overrides incongruent proprioceptive inputs in TD group but not in autistic	N/I
Ropar et al. (2018)	UK	ASC = 29, VAM TD = 27, CAM TD = 28	RCT	Clinical diagnosis (ADOS/ADI-R)	TD	Rubber hand illusion	ASC < TD	Autistic group, like younger mental aged-matched controls, showed reduced embodiment of the spatially incongruent, but temporally congruent, hand compared to chronologically age-matched controls at shorter temporal delays	0

Note: Abbreviations: *ADI-R*, Autism Diagnostic Interview-Revised; *ADOS*, Autism Diagnostic Observation Schedule; *ASC*, autism spectrum condition; *CAM*, chronological age matched; *nRCT*, non-randomised controlled studies; *RCT*, randomised-controlled studies; *TD*, typically developed; *VAM*, verbal age matched

[a]The rubber hand illusion is a paradigm whereby perceived hand ownership can be transferred to a rubber hand after synchronous visual and tactile stimulation

Table 7 Participant characteristics of studies on visuo-tactile synchrony and autism

Study	Mean age	Mean IQ	Level of functioning
Cascio et al. (2012)	ASC = 11.9, TD = 13.4	ASC = 101.2, TD = 102.7	N/I
Greenfield et al. (2015)	ASC = 12.63, VAM TD = 7.88, CAM TD = 12.17	N/I	N/I
Ropar et al. (2018)	ASC = 12.6, VAM TD = 7.94, CAM TD = 12.6	N/I	N/I

Note. Abbreviations: *ASC*, autism spectrum condition; *CAM*, chronological age matched; *N/I*, not indicated; *TD*, typically developed; *VAM*, verbal age matched

Intervention Studies on Temporal Synchrony in Autistic Individuals

Two intervention studies on temporal synchrony were included in the systematic review. Griffioen et al. (2020) used six weekly sessions of 30-min-long dog-assisted therapy with autistic individuals and individuals with Down's syndrome. Intervention activities included psychomotor and socialisation skills that would ensure aligned motor action between the child and the therapy dog. While the results showed a significant increase in synchronous interactions between autistic children and their therapy dogs, the number of participants ($n = 10$) in the study limits the generalisability of the findings.

Another study provided 10 h/week of classroom intervention, which provided a supplementary curriculum targeting engaged imitation, joint attention and affect sharing (Landa et al., 2011). Additionally, 38 h of parent education and 1.5 h of home-based parent training was also given. At the end of the intervention, Landa et al. (2011) reported a significant increase in socially engaged imitation with eye contact in autistic toddlers. The study provided evidence for development in temporal synchrony in dyadic interactions.

Both of the intervention studies included in the systematic review concluded an increased performance in social temporal synchrony in autistic individuals after the intervention.

Discussion

This is the first study examining temporal synchrony in autism across all domains in which this has been previously examined by means of a systematic review. The systematic review identified the main characteristics of studies and participants as well as the types of synchrony and the study paradigms. Results showed that autistic participants tended to display more temporally asynchronous behaviours when performing tasks that required audio-visual, audio-motor, visuo-tactile, visuo-motor, social motor, and conversational sensory integration. Intervention studies also showed significant improvements to interpersonal and social synchrony in autism when temporal orders were considered. However, sample sizes were generally small and not justified, therefore, future studies should attend to ensuring adequate statistical power, as well as experimental rigour. Taken together, our findings point to the generality of temporal synchrony differences in autistic individuals compared to typically developing individuals. This suggests that temporal synchrony is a promising concept for explaining some of the differences between autistic and typically developing individuals in their daily life functioning and experiences and may also represent a promising diagnostic marker and/or intervention target.

