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**Portable Psychophysics:
A novel approach to evaluate temporal processing
in basic research and clinical settings**

by
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Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 65,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

Nicola Domenici
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Abstract

To perceive and interact with the environment functionally, our brain must simultaneously encode and decode various temporal cues and efficiently combine them across different senses. Nonetheless, not all sensory modalities exhibit equally valuable temporal resolutions, being auditory the primary sensory modality through which time is precisely experienced. Consequently, such a combination is not a linear process, and temporal information perceived across individual sensory streams shows several grades of relevance when performing duration estimations. To date, however, it is still unclear how temporal processing occurs within the brain, along with how auditory impairments during development might determine plastic changes that negatively affect time perception. Powerful insights can be obtained by investigating temporal processing in individuals whose auditory perception was impaired during critical developmental stages, when the brain experienced the most plastic properties. Interestingly, both the absence of hearing experience during development, such as in congenital and early deafness, and its deterioration, such as in Developmental Dyslexia, seem to determine a generalized reduction of temporal sensitivity across the lifespan. Even though there is solid evidence suggesting that abnormal auditory experience might affect temporal processing, there is a surprising lack of behavioral evidence aiming at bridging temporal impairment in deafness and Developmental Dyslexia. I thereby first investigated temporal processing in these populations using classing psychophysical techniques. I thus developed two different tasks directly designed to evaluate visual temporal abilities, with a specific focus on the magnocellular properties of temporal perception. Being particularly prone to be shaped by abnormal sensory experience during development, magnocellular cells should in fact reflect different temporal encoding according to the nature of the auditory impairment. Then, due to the COVID-19 pandemic and the consequent, inevitable difficulties emerged in data collection, I decided to foster a remote and safe approach to psychophysical testing. I therefore conceptualized, designed, and validated *PsySuite*, an Android App aimed at providing a reliable and easy-to-use tool to assess perceptual measurements while respecting social distancing restrictions. *PsySuite*'s feasibility in performing remote data collection was evaluated through extensive hardware and behavioral testing, allowing to determine the reliability of the produced stimuli and the generalizability of the results obtained with the App. After establishing *PsySuite*'s effectiveness and stability, I developed a portable version of a psychophysical task specifically designed to gauge and enhance temporal perceptual skills in typical adults. With this newfound, novel approach, I then investigated temporal processing in deaf and dyslexic participants.

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Chapter 1

Introduction

At the time of the Vietnam War, the American pilot Jeremiah Denton was held captive by the North Vietnamese army after his plane crashed behind enemy lines. While confined, Denton was forced to attend a televised press conference by his captors to witness the American prisoners' condition. During the broadcast, as the American pilot was answering the interviewers' questions reporting that no rights violation was taking place, he repeatedly blinked his eyes in Morse code spelling the word 'T-O-R-T-U-R-E' to communicate – without being noticed – the actual captives' conditions (M. L. Bartlett et al., 1999).

1.1 Temporal Representations in Sensory Environments

Even though the brain constantly interfaces with a wide range of temporal scales, from microseconds to daily circadian rhythms, temporal processing appears to be most sophisticated within the milliseconds-to-second range (Buonomano, 2007; Buonomano & Karmarkar, 2002; Hardy & Buonomano, 2016). It is within this range that humans, for example, code and decode the complex temporal structure of signals involved in communication (Schirmer, 2004; Shannon et al., 1995). Surprisingly, the brain's natural ability to generate and interpret milliseconds-to-second intervals is refined to such an extent that language itself can be reduced to a pure temporal code, like the Morse code. The brain's ability to decipher temporal patterns occurring within this range is so impressive that communication can be developed with just the blink of an eye, as in the case of Danton's interview.

Besides producing and understanding language, accurate milliseconds-to-second timing is also fundamental to perceiving and functionally interacting with the environment. On the perceptual side, for example, motion processing in both the visual (Johansson, 1976) and the tactile domain occurs within the milliseconds-to-second range. On the motor side, muscles coordination and control develop within tens of milliseconds as well (Diedrichsen et al., 2003; Ivry, 1996).

One of the fundamental questions related to temporal processing is whether it relies on a centralized, dedicated process or is encoded through different networks across the brain. On the one hand, if timing

perception processes are centralized, performing temporal judgments in the visual, auditory, or tactile modality would recruit the same group of neurons regardless of the sensory modality involved. The same group of neurons would be recruited when performing motor control and coordination, too. On the other hand, if temporal processing is a distributed mechanism, the brain would recruit different areas depending on the sensory modality and the task involved when evaluating temporal information. Thus, different networks would process timing in the visual, auditory, tactile, and motor domains.

Time perception as a centralized process

In the mid of the last century, Treisman (Treisman, 1963) theorized the existence of a centralized, internal clock, supporting the notion of dedicated timing processes involved in temporal perception. The term *internal clock* refers to a hypothetic neural mechanism in which a pacemaker emits a series of pulses, through which it is possible to estimate time events. When an interval is to be calculated, the interval's onset activates a trigger switch so that the counting process begins: an accumulator stores the pulses emitted by the pacemaker, and the duration of the interval is then estimated using the total number of pulses. Interestingly, Wearden and colleagues demonstrated that the behaviour of both the switch and the pacemaker can significantly vary depending on the sensory modality involved, and that the two effects are separable (Wearden et al., 1998). As a consequence, for example, auditory stimuli are judged longer than lights of equal durations (Wearden et al., 1998), a trend that is constant across development (Droit-Volet et al., 2004). More recently, some authors proposed the existence of a separated pacemaker for each sensory modality (Gamache & Grondin, 2010; Haß et al., 2008), a view that has been then supported by behavioral evidence (Indraccolo et al., 2016). Each of these pacemakers emits pulses at specific frequencies, and these frequencies are then modulated by sensory events occurring within the same sensory modality (Kanai et al., 2006). Nonetheless, within the proposed view the trigger switch and the counting processes are still developed within a central hub. Even though there is still scarce physiological evidence for a clock-like counter in the human brain, it has been suggested that both the pacemaker and the accumulator might be linked to cerebral oscillations (Treisman, 1984; Treisman et al., 1990, 1994).

The notion that a common, centralized mechanism regulates time perception has been supported by various research, such as the ones in which temporal perceptual learning occurred. In an elegant study, Karmarkar and Buonomano trained participants for 10 days using a 100 ms temporal interval delimited by two 1 kHz tones. At the end of the training, the author found that the improvement in performance extended to 100 ms intervals delimited by 3.75 kHz tones and 1 kHz sounds lasting 100 ms. However, the training effect did not generalize to 200 ms, 1 kHz sounds delimited intervals. They concluded that the benefit of temporal

training using a specific interval generalizes to perceptually distinct stimuli (Karmarkar & Buonomano, 2003) but does not generalize across untrained intervals.

A similar generalization has also been found in the somatosensory modality. Nagarajan and colleagues trained participants using a temporal interval discrimination task for 10-15 days (Nagarajan et al., 1998). Each interval was delimited by sinusoidal vibrotactile stimulation presented either at the thenar eminence or at the middle or ring finger's distal tip. At the end of the training, the authors found that temporal improvements generalized to different skin portions of the trained hand and corresponding untrained skin location in the untrained hand. Furthermore, temporal perceptual improvements were also found when testing participants using a comparable interval discrimination task in the auditory modality. Thus, temporal perceptual learning generalized across different skin portions (within modality) and across different senses (between modalities). Interestingly, it has also been found that the effect of temporal perceptual learning generalizes to the motor domain, as learning to discriminate auditory intervals determines a consequent improvement in motor timing (Meegan et al., 2000). As the benefit of temporal perceptual learning generalizes not only between perceptually distinct stimuli within the same modality (Karmarkar & Buonomano, 2003) but also between different sensory modalities (Nagarajan et al., 1998), as well as to the motor domain (Meegan et al., 2000), temporal processing appears to develop across the same neural circuitry.

Another perceptual phenomenon that has been used to test the validity of a centralized timing framework is the central tendency effect (also known as 'regression to the mean'). The central tendency effect in temporal processing refers to the observation that, when presenting a series of different temporal intervals, the resultant perceived duration of each of them is regressed towards the mean of the various presentations (Murai & Yotsumoto, 2016). In their work, Murai and Yotsumoto (2016) investigated temporal central tendency effects in the visual and auditory modality, using both sub- and supra-second interval timing. They found that, when asked to reproduce sub-second intervals, temporal reproduction resulted significantly more regressed towards the mean for the visual rather than the auditory modality. Conversely, in the supra-second condition regressions towards the mean resulted in comparable magnitude between sensory modalities. A similar pattern of results was also found after testing participants using a temporal interval discrimination task, as larger central tendency effects were highlighted for intervals delimited by visual signals rather than for intervals delimited by sounds. The authors then concluded that these results support the existence of two separated timing mechanisms in the human brain. Specifically, they suggested that modality-independent and centralized timing mechanisms determine the central tendency effect in the supra-second range. The central tendency effect in the sub-second range, however, is better explained by the combined inference of modality-dependent and a-modal timing mechanisms (Murai & Yotsumoto,

2016). These results partially clash with the idea that time is a centralized process, exclusively developed within a single neural network. Unsurprisingly, many studies started to query the notion of a centralized hub involved in timing processing, favoring the conceptualization of a more distributed, widespread series of cerebral mechanisms.

Time perception as a distributed mechanism

In recent years, many evidence has significantly challenged the notion of a centralized timing mechanism, including those collected using sensory adaptation. Prolonged exposure to a repeated stimulus (adaptation) coherently shifts the perception of a subsequent stimulus away from the adaptor itself (perceptual aftereffect). Using the main peculiarity of sensory adaptation, in a compelling study Johnston and colleagues elicited spatially localized distortions of visual time events (Johnston et al., 2006). They found that adaptation to fast translational motion (i.e., the motion pattern in which all points of a moving percept move uniformly following the same line or direction) induces significant distortions of the perceived duration of a subsequently displayed stimulus, so that it is perceived as shorter in time. These temporal aftereffects are tied to the adapted region of the space (Burr et al., 2007, 2011), as they appear to be developed along with coordinates anchored to the real-world (i.e., spatiotopic coordinates) rather than coordinates based on the image reflected on the retina (i.e., retinotopic coordinates). Notably, only translational motion elicited spatially selective duration distortions, whereas circular or radial motion, as well as image sectors moving in orthogonal or opposing directions, did not change the perceived duration of the subsequently presented stimulus (Fornaciai et al., 2016). Duration aftereffects can be similarly elicited in the tactile domain (Watanabe et al., 2010), even though active movement between the adapting and the judgment phases appears to cancel them (Tomassini et al., 2012). These results significantly advocated against the existence of a centralized timing mechanism. Remarkably, the spatial selectivity of adaptation (i.e., the tendency to distort time in a specific part of space) is the crucial element challenging the idea that one single internal clock subtends temporal processing. In light of the results discussed, a more plausible speculation is that multiple clocks, selectively modulated by sensory history, characterize temporal processing in the brain.

In a more recent study, Anobile and colleagues used motor adaptation to elicit spatially localized temporal distortions in the visual modality (Anobile et al., 2020). In their study, the authors induced motor adaptation aftereffects by asking participants to tap mid-air with their index finger under the monitor placed horizontally in front of them. After adaptation, a visual drifting grating was displayed around the same spatial position in which motor adaptation occurred, and participants had to judge its duration by comparing it with the duration of a similar grating displayed in an unadapted spatial position. The authors found that adapting to high-frequency tapping (~ 7 Hz) determined an underestimation of the subsequent visual

stimulus duration, in line with the results obtained using uni-sensory stimulation (Ayhan et al., 2009; Burr et al., 2007; Johnston, 2012; Johnston et al., 2006). Again, this result adds evidence for the existence of multiple clocks that operate at the uni-sensory level and – at least – at the visuomotor level.

On a final note, evidence suggesting that different non-specific factors can modulate time perception is also conflicting with the idea of a centralized time processing mechanism. For example, Rammsayer and Lima demonstrated that temporal discrimination abilities are finer when stimuli are continuous tones rather than empty intervals delimited by sounds (Rammsayer & Lima, 1991). In their work, the authors presented to the participants a series of stimuli to be temporally discriminated against. Stimuli were either 1 kHz sounds lasting 50 ms or 50 ms empty interval delimited by 3 ms clicks. Indeed, observed performance was significantly better for the first type of stimuli than for the second one. According to the authors' conclusions, temporal encoding is highly dependent on perceptual processing, as it appears to be more specialized in finely estimating the duration of filled intervals rather than empty ones. Interestingly, these results are further supported by evidence suggesting that tones are processed more efficiently than clicks and that this difference build-up at a low level of information processing, beyond cognitive control (Klump & Eady, 1956).

Temporal Processing and Sensory Representations

Recently, Shi and Burr proposed that timing perception consolidates from a combination of adaptive recalibration and minimized predictive errors, suggesting that our sense of time emerges from various inferences of available sensory signals (Shi & Burr, 2016). This view is strengthened by the consideration that no specific region of the brain solely dedicated to temporal perception has been found yet, and that all sensory signals contain fundamental temporal cues, regardless of the modality involved. Thereby, temporal processing might differ across sensory modalities due to the heterogeneous ways in which sensory stimulations are encoded and decoded. Notably, this conceptualization utterly challenges the notion of a centralized temporal hub proposed by pacemaker-accumulator models and intrinsically determines a temporal processing hierarchy where some sensory systems are temporally more accurate and precise than others. A similar conceptualization was already developed within the *Modality Appropriateness Hypothesis* (Welch & Warren, 1980), a theory positing that, in front of multi-modal stimulations, the more reliable sensory system for the encoded features has a dominant role in determining the perceptual outcome. For instance, vision often dominates bi-modal audiovisual spatial localization as it shows a higher spatial acuity when compared to the auditory system. The theoretical interpretations of Shi and Burr, as well as the *Modality Appropriateness Hypothesis*, are supported by strong pieces of evidence that will be further discussed in the following section.

For example, Grondin and Rousseau demonstrated that interval timing worsens when inter-modal, rather than intra-modal, temporal intervals are displayed (Grondin & Rousseau, 1991). Again, a similar pattern of results is inconsistent with the idea that temporal processing occurs in a specific, supra-modal area, nor that a centralized neural network encodes time regardless of the stimulations' features. Instead, the authors assumed the existence of two different timekeeping processes: one exclusively related to a given sensory modality, which might be determined by the specific peculiarities of each sensory system, and one a-specific, through which intermodal temporal discrimination is performed. Thereby, temporal processing is tied to the perceptual properties of the stimuli to be processed, as the efficient encoding and decoding of a given interval depend on various aspects, such as its temporal context (Jazayeri & Shadlen, 2010; Jovanovic & Mamassian, 2020; Mamassian & Landy, 2010; Murai & Yotsumoto, 2016) and the sensory modality in which the interval is conveyed (Murai & Yotsumoto, 2016). Interestingly, there is considerable evidence further supporting a hierarchical distribution of temporal abilities, indicating that auditory is the most reliable sense to process temporal information and vision is the less reliable one. In line with the *Modality Appropriateness Hypothesis*, whenever multi-modal temporally conflicting events are displayed the human's brain should prioritize hearing, as is the most reliable sense in perceiving temporal patterns, and significantly orient the perceptual outcome towards the auditory information available.

Unsurprisingly, Recanzone evaluated the interaction of auditory and visual stimuli in a sequence discrimination task (Recanzone, 2003). During the procedure, sequences of visual flashes were either presented alone or concurrently with an auditory distractor (sequences of 1 kHz tones or broadband Gaussian noise). Interestingly, it was found that the presence of the auditory distractor significantly changes temporal rate perception, leading to better performance. Surprisingly, the effect was so significant that, when comparing two identical visual sequences accompanied by two different auditory distractors, participants consistently gave their responses prioritizing the auditory information available. The results obtained in this study showed how the auditory system strongly influenced visual temporal rate perception and was consistent with the notion that, in a perceptually conflicting situation, the perceptual system whose reliability is higher dominates the conflict.

In another study, Burr, Banks, and Morrone quantitatively measured the auditory dominance over vision when performing temporal judgments by assessing performance in a temporal bisection task (Burr et al., 2009). In a temporal bisection task, three stimuli are displayed to participants, with the second one being either closer in time to the first or the third. The task is to report whether the second stimulus appeared earlier or later than the temporal midpoint between the two other stimuli. Creating a bi-modal conflict between the stimuli involved in the bisection task (i.e., temporally misaligning the auditory and the visual components of each stimulus), the authors tested the sensory dominance of one of the modalities over the

other. The result of the study showed that temporal judgments were strongly influenced by auditory cues, and that the final temporal judgment was far more determined by the temporal position of the auditory stimulations rather than by the temporal occurrence of the visual stimulations.

