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Synchrony perception across senses: A systematic review of temporal binding window changes from infancy to adolescence in typical and atypical development

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ABSTRACT

Sensory integration is increasingly acknowledged as being crucial for the development of cognitive and social abilities. However, its developmental trajectory is still little understood. This systematic review delves into the topic by investigating the literature about the developmental changes from infancy through adolescence of the Temporal Binding Window (TBW) - the epoch of time within which sensory inputs are perceived as simultaneous and therefore integrated. Following comprehensive searches across PubMed, Elsevier, and PsycInfo databases, only experimental, behavioral, English-language, peer-reviewed studies on multisensory temporal processing in 0–17-year-olds have been included. Non-behavioral, non-multisensory, and non-human studies have been excluded as those that did not directly focus on the TBW. The selection process was independently performed by two Authors. The 39 selected studies involved 2859 participants in total. Findings indicate a predisposition towards cross-modal asynchrony sensitivity and a composite, still unclear, developmental trajectory, with atypical development associated to increased asynchrony tolerance. These results highlight the need for consistent and thorough research into TBW development to inform potential interventions.

1. Introduction

"Synchronicity is an ever-present reality for those who have eyes to see". This quote attributed to Carl Jung highlights a postulated harmony between psychic and physical events (Jung, 1960). Notably, this statement also resonates with psychophysiological functioning, specifically regarding an individual's ability to perceive synchrony across the senses.

Indeed, time proximity serves as a crucial amodal, low-level cue that facilitates the resolution of the "cross-modal binding problem" (Treisman, 1996). It acts as a filter amid the constant influx of multiple sensory inputs, selectively enabling the formation of dot-to-dot connections among stimuli perceived to be temporally aligned (Colonius and Diederich, 2004). This function is essential for imposing order on the myriad kaleidoscopic stimuli in the environment, transforming them into a coordinated series of multimodal, coherent, and distinct Gestalts. The outcome is a holistic representation of the surrounding world, facilitating appropriate interactions with it (Meredith et al., 1987; Murray et al., 2016).

Such a unified perceptual experience is achievable despite the dissimilar transmission velocities and neural transduction rates among the heteromodal components of a compound stimulus. Remarkably, the nervous system tolerates a certain degree of temporal discrepancy before it categorizes these inputs as separate entities. This period, during which multisensory stimuli are most likely to be perceived as simultaneous and thereby merged into a single perceptual event, is defined as the Temporal Binding Window (TBW; Colonius and Diederich, 2004; Dixon and Spitz, 1980; Vroomen and Keetels, 2010). Consequently, the TBW construct allows for the identification and conceptualization of temporal coincidence across modalities not as a state of rigid

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simultaneity, but as an interval where synchrony is perceptually extended.

Two additional amodal factors also contribute to intersensory binding: spatial alignment (i.e., intersensory binding is more likely when the cross-modal inputs are spatially coincident), and inverse effectiveness (i.e., intersensory binding is more likely when the unisensory inputs are less intense) (Stein and Meredith, 1993). However, among the three factors, perceived intersensory synchrony is consistently recognized as the primary, most readily detectable, and most effective cue for multisensory binding (Keetels and Vroomen, 2012).

The literature suggests a precedence of this ability over the other amodal properties. This is based on the limited prenatal availability of spatial attributes, except those related to the infant's own body (Burr and Gori, 2012; Filippetti et al., 2015), and observations that 3-month-old infants can discriminate rhythm, tempo and duration only when relying on multimodal synchronous onsets (Bahrick et al., 2002; Lewkowicz, 1986).

Two factors underscore the importance of investigating intersensory synchrony perception. Firstly, perceived temporal synchrony retains its filtering efficacy, proving essential in determining whether sensory inputs are temporally proximate enough to trigger multisensory integration throughout the lifespan (Colonius and Diederich, 2020). Secondly, the TBW remains an effective proxy for the strength and accuracy of multisensory integration across all the developmental stages (Stevenson et al., 2012, 2018a).

According to Bayesian statistical models, adults combine these low-level cues with prior knowledge derived from experience (i.e., high-level factors), weighting different sensory information based on their relative reliabilities. This inference facilitates multisensory integration across modalities, resulting in greater precision than unisensory estimations (Fetsch et al., 2011; Knill and Pouget, 2004). Research shows that adults make these probabilistic judgments in a statistically optimal manner (Alais and Burr, 2004; Ernst and Banks, 2002), whereas children do not (Gori et al., 2008; Nardini et al., 2008, 2010).

Two primary theoretical frameworks have been proposed to elucidate the development of multisensory integration abilities. However, the specific processes and timelines through which adult proficiency is attained are still little understood (for an overview, see Dionne-Dostie, 2015).

The Late Integration Approach posits that the integration of sensory data into a cohesive perceptual experience is fundamentally a cognitive decision-making process occurring after the initial, separate processing of each sensory input (Burr and Gori, 2012). This concept aligns with the Developmental Integration theory, which suggests that neonates initially have immature sensory systems that operate independently and gradually evolve from disconnection to coordination. This transition is experience-dependent, fostered by the associations that children form through active interaction with their environment (Birch and Lefford, 1963, 1967; Piaget, 1952). This theory describes an uneven pace of sensory development, shaped by the varying utility and maturation timing of each sensory modality at different developmental stages (e.g., during gestation, the sense of touch develops first, followed by the auditory, while vision matures last; Gottlieb, 1971). Consistently, sensory dominance typically prevails over integration until the sensory channels mature, which usually occurs after 8–10 years of age (e.g., Gori et al., 2008; Nardini et al., 2008, 2010). Within this framework, the ability to perceive synchrony and tolerate asynchronies across modalities emerges as a skill that must be learnt through experience and influenced by the maturation rate and possible dysfunctions of the unisensory channels during specific developmental phases.

Instead, the Early Integration Approach suggests that sensory information from different modalities is combined at the outset of the sensory processing pathway. This perspective is consistent with the Developmental Differentiation Theory, which elaborates on Gibson's (1966), (1969) concept of an inherently multisensory nervous system. According to this theory, the perceptual system is naturally coordinated, endowed with an innate ability to detect low-level invariant information across senses. This capability gradually refines, enabling the perception of increasingly specific (i.e., modality-specific) and complex forms of unity (for a review, see Spector and Maurer, 2009). Consequently, both theories acknowledge the crucial, albeit different, role that species-typical multisensory experiences during critical and sensitive pre- and post-natal periods play in shaping perceptual specialization and ecological adaptation (Lewkowicz, 2014). Thus, these perspectives also consider early deprivation as a potential pathway to significant dysfunctions (Bremner, 2017; Lewkowicz and Bremner, 2020).

Within the framework of the Early Integration Approach, Bahrick and Lickliter (2000), (2002) put forward the Intersensory Redundancy Hypothesis. This theory proposes that the ability to perceive intersensory synchrony is innate, crucial for early sensory integration, and foundational for cognitive, social, and motor development. It facilitates intersensory redundancy, where multiple sensory modalities converge to specify the same percept, thereby enhancing its salience through information encoding that activates extensive brain networks. This increased brain activity boosts attention, which in turn enhances perception, learning, memory, and motor function. There is substantial evidence supporting this theory from studies in both adults (e.g., Diederich and Colonius, 2004; Fogassi and Gallese, 2004; Fougnie and Marois, 2011; Lovelace et al., 2003; Nelson et al., 1998; Shams and Seitz, 2008) and children (e.g., Betti et al., 2021; Camponogara and Volcic, 2021; Eördegh et al., 2022; Neil et al., 2006). These studies have demonstrated that effective binding of diverse sensory inputs is associated with enhanced detection, localization, and discrimination of signals, as well as improved attention, memory, learning, and motor skills.

During the early years of life, these enhanced abilities play a crucial role in scaffolding and organizing the development of higher-order processes such as affect discrimination (Flom and Bahrick, 2007), numerical discrimination (Jordan et al., 2008; Wang and Feigenson, 2021), problem solving (Zmigrod and Zmigrod, 2016), and abstract rule-learning (Frank et al., 2009). They also promote orienting and sustained attention to social stimuli (Curtindale et al., 2019), supporting social interaction and learning during infancy and early childhood. In the linguistic domain, they facilitate word comprehension and segmentation (Gogate et al., 2000). Additionally, perceived synchrony among cross-modal inputs is essential for the perceptual segregation of multiple talkers. In the so-called Cocktail Party Problem participants deal with a crowded social setting where different voices and noises overlap and interfere with one another. In such settings, temporal proximity has been shown to facilitate correct perception in both adults and 3- to 5-year-old children (e.g., Lewkowicz et al., 2021, 2022). Furthermore, synchronization between a speaker's dynamic facial expressions and voice significantly enhances infants' detection of prosody, providing a foundational mechanism for recognizing intentions, emotions, and meaning behind speech (Bahrick et al., 2019). In the social domain, the TBW is also associated with non-verbal interpersonal synchrony in typical development (Noel et al., 2018a).

Various conceptualizations support the Intersensory Redundancy Hypothesis's claim that multisensory integration abilities play a critical role in scaffolding the development of a wide range of higher-order processes (e.g., "cognitive cascade"; Ayres, 1972; Rose et al., 2008). Correspondingly, multiple studies have linked the efficiency of multisensory processing to enhancements in children's linguistic, reading, and numerical skills, executive functions, emotion recognition and regulation, empathy, reciprocity, and social cognition (e.g., Beaucage et al., 2020; Della Longa et al., 2021a; Feigenson, 2011; Tenenbaum et al., 2015; Wallace et al., 2020). Additionally, a study by Maitre et al. (2020) has identified a correlation between multisensory functions, sensory reactivity, and internalizing behaviors. Notably, these associations do not extend to unimodal sensory processing (e.g., Bahrick and Lickliter, 2000; Bahrick et al., 2004; Denervaud et al., 2020).

Recent research also suggests that the development and preservation of a functional, pre-reflexive, and embodied sense of a unitary Self,

surrounded by a peri-personal space where Self-Other distinctions are learnt, are rooted in an individuals' exposure to early multisensory experiences (Blanke, 2012; Serino, 2019). This developmental process is believed to begin in utero, mediated by the mother's body, and continues post-natally through both autonomous exploration and infant-caregiver dyadic interactions (Ciaunica et al., 2021; de Klerk et al., 2021; Montirosso and McGlone, 2020; Tsakiris, 2017). Expanding on this framework, affective touch can be understood as a form of early provision of multisensory-rich experiences, (i.e., concurrent tactile, auditory, visual, and interoceptive inputs) that promote higher-order functions such as emotional regulation (Della Longa et al., 2023; Tanaka et al., 2018, 2021).

Fig. 1 shows a graphic representation of the conceptualization outlined above.