The evidence on audio-visual synchrony in this review suggested poor performance of autistic individuals on tasks, and this was found related to speech and linguistic stimuli (Tables 2 and 3) while studies on conversational synchrony also found asynchronous gesture behaviours related to semantic speech in autistic adolescents (Tables 12 and 13). The findings seemed to provide evidence that autistic individuals experience difficulty in temporally integrating verbal and non-verbal communication that might cause social-communication difficulty (de Marchena & Eigsti, 2010). While social-communication ability is considered to be one of the 'core deficits' of autism, and although there are numerous theories on sensory perception in autism (Brock et al., 2002; Happé and Frith, 2006; Mottron et al., 2006), the nature of the links between autism and temporally asynchronous behaviour remains unclear as these theories do not directly address timing aspects of synchronous behaviour. However, it was previously established that poorer temporal acuity across visual and audial information is related to a weaker ability to temporally bind and integrate the two sensory inputs (Stevenson et al., 2014, 2018). Therefore, temporally asynchronous behaviours in autism could result from reduced multisensory integration, as proposed by Stevenson et al. (2014).

In addition to the instability of temporal processing and the lack of temporally synchronous behaviours in audio-, visuo-, and social motor performance in autistic groups, evidence seems to suggest that atypical sensory processing and temporal integration in autism is evident as proposed previously by Wallace and Stevenson (2014). Based on autistic individuals' performances on rubber hand illusion tasks, studies on visuo-tactile synchrony (Tables 6 and 7) also provided evidence that autistic individuals experience body representation difficulties, which might cause temporally asynchronous behaviours and in turn contribute to social and sensory difficulties within the population (Ropar et al., 2018).

Table 8 Studies on visuo-motor synchrony and autism

Study	Location	Sample size	Design	Autism assessment	Comparator	Paradigm	Results	Findings	Effect size in n_p^2
Edey et al. (2018)	UK	Experiment I: ASC = 25, TD = 24; Experiment II: ASC = 21, TD = 22	RCT	Clinical diagnosis (DSM-IV)	TD	Participants were given instructions to assess the duration between the first and second event and were told to tap the spacebar in time with the third and fourth event	ASC > TD	Autistic group exhibited less temporal error than their typically developed counterparts in the visual task	0
Kawasaki et al. (2017)	Japan	ASC = 24, TD = 24	RCT	ADOS	TD	Cooperative tapping task: participants were asked to tap a key alternatively and synchronously with a constant or variable rhythmic PC programme, or a human partner	ASC < TD	Autistic group had greater difficulty synchronising tapping with others	0
Marsh et al. (2013)	USA	ASC = 11; TD = 19	nRCT	ADOS	TD	Rocking chair paradigm: chid participants were given instructions to rock continuously for 30 s while their parent read the child a story, rocking at a pace prescribed by a metronome only they can hear	ASC < TD	Autistic group did not demonstrate a tendency to rock in synchrony with their parents, unlike typically developed group	0

Note: Abbreviations: *ADOS*, Autism Diagnostic Observation Schedule; *ASC*, autism spectrum condition; *DSM*, Diagnostic and Statistical Manual of Mental Disorders; *nRCT*, non-randomised controlled studies; *RCT*, randomised-controlled studies; *TD*, typically developed; *UK*, United Kingdom; *USA*, United States of America

Table 9 Participant characteristics of studies on visuo-motor synchrony and autism

Study	Mean age	Mean IQ	Level of functioning
Edey et al. (2018)	Experiment I: ASC = 38.20, TD = 33.88; Experiment II: ASC = 35.43, TD = 32.77	N/I	N/I
Kawasaki et al. (2017)	N/I	N/I	N/I
Marsh et al. (2013)	ASC = 3.95; TD = 3.76	N/I	N/I

Note. Abbreviations: *ASC*, autism spectrum condition; *N/I*, not indicated; *TD*, typically developed

While there were only two intervention studies included in this review (Tables 14 and 15), Landa et al. (2011) provided evidence for improving socially engaged behaviour in autistic toddlers by layering a supplementary curriculum, which is a promising outcome in terms of the plasticity of social-communication development in autism. However, there are limitations to the generalisability and reliability of the dog-assisted therapy by Griffioen et al. (2020) due to its small sample size of 5. Indeed, the interpretability of both of the intervention studies included in this review is limited due to the limited amount of supporting evidence on the topic.