The auditory dominance over visual information in temporal processing has also been highlighted in similar studies (Chen & Yeh, 2009; Klink et al., 2011). However, one of the most exciting results has been obtained by McGovern and colleagues, who assessed auditory dominance in the temporal domain by using a perceptual learning protocol (McGovern et al., 2016). In their elegant study, McGovern and colleagues developed four different learning protocols, in which experimental tasks consisted of discrimination judgments either in the spatial or in the temporal domain, that could be performed using either visual or auditory cues. Participants were randomly assigned to one of the four possible protocols, and after five days of training, the generalization of the training's effects was tested. Interestingly, some generalizations occurred but were limited to significantly specific constraints. For what concerns the temporal task, specifically, improvement in the auditory modality transfer to the visual modality, i.e., training for five days using sound-delimited intervals determined an improvement in temporal performance when using flash-delimited intervals. However, the corresponding training effect was not observed. When trained using flash-delimited temporal intervals, participants improved performance only in the trained modality, and the training effect did not generalize to the auditory modality.

Evidence supporting the auditory dominance on temporal judgments has also been demonstrated using the *Transcranial Magnetic Stimulation* (TMS) technique. Using TMS, Kanai and colleagues (Kanai et al., 2011) found that the disruption of the primary visual cortex impairs temporal processing in the visual modality but not in the auditory modality. However, disruption of the primary auditory cortex impairs temporal perception in both the auditory and the visual modality, suggesting that the contribution of cerebral areas mainly assigned to auditory processing is fundamental to encoding temporal information properly.

Even though a significant body of evidence has attested temporal auditory dominance, few studies suggest that auditory cues might not always drive cross-modal temporal judgments. In an interesting study (van Wassenhove et al., 2008), Van Wassenhove and colleagues tested temporal perception in the auditory and visual domain using looming stimuli (i.e., stimuli that mimic an object approaching the observer). This kind of stimuli has an inherent evolutionary value (Franconeri & Simons, 2003), and a marked preference for them is already present at birth (Orioli et al., 2018). What was found by the authors is a subjective time dilation associated with visual stimuli increasing in size and auditory stimuli increasing in frequency. Time dilations were consistently found in auditory, visual, and audio-visual presentations. The authors also found that, in audio-visual presentations, the visual input significantly influenced the temporal perception of the concomitantly delivered auditory signal. On the other hand, the auditory inputs did not affect the perceived

duration of the concomitant visual signal, a pattern of results substantially in disagreement with the *Modality Appropriateness Hypothesis*. Interestingly, Sgouramani and colleagues (Sgouramani et al., 2020) found instead that the duration of displays of looming biological motion was overestimated when paired with congruent (or neutral) auditory signals, but not when auditory information was incongruent or was not available.

Most of the evidence shown in this introductory paragraph suggests that temporal information might be encoded and decoded on a sensory modality dependant rather than a-modal basis. Furthermore, little to no evidence supports the notion that time perception mechanisms are centrally distributed within the human brain. Temporal processing appears to be also hierarchically organized across different senses, as the most precise sense dominates the others. Indeed, there is strong evidence supporting the auditory dominance over vision when processing sensory information (Burr et al., 2009; Chen & Yeh, 2009; Klink et al., 2011; Recanzone, 2003), even though somatosensory timing is not considered in the equation as much as the other two. The tactile modality could be considered the ‘intermediate’ sense for temporal processing (Welch & Warren, 1980). This speculation seems to find support considering some empirical findings. First, temporal perceptual learning generalizes from touch to hearing (Nagarajan et al., 1998), but it does not from vision to hearing (McGovern et al., 2016). Second, the physiological interconnection between hearing and touch (Bolognini et al., 2010; Yau et al., 2009) is far more developed than the one between vision and hearing.

As stated by Shi and Burr (Shi & Burr, 2016) and reported at the beginning of this section, it is plausible to assume that temporal perception is built using different sensory inferences made available by the environment, where temporal inter-sensory differences emerge from the different processing mechanisms underlying them. Time is thus best evaluated using the auditory system, while the vision shows the lowest temporal precision among all sensory modalities, with the somatosensory performing somewhere between the two. Considering the significant interconnection between temporal perception and sensory processing, an interesting question is how early sensory experience determines our ability to tell time, and to what extent early abnormal sensory processing shapes how we perceive temporal information. In the next paragraph, both these contingencies are discussed.

1.2 Early Auditory Experience and Temporal Processing

1.2.1 The Cross-sensory Calibration Theory

In paragraph 1.1, we asserted auditory dominance over other senses when processing temporal information. Nonetheless, the role of auditory experience in developing a proper sense of time is still an interesting

aspect to consider, as well as how abnormal hearing processing might impact the human's ability to perceive temporal information across the whole life.

A fascinating possibility is that, during development, the auditory system refines other senses' ability to process specific aspects of temporal information, reflecting cross-modal calibration processes through which temporal perception in the visual and tactile modalities are fine-tuned by auditory processing. Consequently, hearing deterioration during the early stages of development should not allow other senses to benefit from the auditory experience and, thereby, create efficient sensory-specific timing mechanisms. In other words, vision and touch can learn from audition how to perceive time, and this calibration process must occur during the early stages of life. If hearing disruption occurs within the critical period, the proper development of temporal perception is compromised. Evidence supporting this speculation can be found both from studies involving multisensory integration during development and from studies in populations with specific hearing disabilities occurring at critical, early stages of life, such as congenital and early deaf (obviously) and dyslexic (intriguingly) individuals.

In a pioneering work by Ernst and Banks, it was demonstrated that adults with typical development combine sensory information in a statistically optimal fashion (Ernst & Banks, 2002). When simultaneously looking and touching an object, both senses provide significant information for the object's properties estimation. In such a scenario, vision often dominates the integrated percept (Alais & Burr, 2004; Hay et al., 1965; Rock & Victor, 1964), even though, in some cases, the situation is reversed (Heller, 1983; Lederman & Abbott, 1981; Vroomen & De Gelder, 2004). In their work, the authors proposed that the integration of sensory cues coming from different sensory modalities in humans (i.e., multisensory integration) is comparable to a maximum-likelihood integrator, where the cue with the lower variance (i.e., the most reliable) determines sensory dominance. However, this ability to integrate multisensory information does not seem innate but develops over time. Indeed, young children do not integrate sensory cues from different modalities in a similar fashion. In a series of ground-breaking studies, many authors found that multisensory integration is lacking in children up to eight years of age, becoming statistically optimal only at around 10 years of age (Ernst, 2008; Gori et al., 2008, 2012; Nardini et al., 2008; Petrini et al., 2014). For example, Gori and colleagues demonstrated that the integration of visuotactile information in young children is either dominated by vision or touch, regardless of the cues' variance (Gori et al., 2008). In a conflicting situation, touch completely dominates over vision when evaluating the size of the stimulus. However, if the stimulus' orientation is to be judged, vision dominates over touch. The remarkable dominance of one sense over the others during childhood appears to reflect cross-sensory calibration mechanisms, whereupon the most reliable sense dominates and refines the others to preserve the accuracy of judgment.

Gori and colleagues (Gori et al., 2010) further underlied the relationship between sensory dominance (for a given perceptual feature) and the corresponding sensory deprivation, measuring haptic thresholds in sighted and congenitally visually impaired children. Interestingly, they found that haptic size thresholds in blind participants were as good as thresholds measured in sighted peers. However, haptic orientation thresholds were significantly impaired in blind individuals, whose dominant sense for orientation perception (i.e., vision) was lacking since birth. These results support the existence of cross-sensory calibration processes undergoing in the young brain, as when one dominant sense for a given feature is missing during critical, early stages of life, the other senses fail to calibrate themselves for that given feature. This impairment is present in young children and is also maintained in populations of adult individuals with sensory deprivation. In an elegant study, Gori and colleagues demonstrated that, when asking congenitally blind adults to spatially localize an auditory stimulus as closer in space to one of two auditory spatial anchors, performance was so poor that it almost reached a chance level (Gori et al., 2014). These results suggest that Euclidean auditory representations are impaired in congenitally blind participants and that vision is the dominant sense in building spatial representations of the environment. Further research confirmed this (Finocchietti et al., 2015; Vercillo et al., 2017, 2018).

Based on what was discussed in paragraph 1.1 and considering auditory dominance in temporal processing, when hearing is missing during the early stages of life time perception should be impaired in the preserved senses as well.

1.2.2 Temporal Perception in Deafness

To date, solid evidence supporting the disruption of the cross-sensory calibration process in congenital deafness has been highlighted by many studies. For example, Heming and Brown (Heming & Brown, 2005) investigated visual and tactile temporal sensitivity in both congenital deaf individuals and age-matched hearing participants. For the tactile procedure, stimuli were pairs of punctuations delivered at the index and middle fingers of either one or both hands, separated by a variable trail-by-trial interval. For the visual procedure, stimuli were pairs of lights separated by the same variable interval, displayed in different spatial positions across the visual apparatus. The task was to report whether the onsets of the two stimuli within a given pair were simultaneously perceived or not. What they found is that temporal sensitivity was lower in deaf participants compared to hearing controls, as higher temporal intervals within the pairs of stimuli were needed so that the onsets of the two stimuli were perceived as temporally misaligned. This effect was independent of the sensory modality involved and from the stimuli position, suggesting that temporal processing is overall impaired in deaf individuals.

Similar results were obtained by Kowalska and Szlag, which investigated temporal processing in a group of deaf adolescents (Kowalska & Szlag, 2006). In their work, the authors developed two different temporal estimation tasks: a production task, in which participants were asked to actively produce various time intervals (from 1 to 6 s), and a reproduction task, in which participants were asked to replicate the duration of a series of visual standards (from 1 to 5.5 s). Notably, deaf performance was significantly worse than the performance of hearing participants. Conversely to hearing peers, deaf adolescents showed optimal temporal processing only for intervals around 3 s, overestimating intervals shorter than 2 s, and overestimating intervals longer than 3 s. Nonetheless, considering that Kowalska and Szlag involved merely supra-second temporal intervals, they also concluded that the impact of deafness on temporal performance could be potentially explained by differences in the use of time units, as well as in cognitive processes recruited during the task, such as the working memory (Kowalska & Szlag, 2006).

Another interesting study supporting the cross-sensory calibration theory has been developed by Bolognini and colleagues (Bolognini et al., 2012). The authors found that congenitally deaf participants could correctly discriminate the spatial length of tactile stimulations delivered at their index fingers. However, they could not successfully discriminate the temporal duration of similar haptic stimuli delivered in the same skin portions (with stimuli being developed within the sub-second range, lasting either 15 or 25 ms). To deeper investigate the neural substrates underlying the observed temporal impairment, Bolognini and colleagues also performed a TMS experiment using the same behavioral paradigm. They found that in deaf participants the auditory association cortex was recruited when performing both temporal and spatial discrimination, with similar chronometry to the primary somatosensory cortex. In hearing participants, however, the recruitment of the auditory association cortex occurred only when performing temporal discrimination judgments, and at a later stage. Surprisingly, the different chronometry for the auditory association cortex in deaf correlated with the observed temporal impairment, suggesting that the ability to process hearing information during critical, early periods is fundamental to developing reliable temporal perception across different sensory modalities.

More recently, Zhang and colleagues also found evidence that the lack of hearing experience impacts general temporal processing (Zhang et al., 2020). The authors tested congenitally deaf young adults and age-matched hearing participants using a temporal bisection task in the sub-second range, a paradigm already discussed in the previous section. Interestingly, Zhang and colleagues found that temporal sensitivity was significantly lower in deaf rather than in hearing participants. Furthermore, deaf participants also showed a strong bias towards lower intervals, as their bisection point was notably lower than the physical midpoint between the two anchors. These results suggest that early hearing loss impairs visual

sub-second interval timing, further supporting the disruption of cross-sensory mechanisms leading to inefficient temporal processing.

One other piece of evidence in supporting the impact of congenital and early deafness on temporal processing (and, in the broader sense, the disruption of cross-sensory calibration processes) has been given by two studies investigating how different cues are encoded when one sense is missing (e.g., vision) rather than the other (e.g., audition). Blind individuals show critical impairments when creating and utilizing auditory spatial maps (Gori et al., 2014), to the point that completing an auditory spatial metric task becomes incredibly difficult. However, if spatial cues are displayed with coherent, informative temporal cues, the impairments disappear (Gori et al., 2018). Similarly, significant temporal impairments have been highlighted in deaf participants when asked to perform a task requiring the development of a reliable, internal temporal metric (Amadeo et al., 2019). Still, when coherent temporal and spatial cues are simultaneously displayed, deaf participants' performances improve critically. These results combined suggest that blind and deaf individuals show crucial deterioration of the ability to build functional, internal representations of space and time, respectively. However, when additional, congruent information is available, both can use this redundant information to infer the internal metric which is impaired due to the lack of the corresponding, early sensory experience.

It should be noted, however, that there is also some evidence not supporting the cross-modal calibration theory, in which the temporal performance of deaf participants was found to be similar to the one of hearing peers (Mills, 1985; Nava et al., 2008; Poizner & Tallal, 1987).

Mills, for example, tested hearing and congenitally deaf young adults using a series of visual temporal patterns (Mills, 1985). During the procedure, pairs of visual temporal patterns were displayed to participants. Visual patterns were sequences of stimuli spatially displaced on the monitor that appeared at different rates depending on the pattern itself. The position of the stimuli was kept constant, while the timing of appearance changes as a function of the pattern's structure itself. When asked to compare pairs of patterns, deaf and hearing participants reached similar levels of performance, showing that for both groups the task was easier for hierarchically simpler pattern and far more difficult for more complex ones.

Furthermore, Poizner and Tallal (Poizner & Tallal, 1987) performed four different experiments to evaluate temporal perceptual abilities in congenitally deaf individuals. In the first and second experiments, the authors evaluated flicker fusion thresholds for a single circle displayed at different frequencies, or for two circles sequentially displayed with a variable inter-stimulus interval. In the third experiment, participants were tested using a temporal order judgment (TOJ) task for visual stimuli displayed either in pairs or in triplets. In a standard TOJ task, participants are asked which one of two stimuli briefly displayed, separated

by a given asynchrony, occurred first. Interestingly, deaf and hearing participants performed similarly in all tasks, suggesting that temporal processing might not be impaired in the visual domain after early hearing loss. A similar behavioral pattern was also found by Nava and colleagues (Nava et al., 2008), which used a TOJ paradigm to display stimuli both in central and peripheral visual field sectors.

Given the fragmented nature of the pieces of evidence around deafness and time perception, it is hard to ensure that congenital and early hearing loss leads to a generalized, supra-modal impairment in temporal processing. Some studies suggest that congenital and early deaf individuals perform as good as hearing participants when processing temporal information (Mills, 1985; Nava et al., 2008; Poizner & Tallal, 1987), while others support the specular position (Amadeo et al., 2019; Bolognini et al., 2012; Heming & Brown, 2005; Kowalska & Szelag, 2006; Sterritt et al., 1966; Zhang et al., 2020). Nonetheless, the cross-sensory calibration theory is a prolific framework through which shedding light on the topic. Expectations are that cross-sensory mechanisms will be powerful tools in expanding our knowledge about how temporal representations are refined and shaped within the brain, specifically in combination with the absence of auditory processing at critical, early stages of life.

1.2.3 Temporal Perception in Developmental Dyslexia

Until the mid of the 20th century, *Developmental Dyslexia* (DD) was considered a hereditary deficit selectively compromising the visual processing of words, without impacting oral language and non-verbal reasoning skills (Stein, 2018). In the 1950s, however, the notion of DD was twisted by the introduction of Chomsky's principles of "generative phonology" (Chomsky, 1956), and the idea that DD was a pure visual deficit was abandoned in favor of new, theoretical frameworks centered around the acquisition of phonological skills (Liberman, 1982).

The phonological theory of DD suggests that dyslexic individuals fail to acquire the ability to separate a word's sound to match its corresponding grapheme (a process known as *phonemic awareness*). Notably, the successful acquisition of phonemic awareness in children is a powerful predictor of future linguistic and reading expertise (Bradley & Bryant, 1983), and its failed mastery in DD has been associated with abnormalities in the left hemisphere language network (Hampson et al., 2006; Xia et al., 2016). Despite its relevance and its overall diffused acceptance, however, the phonological theory cannot be considered exhaustive. Specifically, the phonological framework does not precisely explain why Dyslexic children fail to acquire phonological skills, as well as what are the pathophysiological processes at the basis of this failure (Stein, 2018).