Conversely, disruptions in the efficient tolerance to intersensory asynchronies are correlated with a cascade of impairments (Bahrick and Todd, 2012; Wallace and Stevenson, 2014) and immune system alterations (Finotti et al., 2018), suggesting they may represent a disruptive factor in human development (Lense et al., 2021; Wallace et al., 2020). Indeed, a broader TBW may lead to interference effects from irrelevant sensory stimuli, causing confusion and necessitating increased processing effort (Wallace and Stevenson, 2014). Specific alterations of the intersensory temporal processes characterize neurodevelopmental disorders, such as autism spectrum disorders (ASD), developmental dyslexia, and schizophrenia (Wallace and Stevenson, 2014). Notably, the TBW has been observed to progressively widen along the continuum from neurotypical to clinical conditions (Di Cosmo et al., 2021; Ferri et al., 2018), with this enlargement associated with the severity of clinically important symptoms in these patients (Feldman et al., 2018, 2019; Kawakami et al., 2020a; Stevenson et al., 2017).

The described functioning is evident in ASD, where reduced orienting to audiovisual synchrony during infancy has been identified as an early measurable antecedent (Baum et al., 2015; Falck-Ytter et al., 2018; Greenfield et al., 2015; Kawakami et al., 2020b) and non-verbal interpersonal synchrony is uncoupled with respect to the TBW differently from typical development (Noel et al., 2018a). Similar enlargements of the TBW are observed in developmental dyslexia, potentially accounting for difficulties in the automatization of grapheme-phoneme conversion (Du et al., 2022; Francisco et al., 2017; Meilleur et al., 2020), and in schizophrenia (Di Cosmo et al., 2021; Haß et al., 2017; Martin et al., 2013; Noel et al., 2018b; Zvyagintsev et al., 2017).

Although these findings are often overlooked and not systematically incorporated into the diagnostic process, sensory integration therapies are increasingly recognized as effective treatments across various clinical domains (Embarek-Hernández et al., 2022; Habib et al., 2016; Schoen et al., 2019). Nonetheless, to fully leverage this potential, it is important to elucidate the typical and atypical developmental trajectories of these mechanisms, as well as the complex and dynamic factors that influence their modulation. The TBW varies according to different sensory combinations (Fujisaki and Nishida, 2009) as well as on the basis of the stimuli order (Dixon and Spitz, 1980; Cecere et al., 2016), complexity (van Eijk et al., 2008), and familiarity (Stevenson and Wallace, 2013). It also changes between individuals (Stevenson et al., 2012) and across development (Lewkowicz, 1996).

2. Aims

As mentioned in the Introduction, multisensory integration abilities change during development, are shaped by experience, and play a key role in modelling cognitive and social competences. These abilities are also altered in several neurodevelopmental disorders such as developmental dyslexia, ASD, and schizophrenia. However, their typical and atypical developmental trajectories, as well as their possible correlations with higher-order functions, remain unclear.

A more precise understanding of these processes could shed some light on multisensory skills development and provide a basis for systematically studying the postulated scaffolding role of cross-modal redundancy. It could also clarify the factors that facilitate or impede this process and their consequent impact. Expanding on this, understanding these mechanisms could turn to be crucial for designing effective preventive, enhancing or rehabilitative interventions. The significant and persistent malleability of the TBW (Röder and Wallace, 2010; Yu et al., 2010) along with documented evidence of its trainability (McGovern et al., 2022; Powers et al., 2009, 2016; Stevenson et al., 2013; Zerr et al., 2019) underscores its relevance and suggests promising opportunities for intervention.

This calls for accurately taking stock of what we currently know about the developmental trajectories of the multisensory temporal processes. Accordingly, the aim of this review is to systematize the existing knowledge about the changes that intersensory synchrony perception undergoes across infancy through adolescence. To date, these developmental changes have not been thoroughly or comprehensively investigated. Two previous reviews briefly addressed the topic, but it does not constitute the center of their investigation, and their analyses are either not systematic (Wallace and Stevenson, 2014) or selectively focused on one specific intersensory combination (i.e.,

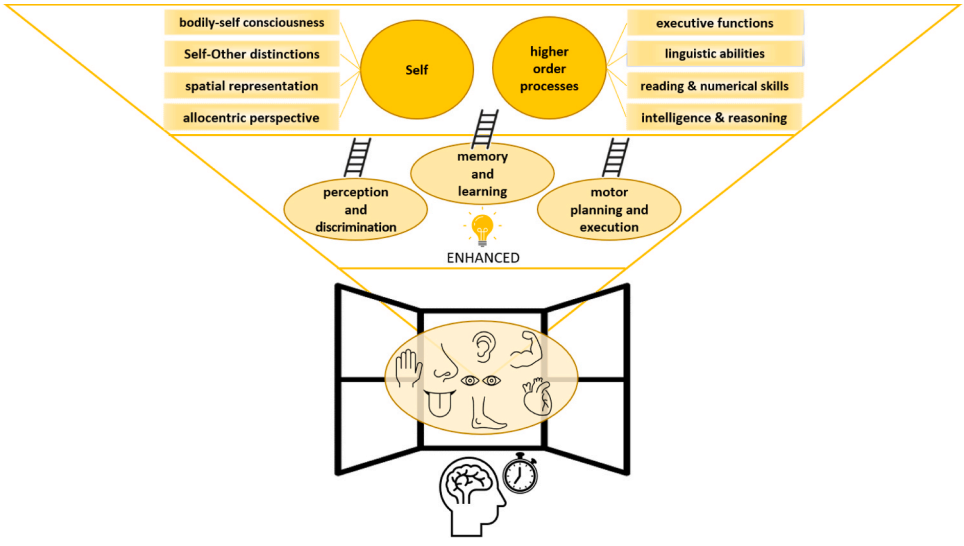

Fig. 1. Representation of the Adaptive Value Associated to Multisensory Integration Processes.

audio-visual; Zhou et al., 2020a).

3. Materials and methods

3.1. Data sources and search strategy

Tolerance to asynchronies has been referred to in a wide variety of ways. For this reason the comprehensive searches conducted through PubMed, Elsevier and PsycInfo databases for the current review involved numerous alternative terms as possible parts of title, abstract or keywords: ("temporal binding windows" OR "temporal binding" OR "temporal window" OR "time window" OR "temporal acuity" OR "temporal processing" OR "temporal window of integration" OR "temporal integration" OR "simultaneity" OR "synchrony") AND ("multisensory" OR "crossmodal" OR "cross-modal" OR "audiovisual" OR "audio-visual" OR "audiotactile" OR "audio-tactile" OR "audiohaptic" OR "audio-haptic" OR "visuohaptic" OR "visuo-haptic" OR "visuo-tactile" OR "visuo-tactile") AND ("children" OR "adolescents" OR "development" OR "infants" OR "toddlers" OR "childhood").

The final search was completed on October 22, 2023.

In addition, the references cited by the selected articles and by the existing reviews on the topic (Wallace and Stevenson, 2014; Zhou et al., 2020a) were scrutinized to include other relevant studies not retrieved through the above-described bibliographical search.

3.2. Inclusion and exclusion criteria

Eligibility was limited to (1) experimental studies (2) published in English (3) in peer-reviewed journals and (4) aimed at analyzing behavioral measures of multisensory temporal processing (5) among infants, children, and adolescents (0–17 years). Neurophysiological studies meeting the selection criteria were screened to identify possible behavioral measures utilized as counterparts to neural or physiological measures.

Exclusion procedure was based on the following criteria: (1) Articles estimating multisensory temporal processes based on age-ranges larger than 6 years were excluded. The choice rested upon the attempt to find a balance between the need to retrieve data for the life-periods considered and the possibility to analyze them reliably, limiting the analysis to studies able to give significant contributions in a developmental perspective. The idea was that the consideration of mean values among overly extended age-groups would have resulted to be unhelpful in gaining accurate insights into gradual modifications of the TBW during development. Conversely, they could have become confounding factors, capable of hampering the possibility to identify with precision the most sensitive periods for the change of these processes. With this aim in mind, age-ranges comprising up to 6-years were instead admitted. The purpose was to consider the possible presence in the literature of inquiries assessing the childhood or the adolescence phase as a whole: the 6-year-range is indeed the span usually considered when identifying them (i.e., from 6 to 11 years of age and from 12 to 17 years of age, respectively). Future reviews that consider broader or narrower age-ranges could help address potential limitations in the present study arising from the selected age-range parameters. (2) Although articles considering multisensory temporal processing alongside with other constructs were included in the review, those encompassing them only indirectly as a means to investigate different processes, were not. (3) Previous reviews of the topic were not considered since they did not aim to report additional data or analyses with respect to the original articles they examined. 4) Studies of nonhuman subjects as well as (5) those based on non-behavioral measures or (6) focusing only on unisensory processes were likewise excluded.

The detailed procedure of study selection and exclusion is illustrated in Fig. 2.

The first Author conducted the database search. Apart from removing duplicates, two Authors independently performed each step of the selection process. Any discrepancies were resolved via a discussion until a consensus was achieved.

3.3. Analysis

The selected articles were systematically analyzed across various

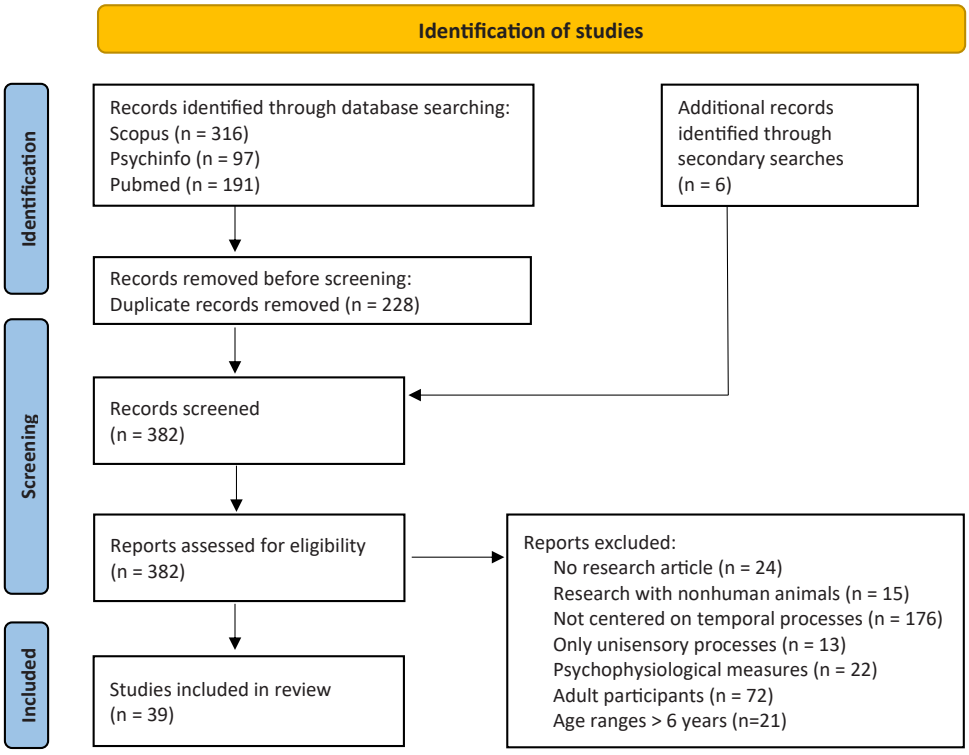

Fig. 2. PRISMA 2020 Flow Diagram of Literature Search and Study Selection for the Present Systematic Review.

dimensions including the definitions employed, the developmental trajectory studied (typical/atypical), participants number and age, the sensory modalities tested, the experimental paradigm implemented, and the findings regarding the width and shape of the TBW.