Table 10 Studies on social motor synchrony and autism

Study	Location	Sample size	Design	Autism assessment	Comparator	Paradigm	Results	Findings	Effect size in n_p^2
Fitzpatrick et al. (2013)	USA	ASC = 11, TD = 7	RCT	DSM-IV	TD	After the initial demonstration of 5 kinds of movements, the experimenter prompted the child to perform the action in synchrony with them	ASC = TD	Autistic group's performance was equivalent to TD group's on many social performance outcome measures. More perceptually based measures of social coordination were not associated with social motor coordination	0
Fitzpatrick et al. (2016)	USA	ASC = 9, TD = 9	nRCT	Clinical diagnosis (DSM-IV-TR)	TD	Participants swung their pendulums while looking at another participant's in either an in-phase or anti-phase pattern	ASC < TD	Autistic group demonstrated less synchronisation in both spontaneous and intentional interpersonal coordination	.27
Fitzpatrick et al. (2017)	USA	ASC = 45, TD = 53	RCT	Clinical diagnosis (DSM-IV-TR)	TD	Interpersonal hand-clapping task in which the experimenter played a 2-person pat-a-cake game with the child	ASC < TD	Autistic group had fewer stable patterns of social synchronisation ability, performed motor movements slower and with more variability in spacing and timing	.24

Note: Abbreviations: *ADOS*, Autism Diagnostic Observation Schedule; *ASC*, autism spectrum condition; *DSM*, Diagnostic and Statistical Manual of Mental Disorders; *nRCT*, non-randomised controlled studies; *RCT*, randomised-controlled studies; *TD*, typically developed; *USA*, United States of America

Table 11 Participant characteristics of studies on social motor synchrony and autism

Study	Mean age	Mean IQ	Level of functioning
Fitzpatrick et al. (2013)	ASC = 6.36, TD = 5.85	N/I	High
Fitzpatrick et al. (2016)	ASC = 13.67, TD = 14.44	ASC = 101.78, TD = 117.22	High
Fitzpatrick et al. (2017)	ASC = 8.65, TD = 8.30	ASC = 101.78, TD = 117.22	High

Note. Abbreviations: *ASC*, autism spectrum condition; *TD*, typically developed; *N/I*, not indicated

Table 12 Studies on conversational synchrony and autism

Study	Location	Sample size	Design	Autism assessment	Comparator	Paradigm	Results	Findings	Effect size in n_p^2
Branigan et al., (2016)	UK	ASC = 15, VAM TD = 15, CAM TD = 15	RCT	Clinical diagnosis	TD	A card game examining whether the participant would tend to refer to an object using the same name as their partner had used for the object or a different name	ASC = TD	The tendency to align on a pragmatically conditioned aspect of language did not differ between autistic and TD groups and was unaffected by VAM/CAM	N/I
de Marchena & Eigsti (2010)	USA	ASC = 20, TD = 15	nRCT	DSM-IV	TD	Gesture-speech synchrony: the start and endpoint of a gesture and its semantically related speech was coded	ASC < TD	Autistic group stories were rated as less clear and engaging, while gestures were less closely synchronised with the co-occurring speech	.04
Georgescu et al. (2020)	UK	ASC = 29. TD 29	RCT	ICD-10	TD	Dyadic interactions (mixed, ASC, TD): (i) participants were asked to engage in a 5-min-long unstructured conversation; (ii) cooperative and competitive debates; (iii) fun tasks (meal planning and knock-knock jokes) and a role play	ASC < TD	All dyad types achieved above-chance interpersonal synchrony, but synchrony was more pronounced in TD dyads compared to both autistic and mixed dyads	.10
Hobson & Lee. (1998)	UK	ASC = 24, TD = 24	RCT	DSM-III-R	TD	A 10-min task in which participants were asked to give both spontaneous and prompted greetings and farewells to a stranger	ASC < TD	Autistic group was less likely to offer spontaneous verbal/non-verbal gestures of greeting/farewell and less likely to establish eye contact. Fewer autistic participants smiled or waved goodbye	N/I
Shah, Bird, & Cook (2016)	UK	ASC = 16, TD = 16	nRCT	Clinical diagnosis	TD	2 avatar faces were shown side-by-side and participants were asked to report if the eye transitions were faster for the standard or comparison	ASC = TD	Autistic and TD groups were equally able to detect the physical differences between comparison eye transitions	0