A fascinating, complementary view has been proposed considering perceptual, rather than phonological, deficits associated with DD. Interestingly, it has been suggested that both a slow recognition of letters and

the impaired ability to sequence their order and sounds might arise from a primary disruption of temporal processing (Stein, 2018), a view that is also coherent with the *magnocellular theory of dyslexia* (Stein, 2001, 2019; Stein & Walsh, 1997) that is introduced at the end of the paragraph.

Considering these premises, the cross-modal calibration theory appears to be an adequate theoretical framework through which conceptualize temporal processing impairments found in individuals with DD. Interestingly, referring to cross-modal calibration mechanisms does not necessarily challenge the magnocellular theory of dyslexia (Stein, 2001, 2019; Stein & Walsh, 1997), which is further discussed across this thesis, but instead might represent a complementary, intertwined explanation to understand its perceptual implications. Indeed, there is a significant body of evidence suggesting that individuals with DD experience abnormal auditory processing, which might be the basis of a more generalized temporal impairment following the cross-sensory calibration theory. Note that some authors proposed that the auditory temporal processing deficits in DD might also be the basis of the phonological processing impairment (Farmer & Klein, 1995; Tallal & Gaab, 2006).

Numerous studies have highlighted abnormal auditory processing in individuals with DD. For example, Halliday and Bishop demonstrated that children with DD showed poorer performances in discriminating the frequency of two sounds than normal-reading peers (Halliday & Bishop, 2006). Interestingly, the higher frequency discrimination thresholds showed by children with DD were independent of their comprehension language abilities and the richness of their vocabulary. Hill and colleagues obtained similar results, testing auditory frequency discrimination abilities in children with and without DD. The authors found that children with DD had higher thresholds during the first round of evaluation and that – albeit slightly improving – they still performed worse than normal-reading peers during the final evaluation, 42 months after the beginning of the study (Hill et al., 2005). Higher frequency thresholds in individuals with DD were found by a significant amount of other studies, suggesting that auditory frequency discrimination is significantly impaired in DD (Banai & Ahissar, 2004; Boets et al., 2007; Dawes et al., 2009; McAnally & Stein, 1996; McArthur et al., 2008; Ramus et al., 2003; Witton et al., 2002; Wright & Conlon, 2009).

Different auditory processing in DD has also been found when considering amplitude discrimination capabilities. In an interesting work, Menell and colleagues demonstrated that adult dyslexic listeners had higher amplitude discrimination thresholds than age-matched control participants (Menell et al., 1999). Moreover, the authors also recorded the evoked scalp potential related to various amplitude-modulated white noise stimuli involved in their study, highlighting that participants with DD showed reduced amplitude modulation following responses compared to normal-reading participants. This reduced scalp activity was consistent with the observed reduced sensitivity to amplitude modulations. Similar behavioral differences between DD individuals and normal-reading peers were also found by subsequent research,

further supporting Menell and colleagues' results and confirming that auditory amplitude discrimination is significantly impaired in individuals with DD (Rocheron et al., 2002; Witton et al., 2002). On a side note, an exciting study by Bishop-Liebler and colleagues showed that long-term trained musicians with DD experience no auditory processing deficits, suggesting that early extensive rhythmic experience might enhance basic auditory processing in individuals with DD (Bishop-Liebler et al., 2014).

In line with the cross-calibration theory discussed in paragraph 1.2.1, impaired hearing processing during the early stages of life negatively impact one's ability to precisely encode time information in the preserved senses. Notably, evidence of a generalized, supra-modal temporal deficit in DD has also been underlined by various research. For example, Hari and colleagues demonstrated that individuals with DD experience a left-right asymmetry in a visual TOJ (Hari et al., 2001), performing worse than normal-reading participants when the first stimulus is displayed in the left hemifield and the second one in the right hemifield. Jaśkowski and Rusiak, however, partially failed to replicate these results (Jaśkowski & Rusiak, 2008) as they found that dyslexics' performance was overall worse than controls, both when stimuli were horizontally (orders of appearance: left-right, right-left) and vertically (orders of appearance: up-down, down-up) displaced. These findings suggest that individuals with DD might have a complex temporal order discrimination problem that is generalized across the visual field rather than sector-based and functionally tied to the stimuli's spatial location.

In a more recent study, Casini and colleagues used three different tasks to evaluate time perception abilities in children with and without DD (Casini et al., 2018). The three tasks involved required both implicit (first task, word identification) and explicit (second and third tasks, visual and auditory temporal bisection) temporal processing. Interestingly, the authors found that children with DD performed worse than control peers in all three experimental sessions. The temporal sensitivity of dyslexic participants was significantly lower than the temporal sensitivity measured in the control group, suggesting that children with DD experience a profound temporal impairment that is generalized between the visual and the auditory modality.

Similar results were obtained by Gori and colleagues (Gori et al., 2020), who tested children with DD using a temporal bisection task involving both the auditory and the visual modality. As highlighted by the authors' results, dyslexic children showed worse temporal performance than control participants when stimuli were displayed using only one modality (either hearing or vision). Surprisingly, dyslexic children also showed optimal multisensory integration when the task involved both sensory modalities at the same time, suggesting that temporal deficits in DD might be related to a selective impairment of uni-modal inputs rather than due to compromised multisensory processing.

In another compelling study, Johnston and colleagues (Johnston et al., 2008) demonstrated that adapting to invisible flickers fails to distort the perceived duration of a subsequent visual stimulus in dyslexic participants while consistently affecting temporal processing in control participants. Nevertheless, sensory adaptation to visible flickers at various frequencies determined spatially localized temporal distortions in both groups, similar to what has already been observed in previous works (Ayhan et al., 2009; Burr et al., 2007; Johnston et al., 2006). The authors concluded that the absence of adaptation responses to invisible flickers observed in participants with DD could be related to dysfunctions at the early, pre-cortical stages of the magnocellular pathway, and are the attestation of irregular cortico-thalamic synaptic communication. The impact of magnocellular dysfunction in individuals with DD has also been highlighted involving slower sequencing and letter reading abilities as well (Howard et al., 2006; Ozernov-Palchik et al., 2017).

Further evidence considering the role of magnocellular stems in developing the DD phenomenology was found in pathophysiological studies. After post-mortem histological investigation of the Lateral Geniculate Nucleus (Galaburda & Livingstone, 1993; Livingstone et al., 1991), abnormal cell morphology and atypical inner layer distribution were highlighted in the dyslexic brain. These findings were then confirmed in vivo using modern neuroimaging techniques (Giraldo-Chica et al., 2015; Müller-Axt et al., 2017).

Concerning temporal processing impairments, magnocellular neurons are fundamental for sensory representation of transient events and are crucial to perceiving rapid changes (i.e., temporal) information (Levitt et al., 2001; P. H. Schiller & Malpeli, 1977). Since temporal deficits in individuals with DD appear to be generalized across senses rather than modality-specific, it is essential to consider that magnocellular type cells have also been found in the medial geniculate nucleus (MGN), which is part of the auditory thalamus (E. L. Bartlett, 2013; Winer, 1984). Notably, post-mortem histological analyses in individuals with DD also highlighted a reduced cellular volume at the MGN level (Galaburda et al., 1994). Significant evidence underlining the role of the MGN in auditory temporal discrimination has also been made available by animal models (Galaburda et al., 2006). Interestingly, magnocellular-like neurons specifically tuned to temporally code transient events have been found in all remaining sensory modalities as well, showing that, at the pre-cortical level, magnocellular cells encode temporal information in the somatosensory and motor domains, too (Fawcett et al., 1996; Hendry et al., 1988; Nicolson et al., 1995).

In summary, networks of magnocellular cells might mediate temporal processing in humans and are sparse throughout the whole brain, as they have been found in the visual, auditory, somatosensory, and motor systems. As all magnocellular cells express a particular set of surface antigens, such as CAT 301, it is plausible to assume that they all derive from the same lineage (Hendry et al., 1988). This type of cell is genetically vulnerable and prone to be damaged during the early stages of life, especially by abnormal sensory experience (Guimarães et al., 1990). Lastly, as their development is mediated by the same

histocompatibility genes that set up their surface signatures (Corriveau et al., 1998), this cell type is particularly vulnerable to autoimmune reactions. This might partially explain the abnormal development of magnocellular cells within the DD phenotype.

According to the magnocellular theory of dyslexia (Stein, 2001, 2018, 2019; Stein & Walsh, 1997), DD is thus considered to be characterized by inefficient temporal processing, as well as the deterioration of visual and auditory sequencing. These perceptual impairments are determined by abnormal development of the magnocellular systems across the brain, which convey transient-specific information and are particularly sensitive to changes across time. In recent years, many facets have been related to the impairment of magnocellular cells in DD, such as genetics (Galaburda et al., 2006; Paracchini et al., 2006), immunological (Hugdahl et al., 1990; Vincent et al., 2002), and nutritional (Horrocks & Farooqui, 2004; Wall et al., 2010) factors. To date, however, insufficient attention has been drawn to the potential influence of hearing impairments exhibited by individuals with DD, and to the potential role of cross-sensory calibration mechanisms during early development. Considering their susceptibility, magnocellular cells might suffer from perceptual impairments occurring during growth. Intuitively, impairments in auditory processing observed in DD might play a key role in developing such generalized, supra-modal temporal deficits, specifically targeting magnocellular functioning and following the principles of the cross-sensory calibration theory.

In light of this brief review of the evidence at our disposal, to better underlie the effect of DD on temporal processing one can quote the words of John Stein, thus redefining DD as a “temporal processing defect, associated with impaired magnocellular neuronal development, that impacts selectively on the ability to learn to read, leaving oral and non-verbal reasoning powers intact” (Stein, 2018).

1.3 Objective of the Thesis

In these prefatory remarks, a series of conflicting pieces of evidence have been conveyed on how the brain encodes and decodes temporal information. The long-lasting debate on whether temporal processing is a centralized and supra-modal mechanism rather than distributed and sensory-specific is still open. Nonetheless, a significant body of research supports the notion that temporal perception is mediated by various spatially localized (Ayhan et al., 2009; Burr et al., 2007; Johnston et al., 2006) and sensory-driven (Shi & Burr, 2016) networks. Considering that sensory modalities process information in different fashions (Welch & Warren, 1980), the theoretical implication of such a view is that temporal processing is hierarchically organized: hearing is the more accurate and precise modality to encode temporal cues, followed by touch and, finally, vision.

Notably, auditory processing is so relevant for the development of a proper sense of time that its absence (such as in congenital and early deafness) or its impairment (such as in DD) during critical, early stages of life might determine a significant, generalized reduction of temporal sensitivity across the preserved modalities. To date, only a few studies highlighted the efficacy of learning-induced improvements in crucial timing abilities in both scenarios (Bishop-Liebler et al., 2014; Vollmer & Beitel, 2011), suggesting that it is possible to enhance temporal processing even after long-term hearing impairment (Vollmer & Beitel, 2011). Whether temporal processing abilities are evaluated in research or rehabilitation settings, a proper estimation of time perception is an altogether invaluable tool. Even though the assessment of temporal skills can be every so often executed in a short-timed fashion, it involves expensive, over-performing setups whose specifics must be kept constant across experimental sessions. For this reason, a proper evaluation of temporal abilities is significantly bounded by the accessibility to research facilities in which those setups are held. Unquestionably, the COVID-19 outbreak strongly impacted such accessibility, slowing down data collections and learning protocol implementations on a broader scale. Due to the pandemic, since 2020 it has become overly challenging to collect experimental data in a consistent manner, especially in specific periods in which the infection peaked and the dropout risk increased. During the last few years various online platforms, such as Gorilla (Anwyl-Irvine et al., 2020), LIONESS Lab (Giamattei et al., 2020), and PsyToolkit (Stoet, 2017), became overly popular in research contexts, in that they aim at tackling the accessibility problem allowing remote data collection with customized scripts. These scripts can be sent to participants who can perform the experiment at home, sending back the results to researchers once the experimental protocol is completed.

While online platforms have been a powerful resource to collect responses to questionnaires and reaction times (Molnar, 2019; Zhong et al., 2020), they have been less than optimal when collecting psychophysical data (Anwyl-Irvine et al., 2021). Specifically, coding experiments around temporal processing and, on a broader scale, perceptual sensitivities need a homogeneous performance across different computers so that the characteristics of the stimuli involved are kept constant for all participants. Unfortunately, this is a condition that is virtually impossible to meet through online testing since each participant runs the code on its own, personal setup with a given combination of hardware and software specifics that might alter stimuli's properties, inducing uncontrolled biases within the procedure.

Given all these considerations, the aim of this thesis is twofold. Even though there is a solid theoretical background supporting the cross-modal calibration theory (Gori, 2015; Gori et al., 2010, 2012; Nardini et al., 2008; Petrini et al., 2014), suggesting that failure of cross-sensory calibration mechanisms might induce a temporally-specific generalized impairment, there is surprisingly lacking or conflicting evidence related to a potential link between temporal impairment in deaf and individuals with DD. Thereby, I firstly

investigated temporal processing in these two populations using classic psychophysical techniques. I developed two different behavioral tasks, explicitly designed to target visual temporal abilities, focusing on the magnocellular properties of temporal perception. Then, due to the COVID-19 pandemic and the consequent complications arising in data collection, I decided to face the accessibility problem. Therefore, the second part of this thesis focuses on conceptualizing and implementing a possible solution to overcome the recent delays in research activities. Ultimately I developed *PsySuite*, an Android App intended to set psychophysics to a cheap, portable, and easy-to-use level. I decided to implement psychophysical experimental protocols using smartphones as they match all the requirements listed above. I proceeded with the validation of *PsySuite* following a strict and diligent procedure, considering two different facets.

On the one hand, I performed a rigorous hardware validation, evaluating stimuli's characteristics (such as onset, offset, and duration) through a TDS 2014B Tektronix oscilloscope. Hardware validation was necessary to confirm that *PsySuite* delivered stimuli matched the experimenter's input parameters, as well as to avoid setup standardization issues similar to the ones that occurred via online testing. On the other hand, I also performed a behavioral validation, strictly aimed at testing whether psychophysical results obtained via classic PC-based setups could be replicated using smartphones. Lastly, I developed a *PsySuite* library specifically designed to test and enhance temporal sensitivity, and I evaluated its ability to determine temporal impairments in deaf and individuals with DD.

Chapter Two

Magnocellular Timing: a Bridge between Deafness and Developmental Dyslexia

Temporal processing within the human brain is plausibly a parcellated, distributed process, emerging from sensory inferences (Shi & Burr, 2016) and selectively affected by the perceptual features of the environment (Kanai et al., 2006; Roelofs & Zeeman, 1951; Terao et al., 2008). To convey temporal information, the brain must thus rely on neurons with fast response properties towards temporal transient events, specifically localized within each sensory system. Within the visual system, magnocellular neurons exhibit similar preferential properties, as they have diphasic impulse response functions befitting to monitor rapid visual changes while maintaining an adequate temporal resolution (Leonova et al., 2003; Levitt et al., 2001; Livingstone & Hubel, 1988), ideally to perceive temporal and motion information. Cells with similar transient properties are also present in the auditory system and are supposed to determine accurate sound sequencing (Stein, 2019). Interestingly, both transient-specific visual and auditory neurons express the same M-specific antibody, CAT 301 (Hendry et al., 1988), and magnocellular sensitivity in both sensory modalities correlates within the same individuals (Talcott et al., 2002), suggesting that visual and auditory magnocellular development undergo similar genetic restraints.

Furthermore, significant evidence supports the hypothesis that magnocellular neurons are susceptible to plastic changes due to experience (Tasker et al., 2002). It has been demonstrated, in fact, that magnocellular cells are heavily influenced by early abnormal experience (Guimarães et al., 1990; Sur et al., 1988), which can lead to significant molecular and morphological changes during neurophysiological development. Undeniably, abnormal hearing experience links both congenital and early deaf individuals with Developmental Dyslexia (DD). In deaf individuals, hearing is obviously missing. In individuals with DD, hearing processing is significantly flawed and, as already discussed in paragraph 1.2.3, impaired acoustic performances have been highlighted when considering both auditory frequency (Banai & Ahissar, 2004; Boets et al., 2007; Dawes et al., 2009; McAnally & Stein, 1996; McArthur et al., 2008; Ramus et al., 2003; Witton et al., 2002; Wright & Conlon, 2009) and amplitude discrimination (Menell et al., 1999; Rocheron

et al., 2002; Witton et al., 2002) capabilities. Considering the cross-sensory calibration theory (Gori et al., 2010, 2014) and that inefficient sensory information impairs calibration processes during early, critical stages of life, it is feasible to suppose that compromised temporal processing might arise after maladaptive plastic changes induced by absent or distorted hearing processing. Specifically, magnocellular cells are more likely to be the target of these maladaptive plastic changes, not only because they are the preferential channel through which temporal information is encoded (P. H. Schiller & Malpeli, 1977) but also due to their significant sensitivity to the disruption of early sensory processing (Guimarães et al., 1990; Sur et al., 1988; Tasker et al., 2002).