The term "TBW width" refers to the range of asynchronies, usually expressed in milliseconds, within which individuals are likely to perceive different sensory inputs as simultaneous above a certain criterion. This range comprises two segments: one where sensory input from modality A precedes modality B, and another for the reverse scenario, where B precedes A. Thus, the width of the TBW includes both the asynchrony ranges where A leads and where B leads. If the range of asynchronies where modality A leads is equal to that where modality B leads, the TBW is termed symmetrical, indicating equal tolerance for asynchrony regardless of which modality precedes. Conversely, the TBW is considered asymmetrical if one range is wider than the other (e.g., asynchronies are tolerated at larger delays when modality A precedes modality B). This property, whether the TBW is symmetrical or exhibits a specific type of asymmetry, is described as the "TBW shape".

In processing the data, studies reporting multiple experiments or using different stimuli in the same article were counted more than once.

The results comparing the adults' to the minors' outcomes were analyzed with the purpose to enucleate the age at which the developmental TBW reaches its maturity, becoming not significantly different in its width and shape to that of the adults. It is worth noting that such a comparison is influenced by the choice to adopt the classic age-limits to discriminate the developmental period (0–17 years) from adulthood (from 18 years). Future investigations could adopt an alternative perspective, referring to the recent conceptualizations that identify the end of adolescence with the age of 24 years (Sawyer et al., 2018).

Articles reporting more than one study were considered with regards to all and only those experiments that met the current review's inclusion and exclusion criteria.

The current study was conducted in compliance with the PRISMA 2020 guidelines for systematic reviews (Page et al., 2021).

4. Results

Applying the specified criteria reduced the pool of studies eligible for this review to 39, encompassing a total of 2859 participants. For a synthetic overview, see Table 1.

Although the first retrieved study focusing on perception of synchrony across the senses dates back to 1979, most of the articles were written after 2010 (n=29), coherently with the relatively recent increase in interest in the literature for the multisensory perspective (Stein et al., 2020).

4.1. Definitions around intersensory synchrony perception

Twenty articles (2, 3, 6, 7, 9−12, 16, 18, 20, 21, 25, 26, 28, 30−32, 38, 39), did not outline a specific construct with which to indicate the participants' multisensory temporal acuity, simply referring to it as the ability to detect synchrony across modalities.

In contrast, the other articles employed a variety of terms to describe this concept: "temporal binding window" (n=10) (1, 8, 13−15, 17, 34−37), "intersensory temporal synchrony window" (n=1) (19), "intersensory temporal contiguity window" (n=3) (22, 23, 29), "simultaneity window" (n=2) (4, 5), "temporal simultaneity window" (n=1) (33), "temporal window of simultaneity" (n=1) (24), "synchrony window" (n=1) (27).

Differences in terminology were not only lexical but also conceptual. Lewkowicz (1996) (19) introduced the expression "intersensory temporal synchrony window", which was later changed to "intersensory temporal contiguity window" (Lewkowicz, 2000) (20), to indicate the younger participants' tolerance to asynchronies. The author defined it as the minimal temporal gap necessary for two sensory inputs to be perceived as asynchronous. This distinction emphasizes the differences in the assessment methods between younger and older participants: assessments for the former generally rely on group measures based on aggregate data, while those for the latter involve estimating individual thresholds, proxied by the TBW construct.

The use of the locution "simultaneity window" and similar expressions reflects a subtle, yet significant, distinction based on the consideration that judgments of synchrony differ from the perception of the cross-modal integration (i.e., "binding") consequences.

4.2. Type of developmental trajectory investigated

Ten of the selected studies were meant to investigate the TBW construct in a context of atypical development. In particular, 5 studies (1, 3, 8, 25, 26) involved participants with a diagnosis of ASD, 1 study (34) focused on infants at high risk of developing an ASD, 2 studies (16, 29) tested subjects with specific language impairment, 1 study (37) examined adolescents with early onset schizophrenia, 1 study (3) investigated children with developmental disabilities other than ASD, and 1 study (35) considered children with developmental dyslexia. Eight of the studies about atypical development also involved typically developing children and/or adolescents as controls (1, 3, 8, 16, 29, 34, 35, 37).

Twenty-nine studies exclusively involved typically developing subjects (2, 4−7, 9−15, 17−24, 27, 28, 30−33, 36, 38, 39).

4.3. Number of participants

On average, studies focusing on typical development involved 47 children or adolescents (*SD*=30, *range*=12–96). Among these articles, those comparing different age-groups considered mean samples of 20 (*SD*=9, *range*=3–47). However, the distribution of participants across different age-groups within the same study was not always balanced, showing a mean difference of 2 individuals (*SD*=4, *range*= 0–18).

The literature on atypical developmental trajectories was based on smaller total sample sizes, with an average of 26 atypically developing participants per study (*SD*=11, *range*=15–53). Among these studies, only one compared different age-groups (1) with an average of 23 atypically developing participants per age-group (*SD*=7, *range*=16–31).

4.4. Age of participants

Infancy (i.e., 0–1 years) was the most studied age-group (n=17) (2, 6, 7, 9−11, 18−22, 28, 30−32, 34, 39), while toddlers (i.e., 1–2 years) were considered only by 2 articles (3, 34). Ages between 3 and 5 years (preschool years) appeared in mean in 6 studies, while those from 6 to 11 years (school years) in 10, with overrepresentation of 7- (n=13) (1, 4, 5, 8, 12, 14−17, 24, 27, 29, 33) and 11-years-old children (n=14) (1, 4, 5, 12−17, 24, 27, 33, 35, 36). Ages from 12 to 17 years (adolescence) appeared in 8 studies (1, 5, 14, 15, 24, 35−37).

Preschool years were mostly investigated by the literature on atypical development, while other ages more by studies focused on typical development. Concurrently, literature on atypical development concentrated principally on ages between 3 and 7 years (n=5) (3, 8, 25, 26, 29), whereas studies about typical development focused primarily on school years (n=10) (4, 5, 12−15, 17, 24, 27, 33) and infancy (n=16) (2, 6, 7, 9−11, 18−22, 28, 30−32, 39). Notably, only one study investigating infants addressed atypical development (34).

Although all ages up to 11 years were analyzed individually by at least one of the examined studies, more frequently the TBW width of participants was measured on groups of subjects representing broader age ranges. If most articles on typical development analyzed each age individually (e.g., the typical TBW at 6 versus 8 versus 10 years of age) (n = 23) (1, 2, 4−7, 9−12, 18−23, 28, 30−33, 38, 39), studies about atypical development mainly examined data related to broader age-ranges as belonging to a same group, considering together participants with an age difference varying between 2 (n=1) (34), 3 (n=4) (3, 25, 26,

Table 1
Overview of Selected Studies, Sorted Alphabetically, with Details on: Developmental Trajectory Investigated, Sample Sizes, Participants' Age, Sensory Modalities Tested, Experimental Paradigms Used, Definitions Employed, and Key Findings.

Ref (authors, year)		Developmental trajectory investigated (sample size exp. X, exp. Y)	Age of participants (years)	Age range breadth (years)	Inclusion of age differences in statistical analyses	Comparison with adults (sample size)	Sensory modalities tested	Types of stimuli	Experimental paradigm used	Construct investigated	Key findings
1	Ainsworth and Bertone, (2023)	ASD (49), typical development (57)	6–18	1, 6	comparison of age groups		audio-visual	non speech, low level	simultaneity judgment	TBW	TBW narrowing for ASD in adolescence, reducing gap with typical development
2	Bahrick, (1992) (exp.1)	typical development (96)	0 (3 months)	1	no age differences		audio-visual	non speech, complex (objects striking a surface)	habituation and test	synchrony	preference for audio-visual synchrony of objects striking a surface at 3 months
3	Bebko et al., (2006)	ASD (16), other developmental disabilities (15), typical development (16)	1–6	3	correlation with looking time		audio-visual	non speech, complex (ball moving through ramps and cliffs) speech, complex (numbers, story)	preferential looking	synchrony	ASD detect audio-visual synchrony in non-speech, but not in speech, stimuli at ages 1–6; no age-related changes
4	Chen et al., (2016)	typical development (80)	5,7,9,11	1	comparison of age groups	yes (20)	audio-visual	non speech, low level	simultaneity judgment	simultaneity window	audio-visual TBW width adult-like by age 9, shape by age 5; wider for visual- than auditory-leading pairs
5	Chen et al., (2018)	typical development (80)	7,9,11,13	1	comparison of age groups	yes (20)	visuo-tactile	low level	simultaneity judgment	simultaneity window	visuo-tactile TBW width adult-like by age 11, shape by age 7; wider for tactile- than visual-leading pairs
6	Della Longa et al., (2020)	typical development (50)	0 (5 months)	1	no age differences		visuo-tactile	complex (touch on the forehead)	preferential looking	synchrony	at 5 months preference for visuo-tactile synchrony with slow tactile bodily-related input, not with fast
7	Dodd, (1979)	typical development (12)	0 (2–4 months)	1	correlation with looking time		audio-visual	speech, complex (nursery rhymes)	preferential looking	synchrony	preference for audio-visual synchrony with speech stimuli at 2–4 months, no age-related changes
8	Feng et al., (2021) (exp. 1,2)	ASD (24,31), typical development (26,29)	4–7	4	no		audio-visual	speech, syllables	McGurk illusion, simultaneity judgment	TBW	wider TBW in ASD for both speech and non-speech stimuli, especially with visual-leading delays, at ages 4–7
9	Filippetti et al., (2013) (exp. 1,2)	typical development (20,20)	0 (1–5 days)	1	no age differences		visuo-tactile	complex (touch on the face)	preferential looking	synchrony	newborns prefer visuo-tactile synchrony if stimuli are related to their bodies
10	Filippetti et al., (2016)	typical development (14)	0 (5 months)	1	no age differences		visuo-tactile	complex (touch on the cheek)	preferential looking	synchrony	synchrony preference for visuo-tactile bodily-related inputs at 5 months

(*continued on next page*)

Table 1 (*continued*)

Ref (authors, year)	Developmental trajectory investigated (sample size exp. X, exp. Y)	Age of participants (years)	Age range breadth (years)	Inclusion of age differences in statistical analyses	Comparison with adults (sample size)	Sensory modalities tested	Types of stimuli	Experimental paradigm used	Construct investigated	Key findings
11 Gerson et al., (2015) (exp. 1,2)	typical development (40,20)	0 (6 months)	1	no age differences		audio-visual	non speech, complex (drumming)	preferential looking	synchrony	audio-visual synchrony sensitivity enhanced by brief active drumming, not by observation, at 6 months
12 Greenfield et al., (2017) (exp. 2)	typical development (56)	4–11	4, 1	comparison of age groups, age in months as covariate		visuo-tactile	complex (Rubber Hand Illusion)	Rubber Hand Illusion	synchrony	visuo-tactile temporal binding reduces with age from 4 to 11 years
13 Hillock et al., (2011)	typical development (13)	10–11	2	no	yes (14)	audio-visual	non speech, low level	simultaneity judgment	TBW	wider audio-visual TBW for auditory-leading low-level pairs in children aged 10–11 versus adults