Note: Abbreviations: *ADOS-G*, Autism Diagnostic Observation Schedule-Generic; *ASC*, autism spectrum condition; *CAM*, chronological age matched; *DSM*, Diagnostic and Statistical Manual of Mental Disorders; *ICD*, International Classification of Diseases; *nRCT*, non-randomised controlled studies; *RCT*, randomised-controlled studies; *SCQ*, Social Communication Questionnaire; *TD*, typically developed; *VAM*, verbal age matched; *UK*, United Kingdom; *USA*, United States of America

Table 13 Participant characteristics of studies on conversational synchrony and autism

Study	Mean age	Mean IQ	Level of functioning
Branigan et al., (2016)	ASC = 10.10, VAM TD = 10.0, CAM TD = 10.10	Nonverbal IQ ASC = 27.13, VAM TD = 22, CAM TD = 28.60	N/I
de Marchena & Eigsti (2010)	ASC = 15.0, TD = 15.0	ASC = 103.0, TD = 103	High
Georgescu et al., (2020)	ASC = 42.76, TD = 41.31	N/I	High
Hobson & Lee (1998)	ASC = 15.3, TD = 15.2	N/I	N/I
Shah et al., (2016)	ASC = 39.5, TD = 39.1	ASC = 112.19, TD = 111.38	N/I

Note. Abbreviations: *ASC*, autism spectrum condition; *CAM*, chronological age matched; *N/I*, not indicated; *TD*, typically developed; *VAM*, verbal age matched

Quality of the Evidence

Our quality assessment identified some studies with very small autistic participant samples of $n = 5$ (Griffioen et al., 2020) and $n = 9$ (Fitzpatrick et al., 2016) and many others with sample sizes of only 15–30 and no power calculations to justify such small groups. More attention should thus be paid to statistical power in future studies in order to achieve more definitive results.

It was also established that the reporting of participant characteristics in the studies of temporal synchrony in autism was generally poor. While half of the studies included in this review reported recruiting high-functioning autism groups, the remainder did not report the level of functioning of the participants. More than half of the studies also did not provide information regarding mean IQ scores. It is evident that temporal synchrony performance should be assessed in autistic individuals with low levels of functioning, low IQ scores and/or an intellectual disability (ID) to ensure that these individuals are not under-represented and that the reporting of these characteristics should not be neglected. The importance of such participant characteristics has been examined previously: it was established that the proportion of individuals on the spectrum with ID is close to 50%, yet there tends to be a selection bias in all fields of autism research that leads to the under-representation of the autistic population with ID (Russell et al., 2019).

Table 14 Intervention studies on temporal synchrony and autism

Study	Location	Sample size	Autism assessment	Comparator	Paradigm	Results	Findings	Effect size in n_p^2
Griffioen et al., (2020)	The Netherlands	ASC = 5, DS = 5	Clinical diagnosis	DS	Dog-assisted therapy: 6 weekly sessions of 30 min. Categories coded: moving towards each other, moving to therapist, moving to object, moving ahead, stop of movement	ASC > DS	Significant increase in synchrony between autistic children and their therapy dog over time	.38
Landa et al. (2011)	USA	ASC = 50	DSM-IV	Non-interpersonal synchrony group (non-IS)	Interpersonal synchrony (IS) intervention for 10 h/week for 6 m; 38 h of parent education; and home-based strategies. The IS group received a supplementary curriculum targeting socially engaged imitation, joint attention, and affect sharing	IS > non-IS	Significant improvement in socially engaged imitation, initiation of joint attention and shared positive affect. Significant treatment effect was found for socially engaged imitation, with more than doubling of imitated acts paired with eye contact in the interpersonal synchrony group after intervention	N/I