Despite temporal impairments highlighted in deafness and DD, only one study tried to directly fill the theoretical gap between magnocellular processing in these two conditions. In their enthralling work, Stevens and Neville (Stevens & Neville, 2006) investigated motion perception in early and congenital deaf participants, as well as in individuals with DD, by the use of an automated peripheral kinetic perimetry task. The task was to respond as quickly as possible to a light moving from the periphery toward the center of the visual field. The authors found that participants with DD experienced a reduced motion sensitivity, while deaf participants showed enhanced motion detection capabilities when compared to hearing, non-dyslexic participants. These results support the highly neuroplastic properties of the magnocellular neurons and highlight the possibility that sensory experience could significantly alter magnocellular information processing. Nonetheless, these results also keep open why temporal processing seems to be impaired in congenital and early deaf individuals and whether it is possible to add coherent motion information to help them develop an internal, veridical temporal metric. Conversely, a generalized magnocellular deficit should emerge when testing participants with DD using a task specifically involving magnocellular processing, with a specific impairment tailored around temporal perception.

2.1 Magnocellular Temporal Processing in Deafness

At the beginning of the '60s, Paul Fraisse asserted that "Hearing is the main organ through which we perceive change: it is considered the time sense" (Fraisse, 1963). As discussed in paragraph 1.1, many researchers found evidence supporting his conceptualization (Burr et al., 2009; Recanzone, 2003; Repp & Penel, 2002). Powerful insights onto how temporal processing is encoded within the brain also arise from studies investigating how the absence of early auditory experience negatively impacts time perception (Bolognini et al., 2012; Heming & Brown, 2005; Kowalska & Szelag, 2006; Pavani & Bottari, 2011; Zhang et al., 2020).

It is hard to outline a general conclusion on the role of early auditory experience in refining temporal processing, considering the fragmented results available in the literature. Nonetheless, evidence from

impaired cross-sensory calibration processes consolidates Fraisse's original theory, suggesting that hearing might be the sense specialized in encoding temporal information (Amadeo et al., 2019; Gori et al., 2012, 2017). Interestingly, an aspect rarely considered when evaluating temporal capabilities in congenital and early deafness is the role of dynamically displayed information: most of the studies investigating time perception in deafness involved static stimuli presented in a specific part of the visual field (Kowalska & Szelag, 2006; Mills, 1985; Mioni et al., 1998; Nava et al., 2008; Pavani & Bottari, 2011) or a localized portion of the skin (Bolognini et al., 2012). Such an approach offers little understanding of how temporal information in congenital and early deaf individuals is encoded in a more ecological setting, where space and time are often blended together. Furthermore, it gives no cognizance of how magnocellular processing impacts temporal evaluations, given that magnocellular cells undergo significant neuroplastic changes after early sensory loss (Guimarães et al., 1990; Stevens & Neville, 2006).

In light of these considerations, we decided to evaluate temporal processing in congenital and early deaf individuals within two different scenarios. In the first case, we investigated temporal sensitivity in deaf and hearing participants when only temporal cues were displayed. In the second case, we evaluated similar temporal abilities providing intermingled temporal and coherent, dynamically displaced spatial information, presenting stimuli that simultaneously moved across space and time. We hypothesize that, if the absence of early hearing experience generally alters temporal processing, deaf individuals should not successfully perform the task when relying on temporal cues alone. Conversely, as magnocellular processing is enhanced in congenital and early deaf individuals (Stevens & Neville, 2006), deaf participants should significantly benefit from the additional transient, spatiotemporal information when performing temporal judgments.

To this end, we tested participants using a visual temporal oddball-like task by replicating a paradigm used in previous research (van Wassenhove et al., 2008). Our choice was supported by the fact that this paradigm already proved to be effective in incorporating spatiotemporal cues when investigating temporal processing mechanisms. In the first experiment, we evaluated temporal processing in deaf and hearing participants by the sole use of temporal cues, displaying static stimuli during the whole procedure. In the second experiment, we manipulated the spatiotemporal dynamics of the presented stimuli, adding informative, coherent magnocellular cues such as those provided by motion patterns.

Participants

A total of 32 participants were recruited for this study, in line with previous, similar research (Amadeo et al., 2019; Bolognini et al., 2012; Kowalska & Szelag, 2006). 15 deaf (Age: $M=59.8$ y, $SD=14.45$ y) and 17 hearing (Age: $M=35.05$ y, $SD=13.81$ y) individuals were tested in the first experiment, while eight deaf and eight participants were tested in the second experiment.

Since participants were drawn from a small pool (as less than 1 per 1000 live births is born deaf in Italy (Bubbico et al., 2007)), sample size was heavily determined by resources constraints (i.e., availability of such participants). As stated by Lakens (Lakens, 2022), when resources are a limiting factors all reported effect sizes must be interpreted through a power sensitive analysis, to discuss statistically relevant findings as a function of the minimum effect detectable with the selected sample size. In Experiment 1, a total of 32 participants were tested (17 hearing and 15 deaf, see Table 2.2): considering $\alpha=0.05$, $1-\beta=0.8$, $n_1=17$, and $n_2=15$, the minimum effect detectable in a independent sample t-test is $d=0.9$ (one-tailed, in line with our experimental hypothesis), while we highlighted and discussed a difference between means of $d=0.91$. In Experiment 2, a total of 16 participants were tested (8 hearing and 8 deaf, see Table 2.2): considering $\alpha=0.05$, $1-\beta=0.8$, and $n=16$, the minimum effect detectable in an 2 x 2 ANOVA with two groups is $f=0.50$, while we highlighted and discussed a main effect of $f=0.6$ ($\eta^2_p=0.262$). Since in both experiments we observed statistical effects whose effect sizes were higher than the minimum effect size detectable with our

ID_Participant	Gender	Age (years)	Age of deafness detection	Hearing aid use	Age at first use hearing aid	Age at LIS learning
D01	F	64	Birth	No		15 years old
D02	M	73	Birth	No		5 years old
D03	F	69	1-2 years	No		30 years old
D04	F	57	1-2 years	No		12 years old
D05	F	38	Birth	Yes	5 years old	21 years old
D06	F	64	1-2 years	No		12 years old
D07	M	71	2-4 years	No		16 years old
D08	M	56	Birth	Unknown		Unknown
D09	F	28	3 years old	Past use	6 years old	6 years old
D10	F	58	Birth	Yes	5 years old	26 years old
D11	M	44	Birth	Yes	7 years old	5 years old
D12	M	75	4-7 years	No		7 years old
D13	F	69	Birth	No		4 years old
D14	F	52	Birth	Unknown		Unknown
D15	F	79	Birth	Unknown		Unknown

Table 2.1 Demographic information about deaf participants obtained via self-report questionnaires. Missing information was marked as ‘Unknown’.

sample sizes, we concluded that the number of participants was sufficient to support the interpretation of our results.

All deaf participants were signers and knew the Italian sign language (LIS) at the time of testing. All participants had normal or corrected-to-normal vision, and no participants in the control group had a history of neurological disease. All participants were naïve to the purpose of the study and gave informed consent prior the participation in the experimental procedure. Data collection was performed at the Istituto Italiano di Tecnologia, in Genova. Testing procedures were developed following Helsinki's declaration and were approved by the local ethical committee (Comitato Etico ASL3, Genova).

Demographic information for deaf participants, such as age of deafness detection, early hearing aid usage, and age at LIS learning, were collected via self-report questionnaires and are reported in Table 2.1, while participants' distribution across experiments is reported in Table 2.2.

<i>Experiment 1</i>				
<i>Group</i>	<i>n</i>	<i>Mean Age (years)</i>	<i>St. Dev Age (years)</i>	<i>Gender Distribution</i>
Deaf	15	59.8	14.45	5M, 10F
Hearing	17	35.06	13.81	6M, 12F
<i>Experiment 2</i>				
<i>Group</i>	<i>n</i>	<i>Mean Age (years)</i>	<i>St. Dev Age (years)</i>	<i>Gender Distribution</i>
Deaf	8	61.5	11.3	3M, 5F
Hearing	8	44.75	12.85	2M, 6F

Table 2.2 Sample size, age means, age standard deviations, and gender distributions of participants recruited in Experiment 1 and 2 respectively.

Apparatus and Stimuli

Stimuli were generated via Matlab v. 2019b through the Psychtoolbox routines and were displayed on a 24" Asus VG248QE LCD monitor with a resolution of 1920 x 1080 pixels and a refresh rate of 100 Hz. During the procedure, participants sat in a dimly lit room in front of the monitor, at a viewing distance of 57 cm. Task instruction for the hearing group was verbally given by the experimenter, while for the deaf group was given with the support of a LIS interpreter.

In both experiments, a sequence of five visual stimuli was presented at the center of the screen during each trial. Each sequence consisted of a Reference stimulus, repeated four times, and a Target stimulus displayed only once. The position of the Target stimulus within the sequence was fixed across all experimental

procedures, as it was always displayed as fourth, and participants were informed about the Target's position before the beginning of the experiment. This specific sequencing pattern avoided possible confounds on stimulus position (van Wassenhove et al., 2008). Furthermore, as the first stimulus of a sequence is often overestimated (Rose & Summers, 1995), presenting more than one Reference was a necessary expedient to give participants enough comparisons. There are also specific advantages in displaying stimuli following this pattern. Notably, oddball temporal estimation is highly dependent on attentional orienting and the unpredictability of the oddball itself (Schindel et al., 2011; Tse et al., 2004; Ulrich et al., 2006). Therefore, locking the Target's position within the sequence should minimize the effect of attentional orienting (van Wassenhove et al., 2008) and nullify Target's unpredictability. It is plausible to assume that temporal estimation in an oddball-like task involves low-level perceptual processes, which are targeted when evaluating the disruption of cross-sensory calibration mechanisms.

At the beginning of each experimental session, five training trials (subsequently discarded) were displayed to ensure that participants understood the task. In all training trials, the task was significantly simplified so that it was easy to determine whether task instructions were successfully recognized, as performance at ceiling level was expected. During the training phase, the experimenter and the LIS interpreter, when needed, supervised participants' behavior. At the end of the training, participants were asked whether the task was straightforward. Otherwise, a second explanation would have been given. Nonetheless, none of the participants required a second explanation since they all reached ceiling performance in the training session.

Experiment 1

A schematic representation of both Experiment 1 and 2 designs is reported in Figure 2.1. In Experiment 1, all stimuli displayed in the sequence were grey disks with a 2° visual angle diameter, presented against a black background. The duration of the Reference stimuli was fixed at 500 ms, while the duration of the Target – the fourth stimulus of the series – changed across trials, being one out of six possible durations (380, 450, 480, 520, 550, or 620 ms). The interval between the stimuli was randomized, ranging between 750 and 950 ms on a 25 ms step basis, to avoid participants relying on rhythmic cues to perform the task. At the end of each trial, participants had to indicate whether the Target lasted longer than the Reference stimuli, pressing a key on the keyboard. The subsequent trial started only when participants responded, so they did not have temporal constraints while performing the task. In the deaf group, each participant performed, on average, 51 trials, 18% of which were used as catch trials (as the Target lasted significantly less or more than the References) and not considered in the final analysis. Each participant performed on average 54 trials in the hearing group, 10% of which were used as catch trials and were not considered in the final analysis.

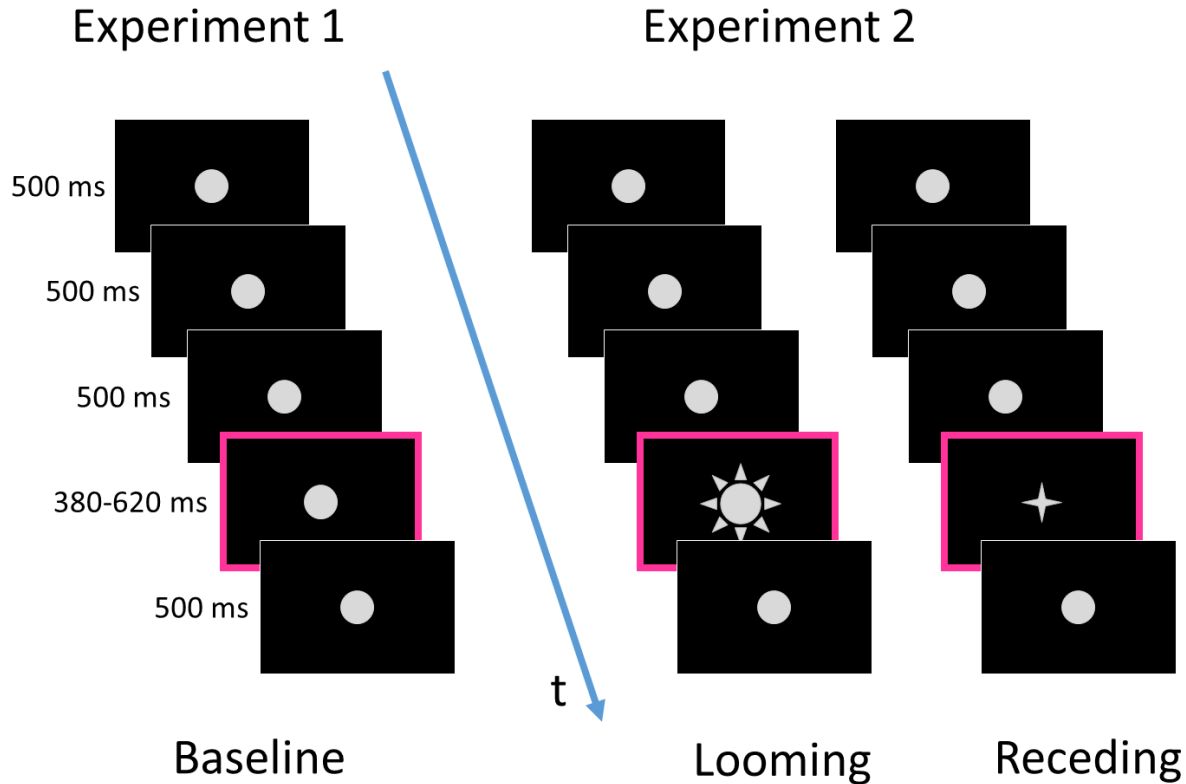


Figure 2.1 Experimental designs for the visual temporal oddball-like tasks.

Experimental designs for both Experiment 1 (left panel) and Experiment 2 (right panel). In both representations the Target stimulus, that was always the fourth of the sequence, is highlighted with the magenta frame.

Experiment 2

In Experiment 2, two different experimental protocols were developed. All experimental parameters (including Target's durations and the number of trials) were kept constant within both protocols, with the only exception being the Target stimulus that dynamically changed in size according to the experimental condition. In the *Looming* condition, the Target stimulus progressively expanded its diameter, increasing in visual angle size from 2 to 5°. In the *Receding* condition, the Target stimulus progressively reduced its diameter, decreasing in visual angle size from 5 to 2°. Both conditions were separately delivered so that the Target was either increasing or decreasing in size. The speed of increase/decrease was not constant across trials, as it was expressed as a function of the Target's duration. Therefore, when the Target lasted longer, the disk changed its size at a slower rate. From the longest to the shortest Target's duration, speeds of increase/decrease were as follows: 4.84, 5.45, 5.77, 6.25, 6.66, and 7.89 %/s.

The order of experiments and experimental conditions was counterbalanced for participants who took part in Experiments 1 and 2 to avoid learning interference. In fact, participants could either start with Experiment 1 or with any of the Experiment 2 conditions, then perform the remaining tasks in random order.