Ref (authors, year)	Developmental trajectory investigated (sample size exp. X, exp. Y)	Age of participants (years)	Age range breadth (years)	Inclusion of age differences in statistical analyses	Comparison with adults (sample size)	Sensory modalities tested	Types of stimuli	Experimental paradigm used	Construct investigated	Key findings
14 Hillock-Dunn and Wallace, (2012)	typical development (30)	6–17	6	comparison of age groups, correlation with TBW width	yes (15)	audio-visual	non speech, low level	simultaneity judgment	TBW	narrowing of audio-visual TBW for low-level stimuli persists past age 17
15 Hillock-Dunn et al., (2016)	typical development (30)	7–17	6	comparison of age groups	yes (14)	audio-visual	speech, syllables	McGurk Illusion	TBW	adult-like audio-visual TBW for syllables at ages 7–11
16 Kaganovich et al., (2014)	specific language impairment (15), typical development (15)	7–11	5	no	yes (15)	audio-visual	non speech, low level (on complex background)	simultaneity judgment	synchrony	at ages 7–11 reduced audio-visual temporal accuracy in specific language impairment; immature in neurotypical versus adults
17 Kaganovich, (2016)	typical development (31)	7–8, 10–11	2	comparison of age groups	yes (16)	audio-visual	non speech, low level (on complex background)	simultaneity judgment	TBW	at ages 10–11: audio-visual TBW for low-level stimuli wider versus adults, narrower in auditory-leading delays versus ages 7–8
18 Lewkowicz, (1992) (exp. 2)	typical development (48)	0 (4,8 months)	1 (1 month)	comparison of age groups		audio-visual	non speech, complex (moving disk)	habituation and test	synchrony	at 8 months better audio-visual asynchrony discrimination than at 4 months post habituation to synchronous inputs
19 Lewkowicz, (1996) (exp.2,3,4)	typical development (96,96,32)	0 (2,4,6,8 months)	1 (1 month)	comparison of age groups	yes (10)	audio-visual	non speech, complex (bouncing disks)	habituation and test	intersensory temporal synchrony window	no age-related changes at 2–8 months, TBW wider for visual- than auditory-leading pairs, and larger than in adults
20 Lewkowicz, (2000) (exp. 3)	typical development (96)	0 (4,6,8 months)	1 (1 month)	comparison of age groups		audio-visual	speech, syllables	habituation and test	synchrony	discrimination of audio-visual asynchrony in

(*continued on next page*)

Table 1 (*continued*)

	Ref (authors, year)	Developmental trajectory investigated (sample size exp. X, exp. Y)	Age of participants (years)	Age range breadth (years)	Inclusion of age differences in statistical analyses	Comparison with adults (sample size)	Sensory modalities tested	Types of stimuli	Experimental paradigm used	Construct investigated	Key findings
21	Lewkowicz, (2003) (exp. 3)	typical development (48)	0 (4,6,8 months)	1 (1 month)	comparison of age groups		audio-visual	speech, syllables	habituation and test	synchrony	syllable stimuli at 6 and 8 months, but not at 4 from 4 months, infants detect audio-visual syllable asynchrony, irrespective of syllable type
22	Lewkowicz, (2010) (exp. 1,2)	typical development (32,37)	0 (4,6,8,10 months)	1 (1 month)	comparison of age groups		audio-visual	speech, syllables	habituation and test	intersensory temporal contiguity window	infant perception of audio-visual speech synchrony is subject to the effects of short-term experience
23	Lewkowicz and Flom, (2014)	typical development (60)	4–6	1	comparison of age groups		audio-visual	speech, syllables	same-different discrimination task	intersensory temporal contiguity window	speech TBW narrows slowly from 4 to 6 years; still wider at 6 years than in adults
24	Noel et al., (2016) (exp 1,2)	typical development (36,21)	7–15	1	comparison through sliding window	yes (120,43)	audio-visual	non speech, low level speech, syllables	simultaneity judgment	temporal window of simultaneity	audio-visual TBW width for low-level stimuli narrows until age 51; for syllable adult-like by age 31
25	Patten et al., (2014)	ASD (23)	3–5	3	no		audio-visual	mixed (auditory speech, visual non speech), complex	preferential looking	synchrony	ASD: preference for synchronous speech-object motion, positive correlation with receptive language
26	Patten et al., (2016)	ASD (15)	3–5	3	no		audio-visual	speech, complex (obscured or unobscured faces)	preferential looking	synchrony	presence of faces impairs speech-object motion synchrony detection in ASD with low language abilities
27	Petrini et al., (2020)	typical development (28)	7–8, 10–11	2	comparison of age groups	yes (14)	audio-visual	non speech, low level speech, word	simultaneity judgment, temporal order judgment	synchrony window	experience-dependent mechanisms for audio-visual synchrony perception mature by age 10; task-dependent mechanisms do not yet
28	Pons et al., (2012)	typical development (24)	0 (6 months)	1 month	no age differences		audio-visual	non speech, complex (bouncing ball)	preferential looking	synchrony	brief exposure to asynchrony increases infants' sensitivity to audiovisual synchrony
29	Pons et al., (2013)	specific language impairment (20), typical development (40)	3–7	3	no		audio-visual	speech, complex (monologue)	preferential looking	intersensory temporal contiguity window	wider auditory-leading temporal window in audiovisual speech for children with specific language impairment

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Table 1 (*continued*)

Ref (authors, year)		Developmental trajectory investigated (sample size exp. X, exp. Y)	Age of participants (years)	Age range breadth (years)	Inclusion of age differences in statistical analyses	Comparison with adults (sample size)	Sensory modalities tested	Types of stimuli	Experimental paradigm used	Construct investigated	Key findings
30	Pons and Lewkowicz, (2014) (exp.1, 2)	typical development (48,24)	0 (8 months)	1	no age differences		audio-visual	speech, complex (monologue)	habituation and test	synchrony	infants are more sensitive for audio-visual synchrony in speech than in syllables; not influenced by specific language familiarity
31	Scheier et al., (2003) (exp. 1,3)	typical development (143, 54)	0 (4,6,8 months)	1 (1 month)	comparison of age groups		audio-visual	non speech, complex (moving disks)	habituation and test	synchrony	from 6 months, infants detect audio-visual asynchrony in complex non-speech stimuli, not before
32	Spelke, (1979) (exp. 3)	typical development (16)	0 (3–4 months)	1	no		audio-visual	non speech, complex (stuffed animals hitting a surface)	preferential looking	synchrony	detection of audio-visual simultaneity of toys hitting a surface at 3–4 months
33	Stanley et al., (2019)	typical development (60)	7,9,11	1	comparison of age groups	yes (20)	audio-tactile	low level	simultaneity judgment	temporal simultaneity window	temporal simultaneity window width adult-like by 11 years, shape by 7 years; wider for tactile-leading pairs
34	Suri et al., (2023)	high risk of ASD (35), typical development (53)	0–2	2	no		audio-visual	non speech, complex (bouncing ball) speech, complex (monologue)	habituation and test	TBW	audio-visual synchrony sensitivity low for high-risk ASD infants only with speech inputs; positively linked to larger vocabulary in low-risk infants
35	Wu et al., (2023)	developmental dyslexia (53), typical development (53)	8–12	5	no	yes (37)	audio-visual	non speech, low level	simultaneity judgment temporal order judgment	TBW	dyslexia: wider audio-visual TBW versus neurotypicals, especially in visual-leading pairs; ages 8–12: adult-like width, but not shape: with visual-leading wider than adults
36	Zhou et al., (2020b)	typical development (32)	11–14	4	no	yes (42)	audio-visual	non speech, low level speech, syllables	simultaneity judgment	TBW	adult-like audio-visual TBW at 11–14 years for flash-beeps and syllables
37	Zhou et al., (2021) (exp. 1)	early onset schizophrenia (31), typical development (30)	12–17	6	age as covariate		audio-visual	non speech, low level speech, syllables	simultaneity judgment preferential looking	TBW	wider audio-visual TBW in schizophrenia for both flash-beeps and syllables
38	Zhou et al., (2022)	typical development (94)	3–6	1	correlation with looking time		audio-visual	speech, complex (monologue)	preferential looking	synchrony	ages 3–6: preference for audio-visual speech synchrony regardless of modality order; no age-related changes
39	Zmyj et al., (2011) (exp. 1,2)	typical development (64,32)	0 (7,10 months)	1 (1 month)	comparison of age groups		visuo-tactile	complex (touch on a leg)	preferential looking	synchrony	at 7–10 months preference for visuo-tactile synchrony depends on stimulus resemblance to infant's body

Note: ASD = Autism Spectrum Disorders; TBW = Temporal Binding Window

29), 4 (n=2) (8, 36), 5 (n=2) (16, 35), and 6 (n=2) (1, 37) years (e.g., the TBW in ASD in children versus adolescents).

No study employed a longitudinal design while 23 studies (1, 4, 5, 12–24, 27, 31, 33, 35, 36, 38, 39) were cross-sectional with 11 of them (13–17, 19, 24, 27, 33, 35, 36) involving adult controls. Sixteen articles (2, 3, 6–11, 25, 26, 28–30, 32, 34, 37) analyzed a single age-range without comparing it with the others. This was the case for all the studies about atypical development except 3 (1, 16, 35), and for 9 of the studies focusing on infancy (2, 6, 7, 9–11, 28, 30, 32).

4.5. Sensory modalities tested

Audio-tactile temporal processing was analyzed by 1 article, the visuo-tactile by 6, and the audio-visual by 32. Among these latter, 16 studies employed paradigms based on complex speech (n=7) (3, 7, 26, 29, 30, 34, 38), words (n=1) (27), or syllables (n=9) (8, 15, 20–24, 36, 37). The other 20 audio-visual studies used non-speech stimuli: 11 studies presented the participants with low level flash-beeps (1, 4, 13, 14, 16, 17, 24, 27, 35–37) and 9 studies with more complex stimuli which included moving objects (n=8) (2, 3, 18, 19, 28, 31, 32, 34), or drumming (n=1) (11). In addition, 1 audio-visual article (25) presented mixed speech (auditory) and non-speech (visual) inputs. Twelve studies investigated just one side of the TBW, administering either visual- (n=2) (7, 15), or auditory-leading delays (n=10) (19–23, 25, 26, 28, 30, 34). Nineteen articles instead used both types of stimulus onset asynchronies, contributing to delineate the whole shape of the participants' TBW (1, 3, 4, 8, 11, 13, 14, 16–18, 24, 27, 29, 31, 32, 35–38). In one case authors did not provide information about the modality that was presented first (2).

As regards to visuo-tactile pairs, 1 study (5) investigated intersensory matching through low-level stimuli (flashes and taps), 1 study (12) used the Rubber Hand Illusion paradigm, and 4 studies administered a video with temporally congruent or incongruent strokes either on the face (n=3) (6, 9, 10) or on the legs (n=1) (39). Two studies presented both visual- and tactile-leading delays (5, 10), 2 studies presented only visual-leading trials (6, 9), 1 study used only tactile-leading trials (12), and 1 article did not report information about the order of modalities employed (39).