Note: Abbreviations: *ADOS*, Autism Diagnostic Observation Schedule; *ASC*, autism spectrum condition; *DS*, Down's syndrome; *TD*, typically developed; *USA*, United States of America

Table 15 Participant characteristics of intervention studies on temporal synchrony and autism

Study	Mean age	Mean IQ	Level of functioning
Griffioen et al., (2020)	ASC = 12, DS = 14	N/I	N/I
Landa et al., (2011)	IS ASC = 28.6; non-IS ASC = 28.8	N/I	N/I

Note. Abbreviations: *ASC*, autism spectrum condition; *DS*, Down's syndrome; *IS*, interpersonal synchrony

Limitations

The findings of the systematic review should be considered in the context of several limitations. Primarily, even though this review aimed to summarise the most relevant studies on temporal synchrony in autism, the study selection criteria may reflect the author's personal perspectives, approaches, expertise and training. The quality of the review conclusions is also dependent on the quality of the included studies. Some of those included had significant limitations, such as having very small sample sizes. The review also focused on peer-reviewed studies to help ensure a minimum standard; however, this meant that it was difficult to assess the extent to which publication bias might have been present. Finally, because the studies were judged too heterogeneous in terms of design with only small numbers of studies of each design, no quantitative synthesis was attempted. As this literature reaches a greater level of maturity and more primary studies are published with similar designs, a meta-analytic investigation with moderator analyses will be helpful for further investigating the extent of temporal asynchrony tendency in autistic individuals compared to neurotypical individuals and the person, task, and broader contextual influences on this.

Future Directions

The findings of the systematic review raise the possibility that studies on temporal synchrony in autism could provide new insights into understanding the social communication and sensory difficulties in autism. Temporal synchrony difficulties experienced by autistic individuals in everyday tasks and in more naturalistic settings such as speaking back-and-forth on the telephone without visual cues, engaging in "flowing" one-to-one in-person conversation, and taking turns in social interactions appear to be examples of novel areas for further study. Further, it could be investigated whether temporal synchrony tendencies mediate the association between meeting diagnostic criteria for autism (or showing high levels of symptoms) and everyday differences and challenges experienced relative to typically developing individuals.

Intervention studies targeting improvement on sensory integration and functioning in autism might have effects on the social-communication experiences of autistic individuals: this is an area of potentially significant innovation for impactful interventions and should be investigated further. Likewise, a better understanding of temporal synchrony differences could help communication between typically developing and autistic individuals and inform the adaptation of work and social environments to better accommodate the latter.

Finally, temporally extended body representation in autism in visuo-tactile synchrony studies needs to be investigated further by administering other experimental paradigms aside from rubber hand illusions. This might allow for a better understanding of temporally asynchronous behaviours in autism overall.

Conclusions

This review provided evidence that temporally asynchronous behaviour and atypical temporal processing are evident in autism when autistic individuals are expected to integrate audio-visual, audio-motor, visuo-tactile, visuo-motor, social motor, and conversational information. Results from the included intervention studies also highlight the possibility of improving socially and temporally synchronous behaviours in autistic individuals.

While the cause of temporal asynchrony has not yet been investigated, it may be appropriate to hypothesise that temporal processing and multisensory integration difficulties might cause temporally asynchronous behaviours in autistic individuals, and therefore may contribute to social-communication and sensory difficulties in autism.

It is evident that the clinical representation of autism and the experiences of autistic people is more diverse than the concepts of 'social-communication and interaction, and restricted and fixated behaviours, interests and activities' (APA, 2013). Therefore, it is essential to move away from the 'Core-Deficit Hypothesis' in research and clinical practice, and document alternative profiles of the condition. Further understanding of the mechanisms and outcomes of temporal synchrony may help improve clinical practice and develop new biomarkers and successful interventions to improve possible temporal asynchrony related sensory and social-communication difficulties of autistic individuals.

Declarations

Conflict of Interest The authors declare no conflict of interest.

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