Data Analysis

To evaluate performance, we referred to the Signal Detection Theory (SDT) framework (Stanislaw & Todorov, 1999). In the last years, researchers successfully used SDT to describe sensory information processing when the brain faces a fascinating problem: balancing the forthcoming noise from the external environment and the noise generated by its internal processes (Gold & Watanabe, 2010). For this purpose, through SDT, it is possible to define two parameters able to describe perceptual behavior: the d' (“d-prime”), which is an index of sensitivity related to sensation, and c (“criterion”), which is an index of bias related to non-specific factors such as response cost and prior knowledge. Nonetheless, changes at the c level can also account for purely perceptual effects (Witt et al., 2015).

To evaluate the d' , we used the standard formula:

$$(2.1) d' = Z(\text{Hit rate}) - Z(\text{False Alarm rate})$$

where d' is the difference between the converted z-score proportion of Hit and the converted z-score proportion of False Alarm. As a general rule, a d' value around zero suggests that the perceptual signal added to the noise is not sufficiently powerful to be consistently recognized. In our experiments, a d' around zero indicates that the perceptual information available is insufficient to allow reliable discrimination of the Target’s duration. Conversely, the higher the d' , the better the perceptual performance.

To calculate the c , we used the standard formula:

$$(2.2) c = -\frac{Z(\text{Hit rate}) + Z(\text{False Alarm rate})}{2}$$

where c is evaluated by averaging the converted z-score proportion of Hit and the converted z-score proportion of False Alarm, multiplied by negative one. An unbiased observer shows a c value of zero, while divergences from it denote a bias towards one of the two possible responses. A negative c value identifies a bias involving a more liberal approach. In our experiments, this is represented by one participant’s tendency to more often indicate the Target as the stimulus whose duration was longer. Conversely, a positive c value identifies a more conservative approach. In our experiments, this is represented by one participant’s tendency to more often indicate the Target as the stimulus whose duration was shorter. Even though within the SDT framework there are additional parameters through which it is possible to estimate biases, many authors endorse using c (Macmillan & Creelman, 1990; Snodgrass & Corwin, 1988). Notably, c is often preferred because it assumes that responses are based on a decision variable rather than a likelihood ratio (Richardson, 1994). On a final note, c is unaffected by changes at the d' level, while other parameters might be disrupted by repetitive fluctuations of the d' (McNicol, 2004).

Four possible response outcomes were established to evaluate the d' and c for each trial. We considered a response a 'Hit' when the target lasted longer than the References and participants successfully identified the Target as the longer stimulus. We considered a response a 'Miss' when the Target lasted longer than the References and participants failed to identify the Target as the longer stimulus. We considered a response a 'Correct Rejection' when the Target lasted shorter than the References and participants successfully reported the Target as the shorter stimulus. Lastly, we considered a response a 'False Alarm' when the Target lasted shorter than the References and participants reported the Target as the longer stimulus.

For Target durations higher than the Reference one (i.e., 520, 550, and 620 ms), responses could either be 'Hit' or 'Miss'. For Target durations lower than the Reference one (i.e., 380, 450, and 480 ms), responses could either be 'Correct Rejection' or 'False Alarm'. We decided to label trials using this specific classification for two reasons. On the one hand, the task was to indicate whether the Target's duration was longer than the duration of the Reference. Therefore, we modeled responses accordingly to our participants' ability to efficiently indicate the Target as the longest stimulus within the sequence. On the other hand, following this analysis pattern, we manage not only to define a measure of temporal sensitivity (i.e., the d') but also a measure of response bias (i.e., the c).

To test the reliability of our choice, we also performed a supplementary analysis involving a more canonical approach considering correct and incorrect response rates, obtaining similar results, and supporting the validity of our trials classification. A more general d' was evaluated using the following formula:

$$(2.3) d' = z(\text{Correct Response rate}) - z(\text{Incorrect Response Rate})$$

where the Correct Response rate is the ratio between the sum of 'Hit' and 'Correct Rejection' and the total number of trials, and the Incorrect Response rate is the ratio between the sum of 'Miss' and 'False Alarm' and the total number of trials.

To analyze the results of Experiment 2, we referred to the d' and c obtained in Experiment 1 as Baseline parameters. For each index, we then calculated the difference (Δ) between its value in Experiment 2 and the corresponding value in Experiment 1. Sensitivity differences ($\Delta_{(d')}$) between the two experiments were evaluated according to the following formula:

$$(2.4) \Delta_{(d')} = d'(\text{Looming/Receding}) - d'(\text{Baseline})$$

where $d'(\text{Looming/Receding})$ is the d' value in the Looming or the Receding condition for a given participant, and $d'(\text{baseline})$ is the d' value observed for the same participant in Experiment 1.

Similarly, we evaluated $\Delta_{(c)}$ using the following formula:

$$(2.5) \Delta_{(c)} = c(\text{Looming/Receding}) - c(\text{Baseline})$$

Where $c(\text{Looming/Receding})$ is the c value in the Looming or Receding condition for a given participant, and $c(\text{Baseline})$ is the c value observed for the same participant in Experiment 1.

Quantification and Statistical Analysis

All statistical procedures were conducted using JASP v. 0.14 (Love et al., 2019). In the current work, we used classic parametric statistical tests (Independent t-test for two samples and Two-way ANOVA), as well as parametric regression models (Pearson's correlation), since all samples met normality and homogeneity assumptions (evaluated using Shapiro Wilk and Levene's test, respectively). Statistical significance was defined considering p-values lower than 0.05. No participants were excluded from the final analysis.

Results

Experiment 1

To briefly compare performance between groups, we first ran an Independent t-test for two samples on the proportion of correct responses. Our initial analysis highlighted that hearing participants' performance was overall superior to the performance of deaf participants ($t_{(30)}=2.678$, $p\text{-value}=0.012$, 95 % CU [0.028 0.208], Cohen's $d=1.01$), whose response pattern was significantly closer to chance level ($M=0.55$, $SD=0.15$) than

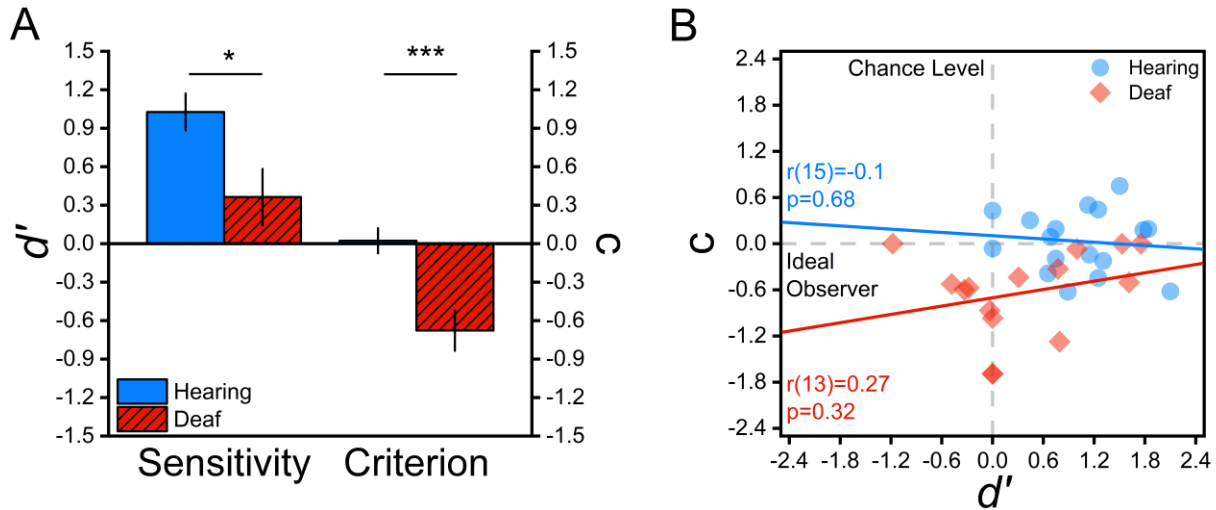


Figure 2.2 Temporal sensitivity, temporal bias, and corresponding correlations between groups.

A) Averaged d' (left) and c (right) across deaf and hearing participants. Performance in the deaf group was worse than performance in the hearing group, as their d' was significantly lower. Moreover, deaf participants showed also a strong bias towards a more liberal criterion. Error bars indicate $\pm$ SEM (*= p -value < 0.05, ***= p -value < 0.001). B) Correlations between individual d' and c values. As no correlation between the two parameters was highlighted, performance bias could not be explained by the inability of deaf participants in doing the task.

the response pattern observed in the hearing group ($M=0.68$, $SD=0.1$). To deeper evaluate differences in performance, we ran statistical analyses on the d' and c .

Using an Independent t-test for two samples, we then compared d' across groups. We found that deaf participants were less precise than hearing ones ($t_{(30)}=2.575$, $p\text{-value}=0.015$, 95% CI [0.174 1.637], Cohen's $d=0.91$) when performing the task (Deaf: $M=0.36$, $SD=0.85$; Hearing: $M=1.03$, $SD=0.6$), confirming our initial analysis conducted on raw performance. Similarly, we used an Independent t-test for two samples to compare c values across deaf and control participants. Our results showed that deaf participants exhibited a bias toward a more liberal approach ($t_{(30)}=3.874$, $p\text{-value}<0.001$, 95% CI [0.331 1.07]), as they tended to identify the Target as the stimulus that lasted longer most of the times (Deaf: $M=-0.63$, $SD=0.57$; Hearing: $M=0.02$, $SD=0.41$). Differences in performance are graphically reported in Figure 2.2A.

We then evaluated the correlation between the d' and c (i.e., between sensory precision and response bias). As no significant correlation was found neither in deaf ($r_{(13)}=0.27$, $p\text{-value}=0.32$) or hearing ($r_{(15)}=-0.1$, $p\text{-value}=0.68$) participants, we excluded the possibility that the observed bias was just an epiphenomenon emerged from the reduced precision observed in the deaf group (Figure 2.2B). Furthermore, the absence of correlation between the two parameters utterly confirmed that c values were not affected by changes at the d' level (McNicol, 2004).

To strengthen our analyses and further support our trial classification, we also ran an Independent t-test for two samples on d' evaluated using correct and incorrect response rates (Formula 2.3). Despite the different approach involved in the evaluation of d' values, our analysis highlighted once again that temporal

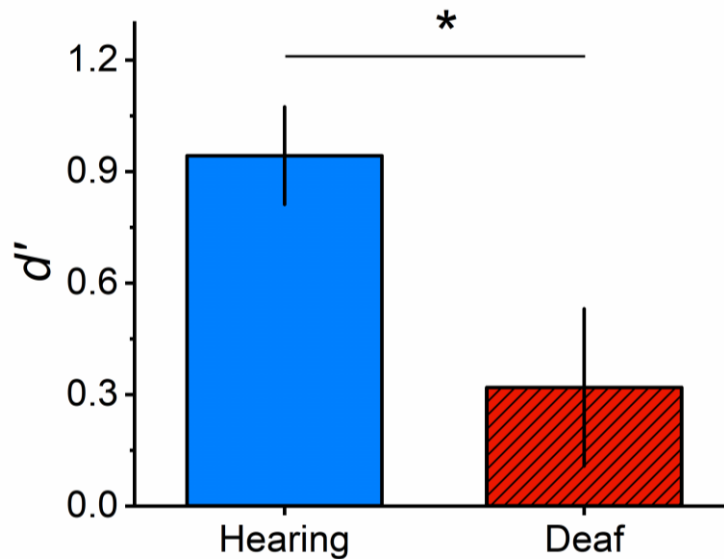


Figure 2.3 Averaged d' for both groups using correct and incorrect response rates.

Changing trials classification led to results that are similar to the ones obtained using a more flexible categorization, as temporal sensitivity was still significantly lower for deaf participants. Error bars indicate $\pm SEM$ (*= $p\text{-value} < 0.05$).

sensitivity was significantly different between groups ($t_{(30)}=2.572$, $p\text{-value}=0.015$, 95% CI [0.13 1.12], Cohen's $d=0.89$), as the d' for deaf participants ($M=0.32$, $SD=0.82$) was notably lower than the d' measured in hearing ones ($M=0.94$, $SD=0.54$), as reported in Figure 2.3.

To better represent our results within the SDT framework, we evaluated the confusion matrices for both groups, and we modeled internal response curves for both noise-alone trials (i.e., when the Target's duration was shorter than the References' one) and signal-plus-noise trials (i.e., when the Target's duration was

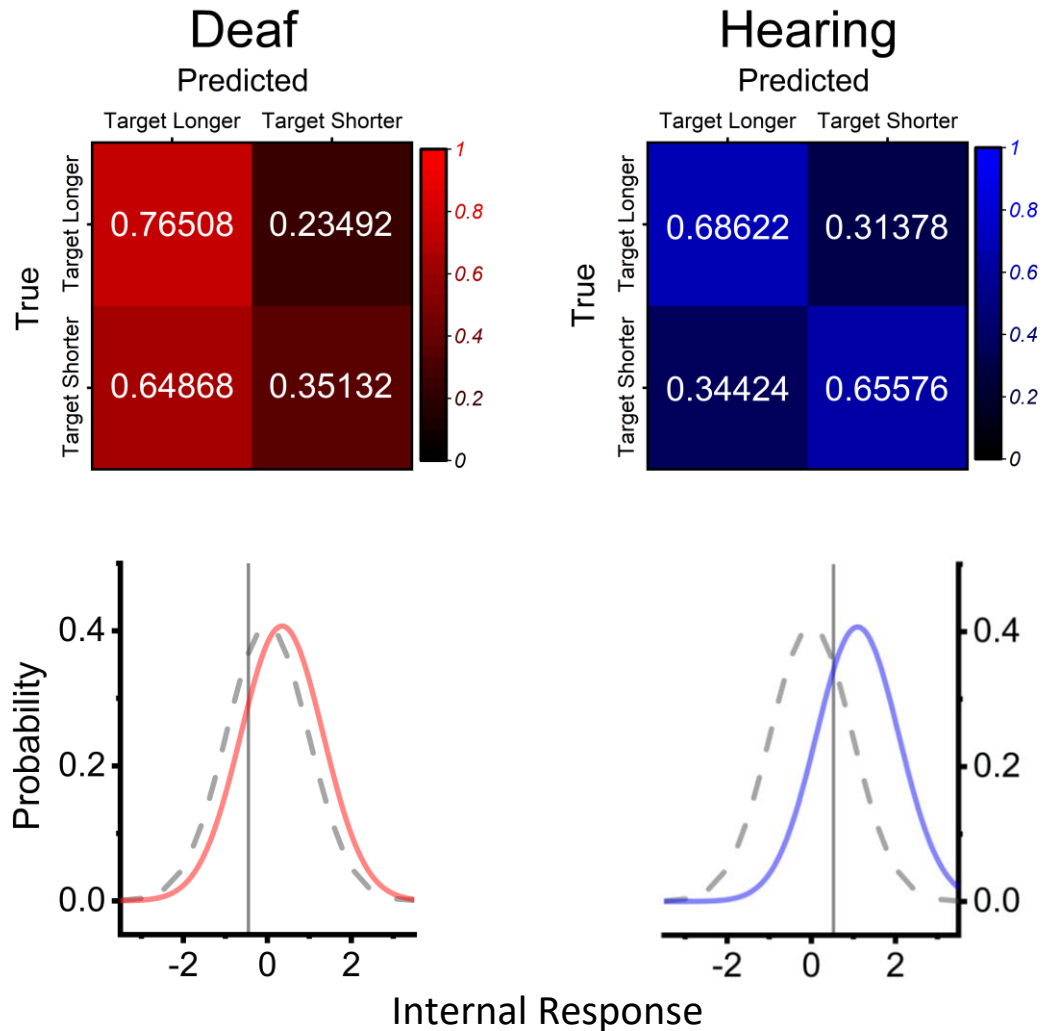


Figure 2.4 Confusion matrices and equivalent internal response distributions for noise-alone and signal-plus-noise trials.