The audio-tactile study (33) displayed two simple stimuli: white noise and a tap induced by a tactile stimulator, presenting the tactile input preceding the auditory one in half of the asynchronous trials, and vice-versa in the other half.

4.6. Experimental paradigms

4.6.1. Eye-tracking techniques: preferential looking tasks and habituation and test tasks

Non-invasive eye-tracking techniques to record gaze patterns were utilized in 23 articles (2, 3, 6, 7, 9–11, 18–22, 25, 26, 28–32, 34, 37–39) and primarily employed to investigate multisensory temporal processing during the first year after birth. All studies involving infant subjects utilized this technique. It was also applied at all the other developmental stages considered by this review, albeit with a progressively decreasing ratio.

The stimuli were visuo-tactile in 4 studies (6, 9, 10, 39) while always audio-visual in the others.

Gaze patterns were analyzed using either preferential looking tasks (n = 14) (3, 6, 7, 9–11, 25, 26, 28, 29, 32, 37–39), or employing habituation and test tasks (n=9) (2, 18–22, 30, 31, 34). In both cases, estimates of the cross-modal thresholds for asynchrony detection were performed at the group level, relying on aggregate data and based on the unity assumption hypothesis. According to this conceptualization, under normal conditions, preference, indicated by longer visual fixations, is shown for concordant over discordant multisensory events (Vatakis and Spence, 2007; Welch and Warren, 1980). Consequently, eye-tracking protocols enable the determination of sensitivity to intersensory asynchrony lags predefined by researchers, rather than defining the temporal interval within which multisensory integration is presumed to occur.

4.6.2. Temporal judgement tasks

The temporal judgement tasks are explicit, two-alternative forced-choice tasks that involve presenting cross-modal stimuli at randomly varied, predetermined delays ranging from objective simultaneity to large asynchronies. Participants are required to make a temporal judgement about these input pairs on each trial.

These tasks are instrumental in determining individual asynchrony perception thresholds, which are then compared across groups.

They demand a high level of sustained attention and the access either to the concept of simultaneity or the comprehension of temporal order, abilities that typically develop with age and are not fully available to individuals before school age (Feagans, 1980; Hoyer et al., 2021; Zhang and Hudson, 2018).

The simultaneity judgment task was employed in 14 studies (1, 4, 5, 8, 13, 14, 16, 17, 24, 27, 33, 35–37), involving both typically and atypically developing participants across a broad range of ages, starting from 4 years but predominantly covering school years and adolescence.

One study (33) used audio-tactile inputs and another (5) visuo-tactile. The remaining studies presented audio-visual pairs (n=12).

In this task, participants are required to judge whether the two cross-modal inputs occur at simultaneously or at different times (Stevenson and Wallace, 2013; van Eijk et al., 2008; Vroomen and Keetels, 2010). It specifically measures two independent perceptual parameters: the width of the TBW and the point of subjective simultaneity (i.e., the point in time at which participants are most likely to perceive the inputs as simultaneous and to integrate them into a single percept).

The temporal order judgment task was administered in 2 studies to both typically and atypically developing participants aged 7–12 years, using audio-visual low-level stimuli (n=2) (27, 35) and words (n=1) (27).

This task challenges participants to determine which of two sensory modalities came first (Stevenson and Wallace, 2013; van Eijk et al., 2008; Vroomen and Keetels, 2010). It quantifies the just noticeable difference, which is the minimal delay at which participants begin to detect asynchrony between the sensory inputs.

4.6.3. Same-different discrimination task

To address the challenges faced by 4-, 5-, and 6-year-old children in completing a simultaneity judgment task, 1 study (23) introduced an alternative paradigm. Following a 20 s familiarization phase with a synchronous audio-visual speech video, the authors exposed the participants to the same face-voice pair at four different stimulus onset asynchronies. The task required the children to verbally indicate, on a trial-by-trial basis, whether the video event seemed the same as or different from the one they had been familiarized with.

Data were analyzed by comparing the number of children in each age group who correctly responded to the various trials presented.

Unlike the classical simultaneity judgment protocol, this task does not allow researchers to gather information about the TBW width or the point of subjective simultaneity.

4.6.4. Tasks based on perceptual illusion

Three studies involving participants as young as 4-year-old preschoolers used tasks based on multisensory perceptual illusions to measure intersensory asynchrony tolerance.

These tasks utilize the perception of an illusory percept, arising from sensory inputs in two different modalities, as an indicator of multisensory binding. This methodology allows researchers to test the temporal constraints for synchrony perception by manipulating the delays between the administered cross-modal inputs.

The first task involved the audio-visual McGurk Effect, where perceptual binding leads participants to perceive an audible "ba" and a

visual "ga" as an illusory "da" or "tha" (McGurk and MacDonald, 1976). This illusion was implemented in 2 studies and was presented to both atypically developing children (8) and typically developing adolescents (15).

The second task employed the visuo-tactile Rubber Hand Illusion, which elicits a feeling of ownership over a rubber hand that is stroked in synchrony with one's own hidden hand (Botvinick and Cohen, 1998). This task was featured in 1 article (12) and was exclusively applied to typically developing children.

In both tasks, asynchrony thresholds were calculated for each participant and then averaged across the group, allowing for a comparison of perceptual fusion likelihood between groups at different stimulus onset asynchronies.

4.7. TBW width and shape

4.7.1. TBW width and shape in typical trajectories

For a synthetic overview of the results regarding typical trajectories, see Fig. 3.

4.7.1.1. Audio-visual. The following paragraphs aim to synthetize the available data about the development of the audio-visual temporal acuity. The developmental trajectory that emerges is multifaceted (for a synthesis, see Fig. 4). Indeed, the sensitivity for the audio-visual temporal asynchrony appears to be significantly influenced by the type of stimulus administered for measuring it. For this reason, the data about the changes of the TBW width for the various phases of development will consider separately the results available for speech (complex and syllables) and non-speech (complex and low-level) stimuli.

Infancy

As regards to speech stimuli, 2-month-old infants were able to detect a 400 ms asynchrony when the visual input preceded the auditory one (7). Interestingly, at 8 months, they detected 500 ms auditory-leading asynchronies either in their native or non-native language (30).

Data on asynchrony detection thresholds for isolated syllables are not univocal. Infants aged 4–10 months detected auditory-leading asynchronies ranging from 633 ms (21) to 666 ms (22) after habituation with synchronous inputs. However, a 300 ms asynchrony was only detected following habituation with asynchronous stimuli (22). These findings underscore the impact of experimental methodologies on TBW assessments, indicating that individuals' tolerance to asynchronies varies depending on the measurement approach. Additionally, the results indicate that short-term experiences differentially influence infants' sensitivity to audio-visual asynchrony perception.

Similar findings about the influence exerted by previous experience are confirmed by studies involving non-speech audio-visual stimuli (11, 28).

Focusing on the temporal synchrony between the sights and sounds of objects impacting on a surface (i.e., toys lifted into the air and dropped to the ground), infants were shown to discriminate it already at 3 months of age (2, 32). However, they failed to discriminate a 1.3 s delay until 6 months of age if the non-speech input consisted in less experienced stimuli (i.e., disks moving against one another) (31).

Additional evidence of the influence of experience on refining sensitivity to intersensory synchrony comes from studies that utilized the auditory and visual cues of a bouncing ball as inputs. When involved in a standard preferential looking paradigm, 6-month-old infants did not seem to perceive a 500 ms audio-visual asynchrony (28). Contrariwise, children between 2 and 8 months of age managed to recognize the asynchrony if preventively involved in a habituation procedure. Specifically, they discriminated a 350 ms asynchrony when the sound preceded a visible bounce and a 450 ms asynchrony when the bounce came before the sound. These data also suggest the possible presence of an already asymmetric shape of the TBW during infancy (19).

No data are available for low-level non-speech stimuli.

Toddlerhood and Preschool Years

Data on toddlers and preschoolers are scarce. The studies describe a general stability of the audio-visual temporal acuity for syllables, complex speech and complex non-speech stimuli at least until 5 years of age (3, 23, 29, 34, 38).

The TBW width for non-speech low-level inputs at 5 years of age has been estimated to be as large as 366 ms (4). It is not possible to say if this measure is different with respect to that associated to previous phases of development, in that 5 years is the earliest age for which this information is available.

School Years and Adolescence

The data about school years and adolescence are not clear. Some studies delineate a protracted refinement of the developmental trajectory (n=4), while others point out adult-like performances already before puberty (n=6).

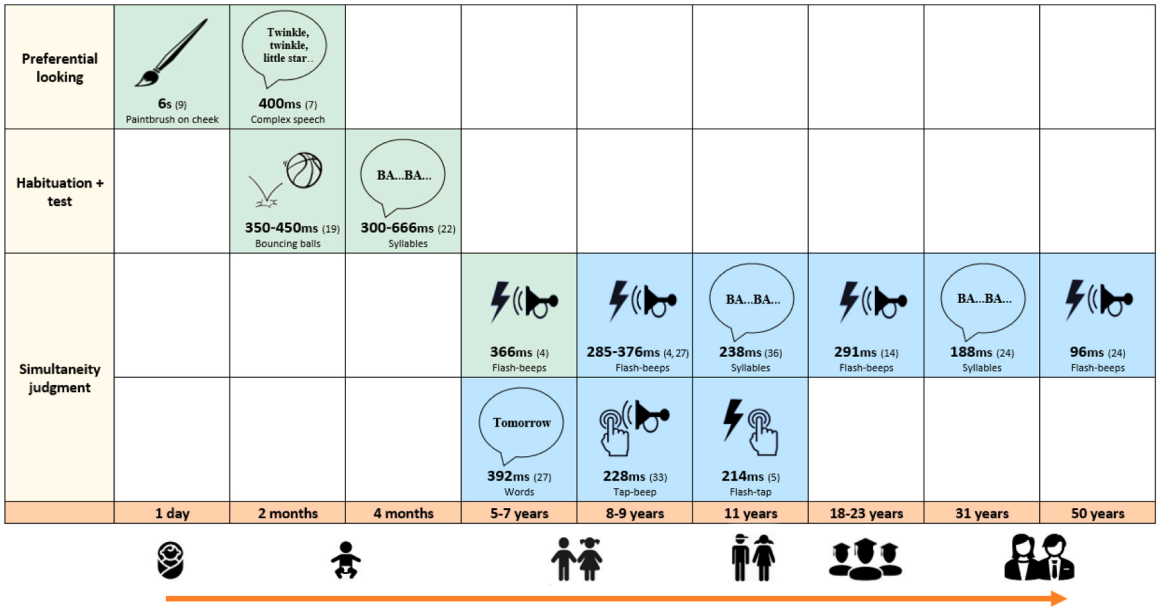


Fig. 3. Age at First Registration (Green Cells) and at Maturity Achievement (Blue Cells) for Intersensory Synchrony Perception in Typical Development Across Studies, Stimuli, and Paradigms. empty cells indicate no records of first registrations or maturity achievements for specified age-task combinations.

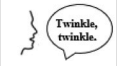
			Infancy	Toddlerhood	Preschool years	6 years	School years	Adolescence	Adulthood
Speech complex	Visual leading		400ms (2 months)	?	600ms	600ms	?	?	?
	Auditory leading		500ms (8 months native or non-native language, after habituation)		600ms	600ms			
Syllables	Visual leading		?	?	?	360-480ms	TBW= 238-315ms	TBW= 238-301ms	TBW= 188-320ms (18-31 years)
	Auditory leading		300ms (4-10 months, after habituation)		666ms (4-5 years) 500ms (5 years, only after familiarization)	360-366ms			
Non-speech complex	Visual leading		450ms (2-8 months, after habituation)	?	?	?	?	?	?
	Auditory leading		>500ms (6 months) 350ms (2-8 months, after habituation)						
Non-speech low-level	Visual leading		?	?	TBW= 366ms (5 years)	TBW= 404ms	TBW= 222-412ms	TBW= 163-399ms	TBW= 96-318ms (18-51 years)
	Auditory leading								

Fig. 4. Graphical Synthesis of the Data Regarding the Development of the Audio-Visual TBW, Divided by Age, Type of Stimulus and Order of Modalities. cells with question marks indicate that no studies have investigated the specified age-task-stimuli combinations.

Studies consistently identify a significant refinement of the individuals' temporal acuity for syllables between 5 and 6 years of age: 6-year-olds seem able to detect asynchronies as low as 360 ms both auditory and visual-leading (8, 23). However, consensus is lacking as to the age at which the TBW width reaches maturity for audio-visual syllables: some authors identified it at around 31 years of age (TBW=188 ms) (24), whereas others already at 7 (TBW=315 ms) (15) or 11 years of age (TBW=238 ms) (36). Such discrepancies may arise from methodological variations across studies. These include differences in statistical analyses (e.g., use of fitted Gaussian or sigmoid functions), or in the experimental paradigms employed (e.g., use of McGurk Effect task or simultaneity judgment task, and variations in the inter-stimulus intervals administered).

As concerns non-speech low-level stimuli, some studies identified a still immature TBW width at 11 (13, 17), 17 (14), or even until 50 years of age (24), with younger participants being more likely to perceive flashes and tones as synchronous at longer delays than adults (adult TBW=96–291 ms). Differently, further studies registered a steeper narrowing trajectory, with the width of the non-speech low-level TBW reaching maturity between 7 and 12 years of age (adult TBW=128–299 ms) (1, 4, 27, 35, 36).

Similarly, the developmental trajectory of the TBW shape was not delineated consistently across studies.

First, the authors disagreed with respect to the symmetrical aspect of the developmental refinement. Some studies found an improvement only or more markedly when considering the auditory-leading pairs (13, 17), while others when examining the visual-leading conditions (35). Despite this, most of the studies agree in describing an already adult-like point of subjective simultaneity early in childhood (4, 14, 27), with the visual-leading side wider than the auditory by 5 years of age (4). Only one study reported symmetry of the TBW from 10 to 11 years of age (13).

Second, some articles speak of a gradual refinement of the TBW (4, 24), whereas others identify a succession of phases of tuning and phases of stability (14).

The examined articles pointed out further differences across age groups beyond those regarding the TBW width and shape.

The first difference concerns the role played by experience-dependent mechanisms in modulating the individual tolerance to asynchronies. The studies found that adults and older children (i.e., ages 10–11), unlike younger children (i.e., ages 7–8), are more likely to perceive cross-modal inputs presented with large asynchronies as simultaneous if the integrated percept is highly familiar (27).

Another age-related difference regards the individuals' reaction times registered during the simultaneity judgment task. Adult participants result faster than children at the longest delays (400 ms and 500 ms), probably because of a greater degree of certainty in audio-visual temporal decisions and a consequently more moderate effort needed for them than for younger participants to fulfill the task (17).

No data are available for complex speech and complex non-speech stimuli, so that we do not know how the TBW develops with respect to these types of stimuli after preschool years.

4.7.1.2. Visuo-tactile. Infancy

The ability to discriminate intersensory synchrony in visuo-tactile pairs appeared to be present shortly after birth. From their first day, infants have been seen to detect and show a preference for synchronous over asynchronous vision and experience of a paintbrush stroke on a cheek or forehead as well as of a caress on a leg (6, 9, 10, 39). However, visual preference for cross-modal synchrony was not present when the stroke on the cheek was too fast (6) or if the administered video showed a wooden block instead of a doll leg (39). Interestingly, visuo-tactile preference for synchronized stimuli seemed to increase quantitatively (i.e., longer total looking time) from 7 to 10 months of age (39).

Toddlerhood, Preschool Years and School Years

No data are available for toddlerhood and those about preschool years are scarce. Information about visuo-tactile synchrony perception of children aged 4–11 was retrieved thanks to a Rubber Hand Illusion task. The study revealed the participants' ability to correctly discriminate delays as low as 400 ms tactile-leading, with accuracy increasing significantly with age (12).

Improvement in temporal acuity during development was also confirmed for flashes and taps. At 7- (TBW=385 ms) and 9-year-old (TBW=300 ms) children showed a large threshold for visuo-tactile simultaneity and a high number of response errors. They were found

to achieve adult levels of accuracy between 9 and 11 years of age (TBW=214 ms at 11 years, 223 ms at 13 years, 230 ms for adults, not significantly different). Interestingly, large individual variability was described for the youngest participants with some 7-year-old children showing levels of temporal function comparable to those of adults (5).

The asymmetry of the TBW shape resulted adult-like by 7 years of age with the point of subjective simultaneity already shifted on the tactile-leading side (5). No younger children were examined from this point of view in the reviewed studies so that no further data are available on the topic.

4.7.1.3. Audio-tactile. Infancy, Toddlerhood and Preschool Years

No data are available for infants, toddlers and preschoolers with regards to audio-tactile stimuli.

School Years

Results concerning school years seem to delineate a developmental trajectory coherent with the general picture of a gradual narrowing of the TBW size with age. At 7 years of age children showed both a wider tolerance to temporally separated audio-tactile inputs (TBW=271 ms) and higher error rates in both synchronous and asynchronous conditions. At 9 years of age the TBW (228 ms) did not significantly differ from that of adults when participants were considered collectively, but it presented a much greater individual variability with some participants displaying considerably lower acuity in multisensory temporal perception. At 11 years children appeared to have reached adult levels of performance across all the considered parameters (TBW=172 ms at 11 years, 174 ms for adults, not significantly different) (33). At 7 years of age the point of subjective simultaneity resulted to be located towards the tactile-leading side. This indicates the presence of the typical adult-like asymmetrical shape of the TBW already at this age (33).

4.7.2. TBW width and shape in atypical trajectories

Literature about atypical development only examined audio-visual pairs, and so no data are available as regards to visuo-tactile and audio-tactile developmental trajectories for this population.

Suri et al. (2023) registered a significantly wider tolerance to auditory-leading asynchronies for social stimuli (speaking face) in infants and toddlers at high risk of developing ASD (TBW=671 ms) with respect to their age-matched controls (TBW=575 ms). The same was not retrieved when considering nonsocial stimuli (bouncing ball) (34). Bebko et al. (2006) were the first to systematically investigate the ability to discriminate asynchrony among a limited age range group of young children with ASD (4–6 years of age) presenting them with side-by-side audio-visual events, both visual- and auditory-leading. They found that participants with ASD showed random looking during both simple (50% of total looking time) and complex (49%) linguistic stimulation failing to detect a 3 s asynchrony. Instead, with non-speech inputs they seemed to prefer synchrony even if somehow less strongly than typically developing controls (60% versus 65%). In the same paradigm, age-matched children with other forms of developmental disabilities (i.e., Fragile X Syndrome, Hydrocephalus, Prader-Willi Syndrome, Down Syndrome, and other disabilities with unknown etiology), behaved more similarly to the typically developing controls looking longer to the synchronous events (mean = 63%) in all three conditions (3). Patten et al. (2014), (2016) expanded knowledge on this domain showing that 3- to 5-year-old preschoolers diagnosed with ASD preferred to direct their gaze towards objects paired with linguistic stimuli when synchronous (55.75%) than when the auditory input preceded the visual one by 700 ms (44.25%) (25). An adaptation of the same experimental design showed that the direction preference did not change in relation to the presence on the video of the uncovered or obscured face of the actor responsible for moving the visual stimulus except for participants who were at least one standard deviation below the normative mean on their receptive language skills. These children indeed appeared to fail to detect synchrony selectively when faces were displayed (26).

Dysfunctions in audio-visual syllable temporal processing for children with ASD between 4 and 7 years of age were reported by Feng et al. (2021) (8) indicating for them an atypically extended TBW (616 ms) due to reduced sensitivity during visual-leading pairs. Instead, the temporal function resulted to be intact when the auditory input came first.

Ainsworth and Bertone (2023) recently expanded the knowledge in this field. They reported that children with ASD between 6 and 12 years show an extended TBW that progressively narrows with age and characterized by a point of subjective simultaneity equivalent to that of the neurotypical controls (1).

An extended tolerance to intersensory asynchronies was retrieved also for children aged 4–6 with specific language impairments. Indeed, they appeared to be less sensitive than age-matched controls to 666 ms offsets of audio-visual speech stimuli, managing to discriminate them only when the visual input led the auditory (29).

Deficits in audio-visual TBW for individuals with a history of specific language impairment were confirmed also for older children aged 7–11 tested with low-level non-speech stimuli. Collectively, they resulted significantly less sensitive than their typically developing controls, even at stimulus onset asynchronies as high as 500 ms regardless of the order of the auditory and visual inputs. Yet, on an individual level, they were characterized by a substantial variability with some participants achieving typical performance and others still showing inaccuracy at the longest delays (16).

Wu et al. (2023) describe a significantly larger tolerance to non-speech asynchronies also for 8- to 12-year-old children with developmental dyslexia (TBW=394 ms) than for their age-matched controls (TBW=316 ms), especially due to a poorer intersensory temporal acuity in the visual-leading trials (visual-leading TBW=241 ms versus 185 ms) (35).

Only one study included in this review analyzed the multisensory temporal function of young patients with early onset schizophrenia. Compared to age-matched controls (age 12–17 years, TBW=265 ms for syllables; 223 ms for flash-beeps), participants with early onset schizophrenia were reported to be more inclined to perceive as synchronous speech and non-speech audio-visual stimuli presented at large stimulus onset asynchronies (TBW=462 ms for syllables; 420 ms for flash-beeps). The authors also pointed out weaker asynchrony sensitivity for them than for 7- to 13-year-old children and adolescents with ASD who took part in the same study (TBW=347 ms for syllables; 283 ms for flash-beeps) (37).

5. Discussion

5.1. Converging findings

The present review aimed to investigate the literature findings as to how multisensory integration temporal function changes across infancy, childhood, and adolescence.

The comprehensive representation that emerged delineates a multifaceted picture.