Within confusion matrices (upper panels), the proportion of observed responses (Predicted) is reported as a function of true, correct responses (True). Note that in the deaf group participants indicated the Target as the longer stimulus about 76% if the time when its duration truly was longer than the References' one, and about 65% of the time when its duration was shorter. Conversely, they indicated the Target stimulus as shorter about 23% of the time when it lasted longer than the References, and about 35% of the time when it lasted shorter. Using confusion matrices proportions, for both groups we managed to model internal response distributions for noise-alone (lower panels, grey, dashed lines) and signal-plus-noise (lower panels, colored lines) trials. When the curves are close to each other, the signal is embedded within the noise and cannot be successfully extracted (such as in the deaf group). Contrariwise, when the two curves are farther away from each other the signal emerges from the noise and can be reliably detected (such as in the hearing group). Vertical, gray lines indicate c .

longer than the References' one). We reported the probability of a given participants' response within each confusion matrix, considering the actual Target's duration (either longer or shorter than the References' one). Internal responses are developed within a single dimension, and participants' responses to the Target are described by a probability distribution function across that same dimension. We assumed that noise-alone and signal-plus-noise trials distributions were normally shaped with equal variances and different means (being noise-alone trials centered at 0), as we did not have reason to believe that different Target duration could produce differently shaped response distributions. We also reported the averaged c value for both groups, indicating the criterion adopted by deaf and hearing participants when choosing an answer. Whenever the internal response is greater than the criterion adopted, participants indicated the Target as the longer stimulus. Otherwise, an internal response lower than the criterion led participants to indicate the Target as the shorter stimulus. Graphical inspection of response distributions utterly confirmed that deaf participants exhibited lower temporal sensitivity compared to hearing ones (Figure 2.4).

Lastly, we evaluated whether non-perceptual, demographical factors could influence our results. Unfortunately, we were not able to balance the age between the two groups ($t_{(30)}=5.018$, $p\text{-value}<0.001$, 95% CI [14.69 31.8], Cohen's $d=1.75$) as deaf participants were on average older ($M=59.8$ y, $SD=14.45$ y) than hearing participants ($M=35.05$ y, $SD=13.81$ y). Due to this disparity, we fitted linear regressions between d' , c , and deaf participants' age to test whether age influenced performance. We also fitted linear regressions between age at sign language learning, temporal sensitivity, and bias, to ensure that observed impairment in performance was not relatable to sign language influences (Figure 2.5). In the end, we found no linear relationship between d' and age ($F_{(1,14)}=1.349$, $p\text{-value}=0.27$, $R^2=0.09$), nor between d' and age at sign language acquisition ($F_{(1,11)}=0.003$, $p\text{-value}=0.95$, $R^2<0.001$). Similarly, we found no linear relationship between c and age ($F_{(1,14)}=0.092$, $p\text{-value}=0.76$, $R^2=0.007$) nor between c and age at sign language acquisition ($F_{(1,11)}=1.968$, $p\text{-value}=0.19$, $R^2=0.164$). Even though there is evidence suggesting that temporal abilities might decrease with age (Baudouin et al., 2006; McAuley et al., 2010; McCormack et al., 1999), the results obtained indicate that demographic factors and late access to sign language communication cannot be accounted for the reduced performance observed in deaf participants. Furthermore, deterioration of temporal perception due to aging was not unequivocally reported in all studies investigating the matter (Hancock & Rausch, 2010; Salthouse et al., 1979; Wearden et al., 1997), suggesting that the link between aging and time perception might be nonlinear. Interestingly, in a recent paper Lamotte and Droit-Volet (Lamotte & Droit-Volet, 2017) demonstrated that differences in temporal sensitivities due to aging can be explained by attention capacities – which decline with age as well. As our experimental design was thought to minimize the inference of non-specific factors, such as attentional orienting (van Wassenhove et al., 2008), we argue that the effect of age should be theoretically minimized in a similar

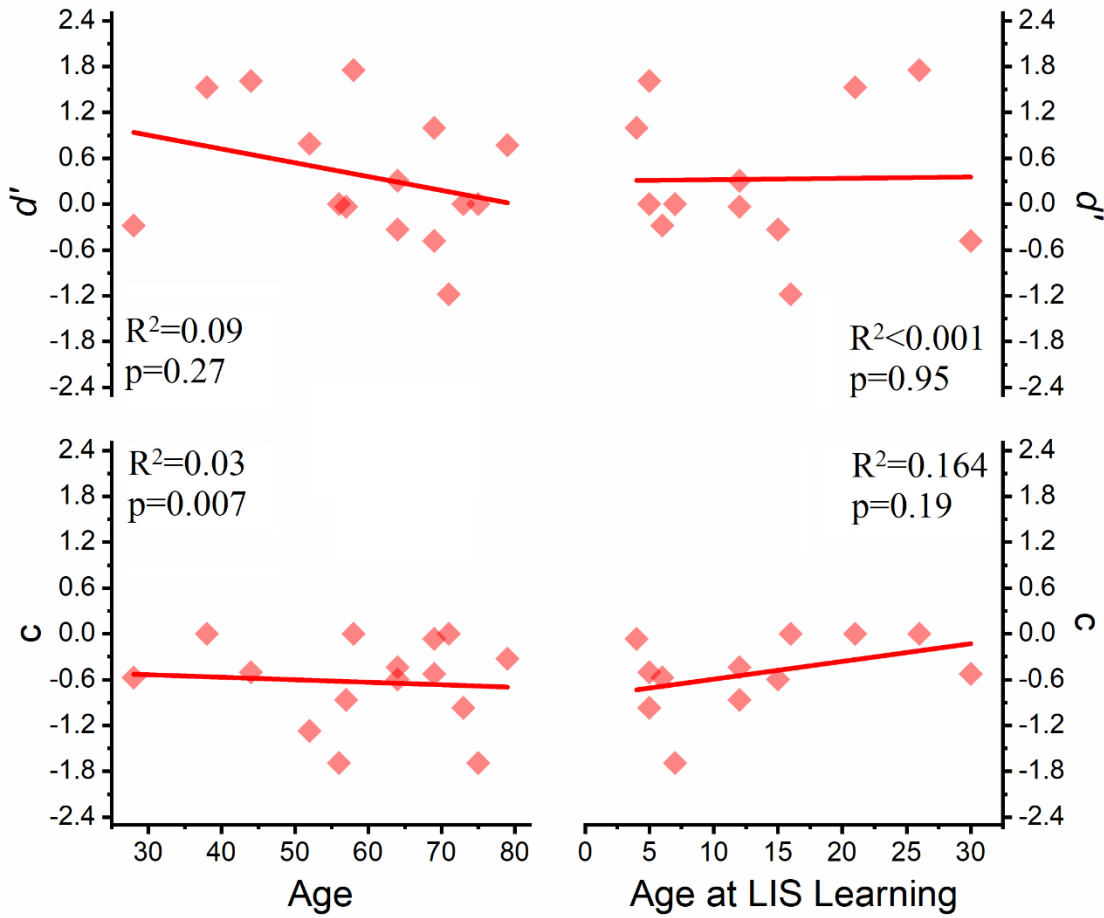


Figure 2.5 Correlations between age, d' , c , and age at which sign language was acquired.

Correlations between age, d' , and c (left panels), and age at which sign language (LIS) was acquired, d' , and c (right panels). Neither the age of the deaf participants, nor the age at which they acquired sign language, significantly correlated with any of the SDT indices used to evaluate temporal performance.

fashion. Nevertheless, the difference in age between the two groups remains a limit of the study, and our findings must be discussed and, eventually, generalized in light of this consideration.

Experiment 2

To assess how manipulating the spatiotemporal dynamics of the Target impacted temporal performance, we ran a Two-way ANOVA with within-subject factor Condition (Looming vs. Receding) and between-subject factor Group (Deaf vs. Hearing) on both $\Delta_{(d')}$ and $\Delta_{(c)}$. For what concern changes at the d' level, we found a significant main effect of Group ($F_{(1,14)}=4.972$, $p\text{-value}=0.04$, $\eta^2=0.18$) but no significant main effect of Condition ($F_{(1,14)}=0.124$, $p\text{-value}=0.73$, $\eta^2=0.003$) nor a significant interaction effect between factors ($F_{(1,14)}<0.001$, $p\text{-value}=0.99$, $\eta^2<0.001$). Considering our statistical design (with only two factors having two levels each) and the absence of an interaction effect, we did not perform any statistical follow-up to describe our results further. These findings suggest that sensitivity in the deaf group increased in both

the Looming ($M=0.78$, $SD=0.93$) and the Receding ($M=0.88$, $SD=0.45$) condition while hearing participants did not acquire any sensitivity change when the Target either expanded ($M=0.11$, $SD=0.77$) or reduced ($M=0.2$, $SD=0.75$) its size (Figure 2.6A).

Regarding changes at the c level, we found a significant main effect of Condition ($F_{(1,14)}=7.288$, $p\text{-value}=0.017$, $\eta^2=0.111$) and a significant interaction between factors ($F_{(1,14)}=6.692$, $p\text{-value}=0.022$, $\eta^2=0.102$), while we found a tendency for Group as well ($F_{(1,14)}=4.373$, $p\text{-value}=0.055$, $\eta^2=0.137$). Post-hoc comparisons (after Bonferroni correction for multiple comparisons, adjusting the $p\text{-value}$ and confidence intervals for comparing a family of 4 estimates) highlighted that, for hearing participants, Δ_c was significantly lower in the Looming ($M: -0.93$, $SD: 0.73$) than in the Receding ($M: -0.39$, $SD: 0.66$) condition

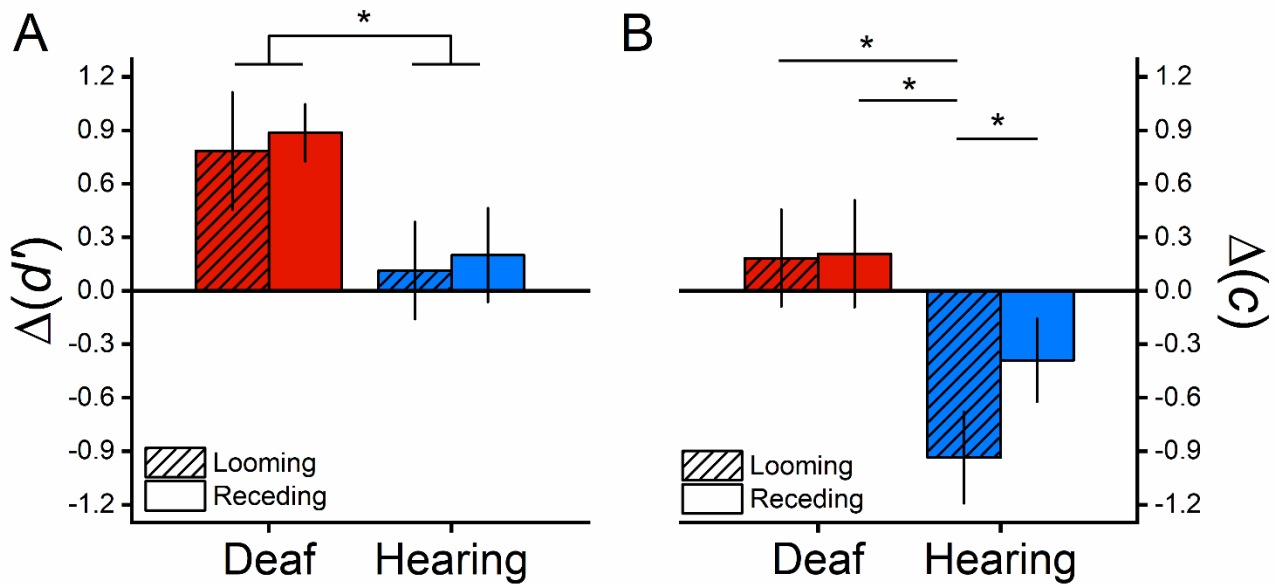


Figure 2.6 Changes in temporal perception induced by the Target's dynamical spatiotemporal manipulation. A) Differences at the d' level observed as the spatiotemporal dimension of the Target was dynamically manipulated. Statistical significance reported in this graph accounts for the main effect of the factor Group. B) Differences at the c level observed as the spatiotemporal dimension of the Target was dynamically manipulated. For both graphs, error bars indicate $\pm$ SEM (*= $p\text{-value}<0.05$).

($t_{(7)}=-3.738$, $p\text{-value}=0.013$, 95% CI [-2.067 -0.203], Cohen's $d=0.78$). Notably, hearing participants' Δ_c in the Looming condition was also significantly lower than deaf participants' Δ_c in the same condition ($t_{(14)}=-3.194$, $p\text{-value}=0.023$, 95% CI [-2.277 -0.124], Cohen's $d=1.5$), as well as deaf participants' Δ_c in the Receding condition ($t_{(14)}=-3.258$, $p\text{-value}=0.019$, 95% CI [-2.302 -0.148], Cohen's $d=1.43$). Conversely, Δ_c did not change across the Looming ($M=0.18$, $SD=0.76$) and the Receding ($M=0.21$, $SD=0.85$) conditions ($t_{(7)}=-0.08$, $p\text{-value}=1$, 95% CI [-0.956 0.908], Cohen's $d=0.04$). Overall, these results are in line with a previous study in which it was demonstrated that Looming visual stimuli induce a time dilation (van Wassenhove et al., 2008), represented by the significant c shift towards negative values. Surprisingly, this

effect was observed only in hearing participants while, on average, c shifts were not measured in the deaf group (Figure 2.6B). Similar to what already done for Experiment 1, we modelled internal response distributions for noise-alone and signal-plus-noise trials for both the Baseline (i.e., Experiment 1), the Looming, and the Receding conditions (Figure 2.7). We included only participants who performed all three experimental sessions within this final analysis. Graphical inspection utterly confirmed that deaf participants' performance was drastically impaired in the Baseline (i.e., Experiment 1) condition when only temporal cues were available to complete the task. Conversely, deaf participants' performance significantly increased in the Looming and the Receding conditions (i.e., Experiment 2) when coherent, dynamic spatiotemporal information was added to the Target stimulus.

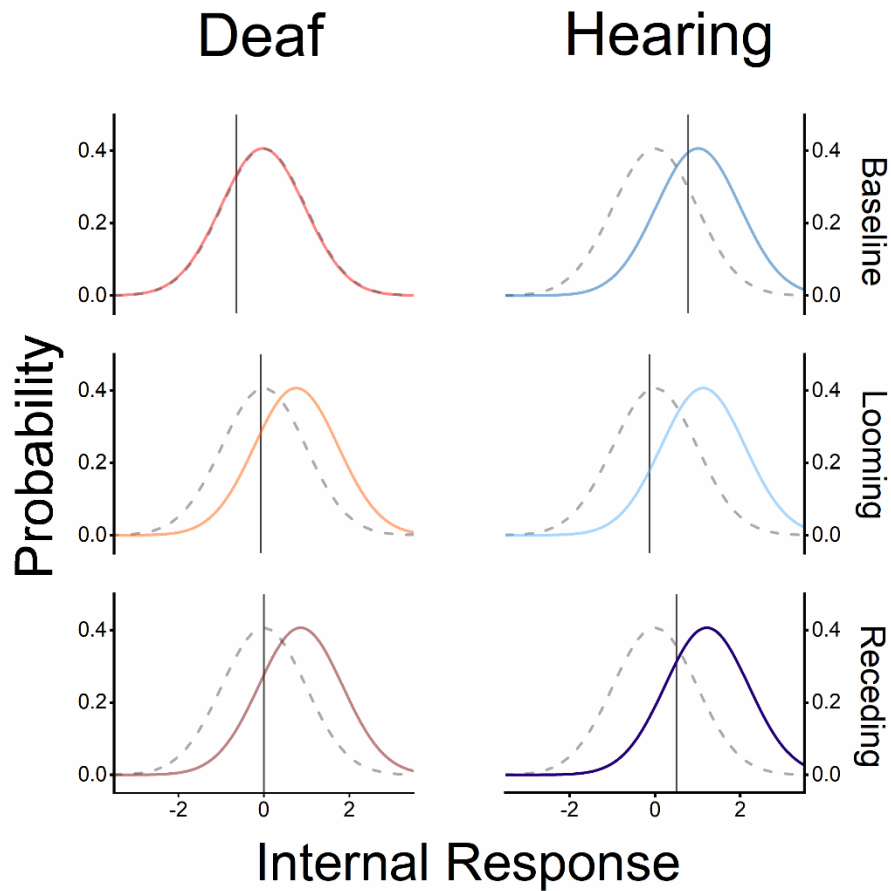


Figure 2.7 Internal response distributions across groups for all experimental conditions.

Dashed, grey lines represent noise-alone trial response distributions, while continuous, colored lines represent signal-plus-noise trial response distributions. These models suggest that deaf participants were not able to successfully perform the task when only temporal information was displayed (as the two distributions overlap), while they improved their performance when coherent spatiotemporal information was added to the Target. Vertical, grey lines indicate c .

Conclusions

In the present study, we bring further evidence that congenital and early deaf individuals exhibit a deeply-rooted, generalized temporal impairment. Our results support the original speculation of Fraisse, suggesting that the ability to process hearing information at critical, early stages of life is fundamental to refining a proper sense of time.