Consistent with the Early Integration Approach (Bahrick and Lickliter, 2000; 2002), the reviewed studies indicate that from birth sensitivity to intersensory synchrony guides attention, especially with regard to visuo-tactile combinations. Thus, from the beginning of life, individuals can rely on this amodal low-level cue to navigate the plethora of inputs they encounter. It is important to note that available data on newborns' propensity for intersensory synchrony do not provide precise insights into their tolerance for intersensory asynchronies. This limitation arises because the only study examining newborns used a single inter-stimulus delay of 5 seconds (Filippetti et al., 2013).

Focusing on tolerance to the intersensory asynchronies, the studies reviewed outline a protracted narrowing of the TBW, with infants requiring considerable larger time lags than adults to perceive inputs as non-simultaneous. This is consistent with the Late Integration Approach, which posits that refined multisensory skills are acquired through

experience (Putzar et al., 2007; Robinson and Sloutsky, 2010). Specifically, during the preschool and early school years, significant changes occur in the TBW. While the tolerance to asynchronies remains stable in the early years of life, with 4-year-olds displaying a sensitivity to audio-visual syllables similar to infants, a substantial refinement occurs by the age of 6, allowing children to discern temporally separate inputs at considerably shorter lags (Lewkowicz, 2003, 2010; Lewkowicz and Flom, 2014; Pons et al., 2013). This period is notable also because it coincides with crucial development of other key functions supposedly grounded in multisensory integration (Bahrick and Lickliter, 2012). Among these functions, body representation and self-regulation are particularly critical, forming the foundation for essential social and cognitive competences and correlating with achievement, mental health, and wellbeing in later life (Della Longa et al., 2021b; Robson et al., 2020).

The investigation of the TBW developmental trajectory thus supports both Early and Late Integration Approaches, suggesting that multisensory abilities development is best understood as an integration of the two hypotheses (Lewkowicz, 2002).

The outlined pattern mirrors the general development of multisensory integration skills, which begin as a broadly tuned and immature propensity at birth, and gradually refine through an experience-dependent process fostering ecological adaptation (Bremner, 2017; Lewkowicz and Bremner, 2020). For instance, this gradual specialization enables children to swiftly adjust to changes in body schema (Cardinali et al., 2009) and to selectively integrate audiovisual cues specific to their native language (Lewkowicz, 2014).

However, the protracted plasticity of the TBW presents a significant downside: it exposes individuals to a potential cascade of disruptions when atypical factors intervene or expected experiences do not occur (Nelson and Gabard-Durnam, 2020). This framework offers a valuable basis for investigating the enlarged TBW observed in atypical development and for hypothesizing about the underlying mechanisms of this dysfunction. Could this alteration in the TBW stem from an insufficient amount of early experience, and, thus, could it be a way to preserve the ability to adapt to a still too unpredictable environment? (Bremner, 2017; Lewkowicz and Bremner, 2020). Alternatively, might this extended TBW originate from specific alterations in probabilistic learning that impair an individual's ability to convert experiences in learnt associations (Ernst, 2008), or from an attentional deficit that hinders the detection of intersensory correspondences (Talsma et al., 2010)? Proponents of Late Integration might attribute these alterations to impairments in specific modalities (e.g., Gori et al., 2020). Indeed, unisensory temporal deficits are documented in various neurodevelopmental disorders such as ASD, developmental dyslexia and schizophrenia (Meilleur et al., 2020; Stevenson et al., 2017). However, these unisensory impairments may also arise from multisensory dysfunctions (Shams et al., 2011).

The enlarged TBW observed in atypical development may underpin the widespread disruptions noted in ASD, specific language impairment, developmental dyslexia, and schizophrenia (Hill et al., 2012), by complicating environmental perception and increasing the cognitive demand required to process sensory information (Wallace and Stevenson, 2014). These disorders are, indeed, characterized by deficits in higher-order processes scaffolded by multisensory temporal efficiency, including executive functions (e.g., Barbosa et al., 2019; Demetriou et al., 2018; Pauls and Archibald, 2016; Ruiz-Castañeda et al., 2020), linguistic capabilities (e.g., deBoer et al., 2020; Schaeffer et al., 2023; Schwartz, 2009; Stein, 2018), as well as bodily-self-consciousness and peripersonal space representation (e.g., Michel et al., 2019; Tordjman et al., 2019). Alterations in the TBW may also account for more specific deficits associated with these clinical conditions. For instance, studies have linked multisensory temporal processing deficits to communicative and social difficulties in ASD (Smith et al., 2017; Stevenson et al., 2018b), phonological awareness and reading accuracy in developmental dyslexia (Francisco et al., 2017; Laasonen et al., 2002), and the severity of hallucinations in schizophrenia (Stevenson et al., 2017).

Previous considerations underscore the importance of early intervention to mitigate the impact of a dysfunctional TBW on higher-order cognitive processes before critical and sensitive developmental periods for their development conclude. Additionally, they highlight the need for a detailed understanding of the trajectory of the TBW in atypical development. In this regard, findings from Ainsworth and Bertone (2023) concerning children and adolescents with ASD are consistent with adult ASD studies (Beker et al., 2018; Feldman et al., 2018), describing a delayed TBW tuning rather than a permanent gap compared to typically developing individuals. However, this scenario remains speculative and broadly outlined. Currently, there is no data specifying when the delay begins or detailing the path and timing through which it reaches typical levels of maturity. Notably, studies not included in this review suggest a different trajectory for individuals with developmental dyslexia, who appear to experience a worsening of TBW alterations between the ages of 20 and 59 (Virsu et al., 2003; Meilleur et al., 2020).

5.2. *Diverging findings*

The reported data are inconsistent in determining the rate and extent of TBW refinement, leaving it unclear whether the TBW reaches maturity before puberty or only after adolescence. It is also ambiguous whether the adult-like asymmetrical shape of the TBW is present in early childhood or is still absent at 11 years of age.

Further complicating the understanding, different combinations of sensory modalities, types of stimuli, and specific components of the TBW follow distinct developmental trajectories, supporting the predictions of the Late Integration Approach (Burr and Gori, 2012).

First, asynchrony sensitivity for audio-visual pairs matures earlier than for audio-tactile and visuo-tactile combinations, likely due to children's pervasive exposure to contingent visual and auditory stimuli, especially after the first two years of life through linguistic interactions (Chen et al., 2018). It is interesting to consider this faster maturation for audio-visual pairs within the framework of the Late Integration Approach. Touch, being the earliest sensory channel to develop and highly experienced in meaningful relationships, especially in early life stages (Cascio et al., 2019; Gottlieb, 1971; Bremner and Spence, 2017), might suggest a developmental advantage for combinations involving this modality. However, the predominant unisensory role of touch in calibrating other modalities could potentially slow intersensory learning for multimodal pairs involving tactile inputs (Gori, 2015). Mechanisms like this could be further explored as a potential underlying factor for the dysfunctions observed in atypical developmental populations.

Second, across all three intersensory pairings, the shape of the TBW appeared adult-like before its size did (Chen et al., 2016, 2018; Lewkowicz, 1996; Stanley et al., 2019), suggesting that the proportional relationship between modalities stabilizes earlier than the specific temporal acuity does. This observation may be attributed to the pervasiveness of specific modality-leading circumstances in everyday life, potentially resulting in modality-specific extended tolerance (Love et al., 2013; Stevenson et al., 2012). In line with Bayesian models (Alais and Burr, 2004; Ernst and Banks, 2002), it is plausible that, sufficient coherent experience renders certain features of inputs reliable enough to consistently influence probabilistic judgement even during development. For instance, in the natural environment visual stimulus energy consistently reaches the retina prior to auditory energy reaching the cochlea, potentially training individuals to tolerate more extended audio-visual pairs when the visual leads the auditory (Pöppel et al., 1990). However, it remains unclear whether the asymmetric shape of the TBW is acquired through experience or if it is an innate characteristic present from birth. In this context, it is relevant to determine whether the enlarged TBW observed in atypical development also involves alterations in its shape, and whether this feature varies across clinical conditions. Currently, the available data are insufficient to resolve these issues conclusively.

Third, the tolerance to asynchronies for low-level stimuli was found to develop earlier than that for complex ones, and to be less extended, akin to observations in adult participants (van Eijk et al., 2008). These discrepancies can be attributed to longer processing times required for complex versus simple stimuli (Stevenson and Wallace, 2013), and to the stronger semantic associations often found in complex stimuli (Fereday et al., 2019; Humphreys and Buehner, 2009; Nolden et al., 2012). For instance, the nervous system's maintenance of an open TBW for a longer period for audio-visual speech stimuli, which are both more familiar and meaningful than arbitrary pairings of flashes and tones, may stem from an anticipation of binding these elements.

The influence of concurrently developing cognitive processes on the TBW also varies with age. Notably, the changing role of experience is paradigmatic: prior knowledge of the stimuli modulates the TBW starting only after 10 years of age (Petrini et al., 2020; Zhou et al., 2020b). Interestingly, the ages of 8–10 years are noted to coincide with findings that describe an immature ability to learn from multisensory experience previously (Gori, 2015). Conversely, short-term perceptual experiences have been shown to influence intersensory synchrony sensitivity as early as between 4 and 10 months of age (Lewkowicz, 2010). This differential influence of experience on perception at various ages aligns with Bayesian modeling of multisensory perception, which posits a rebalancing between low-level cues (i.e., the degree of spatial, temporal, and structural consistency among the signals) and high-level cues (i.e., prior knowledge derived from experience) throughout development. Early on, children predominantly rely on low-level correspondences, such as intersensory synchrony, which they can detect from birth, and which assist them in organizing the multiple sensory inputs they encounter. As development progresses and they gain experience with more complex associations, high-level correspondences gradually become more pivotal in the probabilistic judgements that underpin multisensory perception (Shams and Beierholm, 2022; Verhaar et al., 2022).

5.3. Future directions

The reviewed studies merit recognition for broadening the research pathways with which to examine the TBW. They have adapted a diverse array of methods for young participants and offered insightful perspectives. However, the heterogeneity of constructs, tasks, procedures, and stimuli across studies complicates the clarity and comparability of results.

Key directions for future research are examined below.

5.3.1. More methodologically homogeneous and developmentally focused studies

To confirm and expand upon the current literature findings, future studies should strive for more uniformity in experimental paradigms and statistical methods. It is clear, for instance, that estimating individual thresholds is different from measuring group performances. Likewise, assessing multisensory temporal processes through explicit simultaneity judgments does not equate to measuring the same functions as those involved in verbally reporting the perceived outcomes of an illusion task, or in capturing implicit attentional preferences through the eye-tracking indices.

Research should focus on tasks that are applicable across various ages and cultures, while effectively controlling for confounding variables (e.g., stimulus type and complexity, reiteration and experience effects). For instance, a cross-cultural study by Tanaka et al. (2010) suggested that East Asians exhibit a different reliability of auditory inputs over visual ones for speech perception compared to Western individuals. Such cultural factors could differentially influence the developmental trajectories of the TBW for specific inputs.

Additionally, authors should target narrower age-ranges and larger samples sizes, adopt a unified definition of maturity, and ideally employ longitudinal designs. Cross-sectional comparisons that include adult participants could serve as valuable alternatives. Such standardization would enable researchers to draw more accurate conclusions about the development of the TBW.

5.3.2. Tailoring a task on early childhood characteristics

For the stated purposes, designing a new task tailored specifically to the needs and constraints of young children is more effective than adapting adult-based tasks (e.g., simultaneity judgment) for younger participants. As highlighted in this review, the unique attentional and cognitive developmental phases that toddlers and preschoolers undergo make it difficult to evaluate them thoroughly and consistently using paradigms originally designed for adults or infants.

Specifically, experimental tasks for early childhood must strike a satisfactory balance between minimizing fatigue effects and maintaining precision and thoroughness, both in terms of the number of stimulus onset asynchronies and the trials per stimulus onset asynchrony. Additionally, this task needs procedures that can accommodate the high likelihood of distraction among young participants. From this perspective, tasks that are engaging and utilize implicit methodologies, thereby limiting language and cognitive demands, as well as confounding variables, should be preferred.

The development of a paradigm like the one described is especially relevant given the sparse research on the preschool and early school years, which are characterized by significant changes and considerable individual variability in the TBW. Investigating and measuring the TBW alongside its behavioral correlates could provide valuable insights and expand the scope of existing literature on this topic.

A potential approach is the use of a preferential looking paradigm that captivates children with stimuli such as cartoon characters, adjusting stimulus onset asynchronies via a staircase procedure. This method could overcome the limitations of standard eye-tracking protocols, which depend on aggregate data and preset asynchrony thresholds, thereby allowing for more detailed and individualized measurements. Such a task would enable the homogeneous collection of data regarding the individuals' TBW width and point of subjective simultaneity across different developmental stages. Furthermore, as no study has yet measured the TBW for low-level stimuli in children under 5, incorporating these inputs into the task presents an interesting challenge. This integration would enable analyses of asynchrony tolerance for low-level stimuli compared to that associated with other types of inputs (i.e., non-speech - complex; speech - syllables, words, complex).

Significant advances in the use of eye-tracking tasks to gather more detailed information about the individual's multisensory processing efficiency have been achieved, thanks to Bahrick et al. (2018a), (2018b). However, these protocols are designed to measure aspects of cross-modal integration skills different from the temporal ones.

5.3.3. Digging into atypical developmental trajectories

Consistent with findings from typical early childhood development, the considerable variability observed in atypically developing children underscores the need for targeted analysis and detailed investigation into the factors driving these differences. Future research should clarify whether the TBW impairments are context-specific, varying with task modality and stimuli type, or represent broader impairments that persist across different contexts. Additionally, it is important to determine whether unisensory impairments in temporal processing in these populations precede multisensory ones, whether they are predictive of each other, and how the preference for intersensory synchrony observed at birth in typically developing children compares to that in children who later develop neurodevelopmental disorders.

Current knowledge is constrained by the exclusive analysis of audio-visual inputs and a lack of research on age-related changes in the TBW. Among the studies reviewed that focus on atypical development, only one employed a cross-sectional design (Ainsworth and Bertone, 2023). Moreover, this study compared groups with considerable internal age variability, each defined by a broad 6-year age range (i.e., children

versus adolescents). The use of mean data may obscure significant within-group differences.

More detailed studies are required to fully understand the nuances that distinguish the clinical profiles of various atypically developing populations, which may contribute to diverse paths of cascading dysfunctions. In this context, research on atypical development would benefit from a focus on infancy as part of longitudinal studies. This approach could involve infants who, from birth or soon afterwards, exhibit major risk factors for these conditions, as identified in the literature (e.g., Suri et al., 2023).

Analyses focusing on children and adolescents with developmental dyslexia should be incremented, as this disorder is frequently mentioned alongside ASD and schizophrenia in discussions of dysfunctional TBW. Evaluating tolerance to asynchronies across a spectrum from typical, to difficult, to impaired learning could be timely and useful, providing crucial data for early screening processes. This approach could also be applied to specific language impairment, which is often noted in the histories of individuals diagnosed with developmental dyslexia and appears underrepresented in this review. Furthermore, extending research to other specific learning disabilities (i.e., developmental dyscalculia, dysgraphia, and dysorthography) could prove insightful due to their common comorbidities and established correlations with developmental dyslexia (Willcutt et al., 2019).

Given the growing interest within the literature on attention deficit and hyperactivity disorder (e.g., McCracken et al., 2020; Schulze et al., 2021) in multisensory integration abilities (ADHD), the lack of TBW studies involving participants with this disorder appears to be a surprising shortfall. This gap is especially striking given that findings concerning adults suggest a distinctive pattern of TBW alterations compared to other neurodevelopmental disorders. Specifically, research by Panagiotidi et al. (2017) indicates that the TBW narrows as non-clinical ADHD traits increase, an observation that contrasts with trends observed in previously studied disorders.

The literature on adults using cochlear implants reveals altered multisensory temporal acuity, pointing to a valuable research direction (e.g., Butera et al., 2018). Including early deafened children and adolescents in future studies would be beneficial to gain a deeper understanding of the atypical developmental trajectory of the TBW. Developmental research should equally include individuals who experienced early visual deprivation, as studies indicate they suffer from prolonged impairments in audio-visual temporal acuity, without corresponding deficits in visuo-tactile temporal acuity (Chen et al., 2017).

Additionally, expanding research on early onset schizophrenia, particularly through large-scale studies aimed at early detection, would be valuable. Such efforts would necessarily involve longitudinal designs to track developmental changes effectively.

5.3.4. Expanding the horizons to include the forgotten sensory modalities

The scarcity of information on cross-modal combinations beyond the audio-visual realm also characterizes the domain of typical development and presents a fertile area for future research. Further investigation is required into the less studied exteroceptive cross-modal pairs considered in this review (i.e., audio-tactile and visuo-tactile). Research should also be extended to include other external sensory sources. Among these, there are not only smell and taste but also the vestibular system (i.e., self-motion information derived by the movement of the head in space), and proprioception (i.e., the perception of body position and movements in three-dimensional space). It would be beneficial to enrich the understanding of TBW development by exploring intersensory combinations that include interoceptive stimuli (i.e., signals originating from the visceral organs that allow physiological internal monitoring), following the pioneering work of Della Longa et al. (2020). These stimuli are combined with those arising from the outside, giving rise to complex and continuous perception and to a constant exchange between the environment and the individuals' inner world (Tsakiris, 2017). Expanding research in this direction is essential, given the fundamental role of interoception in regulating energy, memory, emotional experiences, and shaping the psychological sense of Self (Quigley et al., 2021).

A significant limitation must be noted. Despite the variety of methods available for measuring the TBW, the field still has to deal with substantial challenges related to the technical feasibility of delivering, registering, and controlling sensory stimuli, especially those beyond the audio-visual spectrum and outside of laboratory settings (Cornelio et al., 2021).

5.3.5. Considering the role of early experiences

A more complete and systematic approach will deepen our understanding of fundamental temporal processes, whose extended plasticity constitutes both a threat and an opportunity. On the one hand, infants' and children's autonomous exploration of their environment and bodies is essential for sensory development, as confirmed by sensory-deprivation studies (de Klerk et al., 2021; Lewkowicz and Bremner, 2020). On the other hand, recent research underscores the crucial role of social interactions in multisensory learning, particularly when expressed through the countless synchronized multisensory inputs exchanged with caregivers during dyadic interactions (Montirosso and McGlone, 2020). Conversely, these findings suggest that disruptions in caregiving behaviors could hinder the functional development of the ability to correctly integrate sensory inputs across different modalities. This hypothesis is supported by evidence of sensory system dysfunctions in individuals with histories of trauma (Harricharan et al., 2021; Kearney and Lanius, 2022; Rabellino et al., 2020; Stevens et al., 2024; Teicher et al., 2016). Investigating the potential impacts of developmental or complex trauma on multisensory integration temporal processes could provide valuable insights.

Therefore, the early phases of life play a crucial role, demanding further exploration as indicated by research into how parental behavior and sensitivity influence multisensory integration and the processes built on it (Bruce et al., 2022).

Evidence suggesting that the detection of intersensory synchrony is innate and present soon after birth, highlights the importance of investigating multisensory temporal functions during gestation (Nava et al., 2023). This exploration could involve adapting existing paradigms for measuring fetal unisensory sensitivity to include modulated delays between inputs across different modalities. Employing advanced imaging techniques such as 3D and 4D ultrasound sonographies could allow researchers to observe fetal behavioral responses (i.e., movements) to temporally coincident or non-coincident stimulations (e.g., Marx and Nagy, 2015, 2017).

5.3.6. Designing and implementing training activities to sustain the TBW development

The role of experience in shaping the perception of intersensory synchrony, combined with the inherent malleability of the TBW, suggests opportunities for interventions that could enhance the developmental trajectory of typically developing individuals and foster maximal adaptation in atypically developing populations (Stevenson et al., 2016).

In the context of typical development, promising results have been shown by studies that demonstrate the efficacy of short perceptual training programs in adult participants (McGovern et al., 2022; Powers et al., 2009, 2016; Stevenson et al., 2013; Zerr et al., 2019). However, more nuanced outcomes have been observed in a recent training attempt involving children, adolescents and young adults with ASD (Feldman et al., 2023). The authors report post-test results showing high variability in the TBW of atypically developing individuals as compared to their baseline measures. The overall non-significant effect of the training varied according to participants' characteristics: only those with above-average language and cognitive skills experienced the anticipated benefits, exhibiting a narrowing of the TBW. Conversely, participants with lower abilities in these areas showed less narrowing or even an enlargement of their TBW. These findings underscore the need to design

differentiated TBW training programs tailored for individuals with reduced cognitive and linguistic capabilities. Furthermore, they suggest the importance of including these skills as control variables in future studies.

Training programs for children and adolescents could incorporate games designed to motivate active engagement in creating multisensory synchrony, utilizing a wide range of sensory modalities. These programs could be delivered through digital apps or within multisensory rooms, both equipped with technology providing automatic feedback to users. Additionally, these platforms could be tailored to adapt to individuals' specific level of intersensory temporal acuity, ensuring that the training is both personalized and effective.

Studies measuring the effectiveness of these interventions could clarify the nature of the correlations between multisensory skills and various higher-order processes. If the training aimed at refining the TBW is shown to foster a positive feedback loop that enhances functions scaffolded by multisensory integration, the resulting data could provide additional further evidence of the foundational role of these basic temporal mechanisms.

6. Conclusions

Systematically analyzing the existing literature on multisensory temporal processing, this review aimed to highlight the developmental changes in the TBW from infancy through adolescence.

The current results portray a prolonged, narrowing, and composite but still not well-defined developmental trajectory of the TBW and highlight two primary goals for future research. Firstly, there is a need for a more homogeneous and analytical investigation of both typical and atypical TBW developmental patterns. Secondly, the data call for a detailed examination of how these patterns correlate with the concurrent development of cognitive and social competences grounded on multisensory integration. A deeper understanding of these processes could catalyze the creation of enhancing, preventative, and rehabilitative training programs able to trigger positive feedback loops from the bottom-up, starting with modelling the basic building blocks of self-regulation and the embodied Self.

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