The first relevant result of this study is that deaf participants showed a significant temporal impairment when performing a visual temporal oddball-like task. The observed impairment was so pronounced that both the d' and the c reflected this abnormal temporal processing. The reduced d' observed in deaf participants indicates that they could not correctly judge the duration of the target, suggesting that reduced temporal sensitivity might reflect overall 'noisier' timing-related networks in the brain. Temporal cues were insufficient to complete the task so the Target could not be reliably identified and extracted from internal and external noise. Notably, this assumption finds theoretical support in previous research showing that specific sensory information is fundamental to reducing perceptual observation variance (Gori et al., 2008; Nardini et al., 2008).

The second relevant result of this study is that acceptable temporal sensitivity was observed in deaf participants when dynamic spatiotemporal information was displayed together with the Target. Notably, visual spatiotemporal information is primarily processed by magnocellular cells, which should benefit from adaptive plasticity after congenital and early hearing loss (Stevens & Neville, 2006). Conversely, hearing participants did not experience any improvement in temporal performance when the Target dynamically increased or decreased in size, suggesting that spatiotemporal information might be redundant when temporal processing is efficiently developed within the brain. This interpretation is also potentially in line with the SDT theoretical framework. When only temporal cues are available, deaf participants cannot overcome the noise interfering with temporal judgments, whether the noise itself is external or, more likely, internal. However, when spatiotemporal cues are made available, perceptual information is sufficient so that the Target can be detected within the noise, and performance improves as a consequence.

The last interesting aspect that emerged in this study is related to changes at the c level in the Looming condition. Our study found that when the Target was a disk increasing in size, c values shifted towards negative numbers in hearing participants. However, similar changes were not found in the Receding condition, when the Target was a disk reducing its size. Since in the Looming condition hearing participants increased the rate at which they reported the Target as the stimulus lasting longer, they consequently tended to overestimate its duration. This perceptual pattern, similar to the one found within the original research from which we took inspiration (van Wassenhove et al., 2008), can be explained considering that c

modifications account for both decision and perceptual biases (Witt et al., 2015). A possible interpretation for this temporal dilation was given by van Wassenhove and colleagues, as they proposed that non-specific factors (such as contextual salience, attentional and emotional overload) might mediate temporal distortions linked to looming visual signals (van Wassenhove et al., 2008). Curiously, looming signals manifest intrinsic ecological valence, as they represent a stimulus that is rapidly approaching the observer and that, potentially, requires a fast allocation of attentional resources to be processed (Franconeri & Simons, 2003). This could explain why the same temporal dilation does not accompany receding signals that produce similar retinal images.

Nonetheless, a recent study by Sgouramani and colleagues (Sgouramani et al., 2020) demonstrated that temporal distortions associated with looming signals disappeared when using naturalistic displays of biological motion. When congruent (or neutral) auditory cues were combined with the visual stimulation, however, the overestimation of looming signals was restored. Therefore, the absence of modifications at the *c* level in deaf participants is an even more fascinating aspect to discuss. One possible interpretation is that deaf individuals do not associate any negative valence with looming signals, and that hearing processing during development is crucial to acquiring proper awareness about looming stimuli. Unfortunately, this hypothesis seems to be challenged by the fact that looming audio-visual integration is already present at birth (Orioli et al., 2018). Still, auditory information appears to be dominant in eliciting the illusion when naturalistic information is displayed (Sgouramani et al., 2020), thereby suggesting that hearing might be relevant in consolidating specific sensitivity to ecological looming visual signals. Another possible explanation, far more pragmatic, is that temporal impairment in deaf participants was so prominent that it overshadowed any time dilation associated with looming signals. In Experiment 1, deaf participants already showed a clear temporal bias, and thus we speculate that temporal dilation induced by looming signals failed to emerge in some sort of winner-takes-all fashion.

To conclude, with the current work we demonstrated that congenital and early deaf individuals experience profound temporal impairments when judging time events using only temporal cues. Nevertheless, we also observed a significant improvement in temporal performance when coherent, spatiotemporal cues were made available to perform the task. Taken together, these results suggest that the absence of early hearing experience negatively impacts general temporal processing. However, veridical internal temporal representations might be restored using sensory information that is otherwise redundant in hearing participants.

2.2 Magnocellular Temporal Processing in Developmental Dyslexia

In the late 19th century, the French ophthalmologist Louise Emile Javal observed that, while reading, eyes do not move linearly over a line of text, but make rapid, ballistic movements, called saccades. Unsurprisingly, saccades have since then considered a key component of reading, and saccades abnormalities often emerge when recording eye movements in individuals with DD (Biscaldi et al., 1994, 1998; Bucci et al., 2008; Crawford & Higham, 2001; Freedman et al., 2017; Tiadi et al., 2014), even though some studies failed to identify them (De Luca et al., 1999; Vagge et al., 2015). Nonetheless, saccades alone are seldom explanatory of an individual's reading abilities and are barely informative for clinicians, which use phonetic and semantic evaluations for the diagnosis of DD.

While the eyes move, the world's image on the retina is constantly shifting. However, the visual percept that we have of the surroundings remains stable without reflecting this constant retinal displacement. The absence of image blurring while we scan a given scene has been explained by the suppression of the magnocellular pathway at the time of saccades (Ross et al., 1996). Interestingly, this suppression might occur at the early stages of visual information processing, plausibly already at the Lateral Geniculate Nucleus (Burr et al., 1994). It might also be interesting to consider that magnocellular neurons, which yield significant connections to parietal areas involved in visual localization (Ross et al., 1997), also show functional preferential behavior for the encoding of transient, temporally displaced stimuli (Leonova et al., 2003; Levitt et al., 2001). Therefore, the suppression of the magnocellular pathway during saccadic eye movements might determine a distortion in both metrics of the internal representation of space, as well as time.

As expected, saccades induce profound changes in visual perception, such as transient compressions of spatial (Burr et al., 2001; Ross et al., 1997) and temporal (Morrone et al., 2005) information. These perceptual distortions have been explained by the receptive fields' predictive anticipatory remapping along the visual pathway, for which neurons' receptive fields shift towards their post-saccadic position before the onset of the eye movement. Predictive anticipatory remapping behavior has been indeed observed in the Superior Colliculus (Walker et al., 1995), extra striate visual areas (Nakamura & Colby, 2002), Frontal Eye Field (Umeno & Goldberg, 1997), and in the Lateral IntraParietal cortex (Duhamel et al., 1992).

As already discussed in paragraph 1.2.3, a significant body of evidence has been developed, during the last years, focusing on a potential impairment in magnocellular processing in individuals with DD (Stein, 2001, 2018, 2019; Stein & Walsh, 1997). However, most – if not all – of the studies investigating saccadic movements in DD focused on the eye movements' phenomenology, considering saccadic latencies, accuracy, and vergence. Here, we propose a new approach, exploring the saccadic compression of both

space and time in children with DD. Since magnocellular information processing is impaired in individuals with DD, we hypothesize that we should find different transient perceptual distortions at the time of saccades compared to normal-reading peers. Furthermore, we speculate that temporal compressions should reflect a higher grade of disruption than spatial compression since temporal processing impairments have already been extensively marked in individuals with DD, while spatial processing seems to be preserved.

Participants

19 children with DD (Age: M=129.4 m, SD=23.7 m) and 17 normal-reading, age-matched peers (Age: M=124.9 m, SD=23.5 m) took part in the study. Since participants with DD were drawn from a relatively

ID_Participant	Gender	Age (months)	Reading Speed	z-score Reading Speed	Reading Errors	z-score Reading Errors
DD01	F	84	0.4	-1.94	28	7.66
DD02	M	106	1.2	-2.5	15	3.5
DD03	M	176	4.77	-0.57	0	-1.09
DD04	M	120	2.85	-0.91	6	0.67
DD05	M	168	2.15	-2.81	9.5	1.81
DD06	M	173	3.15	-2.33	0	-1.09
DD07	M	115	0.8	-2.96	18	4.43
DD08	M	121	0.51	-3.7	20	5.14
DD09	M	138	2.7	-1.5	14	3.09
DD10	M	117	1.8	-1.8	3.5	-0.13
DD11	M	132	1.02	-3.1	10	1.95
DD12	F	133	1.9	-2.44	18	4.3
DD13	F	112	1.7	-1.91	0	-1.23
DD14	F	118	1.2	-2.88	4	0.03
DD15	M	124	2.12	-1.78	6	0.67
DD16	F	128	1.08	-3.02	4	0.03
DD17	F	148	2.35	-1.93	13	2.78
DD18	M	109	1.2	-2.88	0	-1.16
DD19	M	137	1.47	-2.94	0	-1.23

Table 2.3 Demographic information for participants with DD.

small pool (dependent on the availability of patients attending a local rehabilitative center that did not already started rehabilitation), sample size was heavily determined by resources constraints (i.e., availability of such participants). As stated by Lakens (Lakens, 2022), when resources are a limiting factors reported effect sizes must be interpreted through a power sensitive analysis, to discuss statistically relevant findings as a function of the minimum effect detectable with the selected sample size. In Experiment 1, a total of 34 participants were tested (17 DD and 17 normal reading, see Table 2.4): considering $\alpha=0.05$, $1-\beta=0.8$, and $n=34$, the minimum effect (either fixed, main, or interaction effects) detectable in an ANCOVA

with one covariate and two groups is $f=0.49$, while we highlighted and discussed an interaction effect of $f=0.65$ ($\eta^2_p=0.3$). In Experiment 2, a total of 23 participants were tested (11 DD and 12 normal reading, see Table 2.4): considering $\alpha=0.05$, $1-\beta=0.8$, and $n=23$, the minimum effect (either fixed, main, or interaction effects) detectable in an ANCOVA with one covariate and two groups is $f=0.61$, while we highlighted and discussed an interaction effect of $f=0.62$ ($\eta^2_p=0.28$). Since in both experiments we observed interactions whose effect sizes were higher than the minimum effect size detectable with our sample sizes, we concluded that the number of participants was sufficient to support the interpretation of our results. All participants had normal or correct-to-normal vision, and no participant had a history of neurological disease. All participants were naïve to the purpose of the study, and the legal representatives of the children gave informed consent before any child participated in the experimental procedure. Children with DD were tested in a local rehabilitative center for learning disabilities, whereas normal-reading children were tested at the Istituto Italiano di Tecnologia, in Genova. Testing procedures were developed following Helsinki's declaration and were approved by the local ethical committee (Comitato Etico ASL3, Genova).

Reading speed and errors were assessed using the MT and advanced MT batteries (Cornoldi & Colpo, 1995), depending on the participant's age. Demographic information for the DD group, as well as reading abilities, are reported in Table 2.3. Normalized (z-score) reading speed and errors were evaluated considering the corresponding mean and standard deviation for each participant's reference grade.

There were no premature children among participants recruited for this study, and participants across groups were matched prioritizing age.

Apparatus and Stimuli

Stimuli were generated via Matlab v. 2020b through the Psychtoolbox routines and were displayed on a 24" Asus VG248QE LCD monitor with a resolution of 1920 x 1080 pixels and a refresh rate of 144 Hz. During the procedure, participants sat in a dimly lit room in front of the monitor, at a viewing distance of 70 cm, with the head placed on a chin-rest to ensure a stable recording of eye movements. Saccades were monitored using a Tobii ProSpectrum external eye-tracker, with a sample rate of 1200 Hz. Experimental scripts were constantly interfaced with the eye-tracker's SDK, as functions to start and end recordings, as well as trigger various events occurring during the procedure, were directly integrated within the program used to run the protocol.

At the beginning of the experiment, all participants performed a familiarization session of 20 trials. Familiarization sessions were introduced to help participants acquire confidence with the eye movements to perform during experimental sessions. For each familiarization trial, an initial fixation point appeared on the monitor. After participants maintained gaze fixation over the point for one second, the point

disappeared, and a second fixation point (i.e., the saccadic target), located at 20° of visual angles to the right of the first one, was displayed on the screen. Participants had to move their eyes towards the saccadic target as quickly as possible without moving their heads. Once eye movements were recorded, the subsequent trial started. At the end of each trial in the training session, the participants received feedback about the speed of the movement (i.e., if they were too slow in reaching the saccadic target). In both training and experimental sessions, the first fixation point disappeared after the gaze was continuously maintained over it for at least one second. Saccades were always performed from left (-10° of visual angles considering participants' head position) to the right (+10° of visual angles considering participants' head position).

Stimuli displayed during experimental sessions were vertical, near equiluminant green bars presented on a red background, presented for one single frame (~7 ms). During the training phase, we collected average saccadic latencies for each participant, and we used them to time as precisely as possible stimuli presentations around saccadic onsets.

Experiment 1

In Experiment 1 (Figure 2.8A), we evaluated the compression of visual-spatial information at the time of saccades. To fully involve children in our task, we developed a gamified version of a paradigm already used to investigate saccadic spatial compression in adult participants (Ross et al., 1997). During the experimental procedure, a green vertical bar (subtending 2 x 34° of visual angle) was displayed for one single frame, after a random interval (~ -300, ~ 0, or ~ +300 ms in reference to the saccadic onset), in one of three possible positions in respect to the observer: at -10° (overlapping the first fixation point), at 0° (in the exact center of the screen) or at +15° degrees of visual angle (5° rightward to the saccadic target). After the saccadic movement was successfully performed, a second green vertical bar appeared on the monitor. Participants could control the bar, moving it along the whole screen using the mouse. Participants' task was to reproduce and report the apparent position of the bar briefly displayed around the saccadic movement. Once the participant placed the bar in the desired position, the click of the mouse confirmed the response, and the subsequent trial started.

Each possible combination of spatial positions (left, center, right) and temporal displacements (before, during, and after saccadic onset) was repeated eight times, leading to a total of 72 trials performed by each participant.

Experiment 2

In Experiment 2 (Figure 2.8B), we evaluated the compression of visual temporal information during saccadic movements. As already described for Experiment 1, we developed a gamified version of a

paradigm used in adults to investigate the influence of saccades on temporal processing (Morrone et al., 2005). At the beginning of the procedure, an empty test interval delimited by two sequentially displayed green vertical bars (subtending $2 \times 10^\circ$ of visual angle) was displayed around the first fixation point, with the bars being displayed either 3° to its left or to its right. Vertical bars were separated by a random interval ranging from 60 to 600 ms, and were displayed for one single frame either before (~ 300 ms) or at the onset (~ 0 ms) of the saccadic movement. The bar's order of presentation was randomized across trials, so that it first appeared either the bar placed to the left of the fixation point or the bar placed to the right. The test interval duration was defined by a QUEST algorithm (Watson & Pelli, 1983), following an adapting procedure (parameters used for the procedure were: range=0.2, tGuessSD=1.2, pThreshold=0.5, $\beta=3.5$, $\epsilon=0.01$, $\gamma=0$). Through the QUEST algorithm it was possible to place each trial at the most probable Bayesian estimation of the investigated threshold, allowing for a reliable and fast evaluation of perceptual performance even with a relatively low number of trials.

After participants completed the saccade and maintained the gaze over the second fixation point, a reference empty interval delimited by physically identical vertical bars was displayed around the saccadic target. For the reference interval, green vertical bars were separated by 200 ms and were displayed in random order

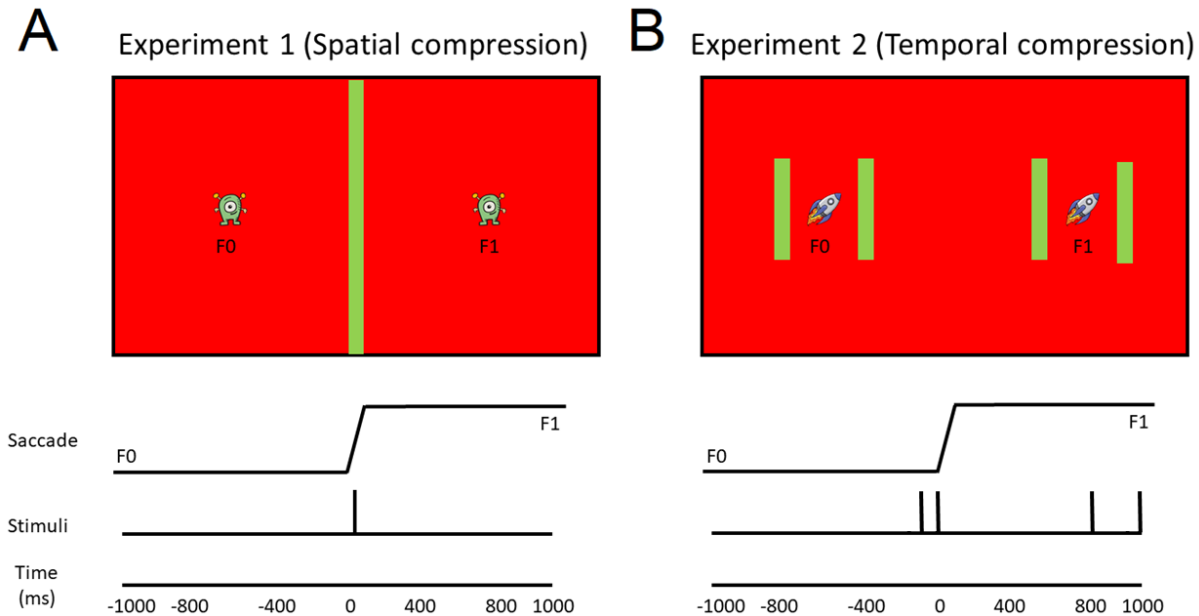


Figure 2.8 Experimental designs used to evaluate spatial and temporal saccadic compression.

Stimuli were briefly presented green, vertical bars displayed on an otherwise empty red screen. A) In Experiment 1, participants had to reproduce the apparent position of the bar tracking it with the mouse. B) In Experiment 2, participants had to compare the duration of a test interval, displayed around the initial fixation point (F0), with the duration of a reference interval, displayed around the saccadic target (F1). Bar delimiting temporal intervals obviously never appeared simultaneously, but were displayed sequentially in random order. To better involve children, to represent both the initial fixation point and the saccadic target we used simple illustrations related to space.

(similarly to the test interval) one second after the end of the movement. At the end of the trial, participants had to verbally indicate which one of the two empty intervals lasted longer.

Each participant performed a total of 60 trials. In half of them the first interval was displayed well before the expected onset of the saccadic movement, while in the remaining half the first interval was displayed at the time of the saccadic onset.

Data Analysis

To evaluate the effect of saccadic compression on spatial and temporal visual information, we first classified each trial performed by the participants by considering the temporal difference between the presentation of the stimuli (either the vertical bar in Experiment 1 or the first empty interval in Experiment 2) and the saccadic onset, fixed at time zero by definition. Thereby, we defined specific time windows for the spatial (-100/+50 ms) and temporal (-200/+200 ms) compressions, considering the time frame in which perceptual distortions induced by saccadic movements have been previously highlighted in adults (Morrone et al., 2005; Ross et al., 1997). For both experiments, we then classified trials considering this specific time frame: all trials in which the temporal difference between the stimuli presentation and the saccadic onset fell within the selected range for both spatial (-100/+50 ms) and temporal (-200/+200 ms) compressions were classified as *perisaccadic*. Otherwise, trials were classified as *aposaccadic* (i.e., the stimuli were displayed well before or after the onset of the saccadic movement).

We decided to follow this approach to compensate for the possible variability present when collecting eye movements in children. Even though we fixed the delay of the stimuli presentation using saccadic latencies collected in the training phase, post-processing analysis allowed us to evaluate the proper, physical temporal intercourse between stimuli presentation and saccadic onset.

For what concern Experiment 1, to obtain a general index of saccadic spatial compression for each participant – regardless of the position of the stimulus, but related to saccade's onset – we evaluated the spatial bias for both *perisaccadic* and *aposaccadic* trials. For *perisaccadic* trials, the bias was evaluated according to the following formula:

$$(2.6) \text{Bias}_{\text{perisaccadic}} = \overline{\sum \hat{x}_{\text{perisaccadic}} - x_{\text{perisaccadic}}}$$

where $\hat{x}_{\text{perisaccadic}}$ is the position of the stimulus as perceived by the participant, and $x_{\text{perisaccadic}}$ is the physical position of the bar, expressed in degrees of visual angle.

Similarly, for *aposaccadic* trials the bias was evaluated through the following formula:

$$(2.7) \text{Bias}_{\text{aposaccadic}} = \overline{\sum \hat{x}_{\text{aposaccadic}} - x_{\text{aposaccadic}}}$$

where $\hat{x}_{\text{aposaccadic}}$ is the position of the stimulus as perceived by the participant, and $x_{\text{aposaccadic}}$ is the physical position of the bar, expressed in degrees of visual angle.

Notably, for stimuli placed to the right of the saccadic target, the difference between the real and the estimated spatial position was multiplied by negative one to match the direction of the saccadic spatial compression, which is centered around the arrival point of the saccade (Burr et al., 2001; Ross et al., 1997). Using these formulas, positive values indicate a shift of the perceived position towards the saccadic target, while negative values denote a mislocalization towards the opposite direction. To evaluate the effect of saccades on visual spatial perception, we then calculated the arithmetical difference between $\text{bias}_{\text{perisaccadic}}$ and $\text{bias}_{\text{aposaccadic}}$ as follows:

$$(2.8) \text{Spatial Bias} = \text{Bias}_{\text{perisaccadic}} - \text{Bias}_{\text{aposaccadic}}$$

Comparing the two biases, whose difference is generally described as spatial bias from now on, allowed us to evaluate spatial distortions expressed by children during saccadic movements while, at the same time, controlling for inherent biases potentially present during fixation.

For what concern Experiment 2, to quantify temporal performance we fitted the following psychometric function into data obtained for each participant, considering in separate analyses *perisaccadic* and *aposaccadic* trials:

$$(2.9) p_{(t \geq r)} = \frac{1}{1 + e^{-\frac{t - \mu}{\sigma}}}$$

where $p_{(t \geq r)}$ is the proportion of trials in which participants indicated the test interval (t) as the one with the longer duration, while μ and σ represent the bias and the sensitivity within performance, respectively. In Experiment 2, the bias is well described by the Point of Subjective Equality (PSE), which is the duration of the test interval perceived as equal to the duration of the reference interval by the participant. The sensitivity is instead indicated by the Just Noticeable Difference (JND) and is the difference in duration needed so that the participant perceived the two intervals as different at least 50% of the time. The result of the fitting procedure is a sigmoid ranging from 0 to 1, showing the cumulative probability that participants indicated the test interval as the longer in duration, being this probability expressed as a function of the different durations of the test interval itself. Considering our experimental design, and precisely the fact that we are evaluating temporal distortions involving the test interval (i.e., the one presented within the *perisaccadic* timeframe and whose duration changes across trials), an increase in PSE denotes a consequent compression

of the test interval's perceived duration. In the optimal situation, we would expect a PSE that is approximately equal to the duration of the reference interval (in our experiment, 200 ms), indicating that the test interval is perceived as identical to the reference interval when the two durations are about the same. Conversely, when the PSE increases (e.g., to 300 ms), the two intervals are perceived as identical when the test duration increases as well, while the reference duration remains fixed. Thereby, a 300 ms PSE indicates that the test and the reference intervals are perceived equal when the first interval lasts 300 ms and the second one lasts 200 ms, suggesting that the perceived duration of the test underwent a compression of 100 ms.

Quantification and Statistical Analysis

All statistical procedures were conducted using JASP v. 0.14 (Love et al., 2019). In the current work, we used classic parametric statistical tests (Two- and Three-way repeated measure ANCOVA), as well as parametric (robust linear regression, Pearson's correlation, and logistic regression) regression models, since all samples met normality and homogeneity assumptions (evaluated using Shapiro Wilk and Levene's test, respectively). Statistical significance was defined considering p-values lower than 0.05. Two participants with DD were excluded from the final analysis as they could not successfully perform saccadic movements in compliance with the experimenter's request. Furthermore, we had to exclude 6 participants with DD and 5 normal-reading participants from the analysis in Experiment 2, as they could not perform enough trials to allow a successful and reliable fitting procedure.

A detailed representation of all participants in Experiments 1 and 2 is reported in Table 2.4.

<i>Experiment 1</i>				
<i>Group</i>	<i>n</i>	<i>Mean Age (months)</i>	<i>St. Dev Age (months)</i>	<i>Gender Distribution</i>
Control	17	124.9	23.5	9M, 8F
DD	17	130.1	24.3	11M, 6F
<i>Experiment 2</i>				
<i>Group</i>	<i>n</i>	<i>Mean Age (months)</i>	<i>St. Dev Age (months)</i>	<i>Gender Distribution</i>
Control	12	129.3	22.8	6M, 6F
DD	11	123.7	22.8	8M, 3F

Table 2.4 Sample size, age means, age standard deviations, and gender distributions of participants recruited in Experiment 1 and 2 respectively.

Results

Experiment 1

To assess the effect of saccadic compression on visual spatial information, we first ran a Two-way repeated measure ANCOVA with within-subject factor Condition (*aposaccadic* vs. *perisaccadic*) and between-subject factor Group (Control vs. Dyslexic) on Spatial Biases, adding Age (expressed in months) as a covariate. As our experimental design involves within-subject (i.e., repeated measures) factors and a covariate, to avoid increases in Type I error we centered the covariate values before performing the analysis, that is, we subtracted the average covariate score from each covariate value to avoid significant estimate distortions (Schneider et al., 2015).

Our analysis highlighted a significant main effect of the Group ($F_{(1,31)}=4.292$, $p\text{-value}=0.047$, $\eta^2_p=0.12$), a significant main effect of the Condition ($F_{(1,31)}=100.95$, $p\text{-value}<0.001$, $\eta^2_p=0.76$), as well as a significant interaction between factors ($F_{(1,31)}=13.165$, $p\text{-value}=0.001$, $\eta^2_p=0.3$). Interestingly, no effect of the covariate Age was found ($F_{(1,31)}=0.007$, $p\text{-value}=0.93$, $\eta^2_p<0.001$). Post-hoc analysis (after Bonferroni correction for multiple comparisons, adjusting the $p\text{-value}$ and confidence intervals for comparing a family of 6 estimates) underlines that Control participants showed a higher spatial bias in the *perisaccadic* than in the *aposaccadic* condition ($t_{(15)}=-9.55$, $p\text{-value}<0.001$, 95% CI [-3.578 -1.961], Cohen's $d=2.72$). As well, children with DD showed a significant spatial bias in the *perisaccadic* condition compared to the *aposaccadic* condition ($t_{(15)}=-4.508$, $p\text{-value}<0.001$, 95% CI [-2.102 -0.485], Cohen's $d=1.54$). Interestingly, the spatial bias expressed by control participants in the *perisaccadic* condition (M: 1.595, SD: 1.335) was significantly higher than the spatial bias expressed by participants with DD (M: 0.364, SD: 1.042) in the same condition ($t_{(32)}=3.893$, $p\text{-value}=0.002$, 95% CI [0.376 2.142], Cohen's $d=1.03$), suggesting that physiological

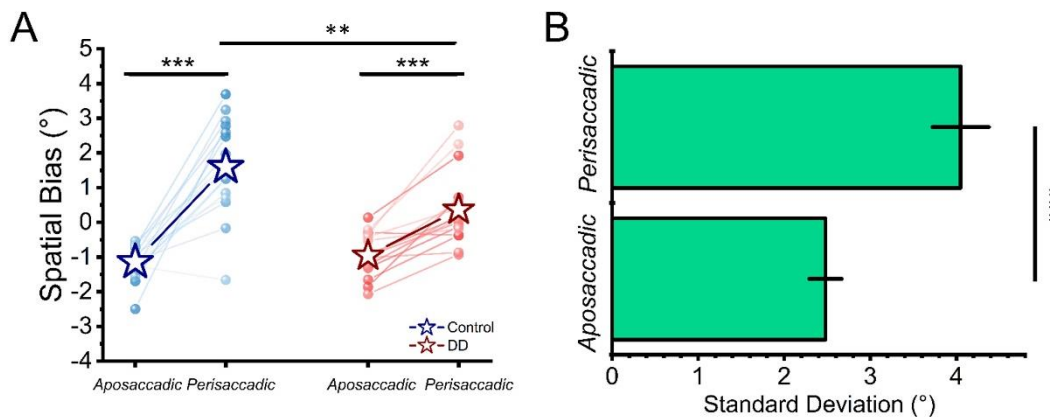


Figure 2.9 Spatial bias and response dispersion during saccadic movements.

A) Spatial bias measured in both control and participants with DD, compared between conditions (*aposaccadic* vs. *perisaccadic*). Stars indicate averaged performance, while each point represent a single participant. B) Response dispersion, measured through standard deviation, between *aposaccadic* and *perisaccadic* spatial judgements. Error bars indicate $\pm$ SEM (for both panels, ***= $p\text{-value}<0.001$).

mechanisms regulating spatial distortions at the time of saccades might be at least partially compromised in children with DD (Figure 2.9A). Lastly, no difference between spatial bias in the *aposaccadic* condition between control participants ($M = -1.144$, $SD = 0.484$) and children with DD ($M = -0.959$, $SD = 0.612$) was found ($t_{(32)} = -0.673$, $p\text{-value} = 1$, 95% CI $[-1.1 \ 0.665]$, Cohen's $d = 0.33$).

We evaluated response dispersion across different conditions to ensure that the spatial bias was not a mere epiphenomenon caused by perceptual noise. Since the spatial distortion induced by the saccadic movement is building within the *perisaccadic* time window, we would expect a higher response variability within this specific timeframe. On the other hand, if response dispersion is constant across conditions, it is plausible to assume that our results are somehow strongly influenced by perceptual observation noise exhibited by our young participants. To evaluate these hypotheses, we ran a Three-way ANCOVA with within factors Stimulus Position (Left vs. Center vs. Right) and Condition (*perisaccadic* vs. *aposaccadic*), and between-subject factor Group (Control vs. Dyslexic) on responses standard deviations. Similar to what was already done before, we controlled the potential influence of the covariate Age over our results. For this analysis, one participant in the control group was excluded as they did not perform any successful trial in the *perisaccadic* condition when the stimulus was placed rightward to the saccadic target. In the end, we found only a main effect of Condition ($F_{(1,60)} = 20.844$, $p\text{-value} < 0.001$, $\eta^2_p = 0.4$), while no main effect of Stimulus Position ($F_{(2,60)} = 0.533$, $p\text{-value} = 0.59$, $\eta^2_p = 0.02$), Group ($F_{(1,30)} = 0.478$, $p\text{-value} = 0.49$, $\eta^2_p = 0.01$), or Age ($F_{(1,60)} = 1.093$, $p\text{-value} = 0.3$, $\eta^2_p = 0.03$) were found. Similarly, interaction effects between Stimulus Position and Group ($F_{(2,60)} = 2.09$, $p\text{-value} = 0.13$, $\eta^2_p = 0.07$), Condition and Group ($F_{(1,60)} = 0.713$, $p\text{-value} = 0.41$, $\eta^2_p = 0.023$), Condition and Stimulus Position ($F_{(2,60)} = 0.061$, $p\text{-value} = 0.94$, $\eta^2_p = 0.002$), and Condition, Stimulus Position, and Group ($F_{(2,60)} = 0.265$, $p\text{-value} = 0.78$, $\eta^2_p = 0.009$) failed to reach statistical significance. Taken together, these results suggest that response dispersion was higher in the *perisaccadic* ($M = 4.05$, $SD = 3.33$) than in the *aposaccadic* ($M = 2.48$, $SD = 1.87$) condition and that the measured spatial bias could not be explained by mere perceptual noise (Figure 2.9B).

Experiment 2

To evaluate the effect of saccadic movements on visual temporal processing, we first fitted psychometric functions into individual participants' data (Figure 2.10A) to define, for each of them, an index of accuracy (i.e., the PSE) and an index of sensitivity (i.e., the JND). To assess whether temporal distortions occurred at the time of saccades, we ran a Two-way repeated measure ANCOVA with within factor Condition (*aposaccadic* vs. *perisaccadic*) and between-subject factor Group (Control vs. Dyslexic) on PSEs, controlling the effect of the covariate Age. Interestingly, we found no main effect of Group ($F_{(1,20)} = 2.15$, $p\text{-value} = 0.16$, $\eta^2_p = 0.1$) nor of Condition ($F_{(1,20)} = 2.632$, $p\text{-value} = 0.12$, $\eta^2_p = 0.12$), but we found a significant interaction effect between factors ($F_{(1,20)} = 7.918$, $p\text{-value} = 0.01$, $\eta^2_p = 0.28$). We also found a tendency for the

covariate Age ($F_{(1,20)}=4.022$, $p\text{-value}=0.06$, $\eta^2_p=0.17$), suggesting that temporal processing might be slightly influenced by age, unlike spatial processing. This result is in line with previous research showing how younger children tend to underestimate the duration of both visual and auditory stimuli (Droit-Volet et al.,

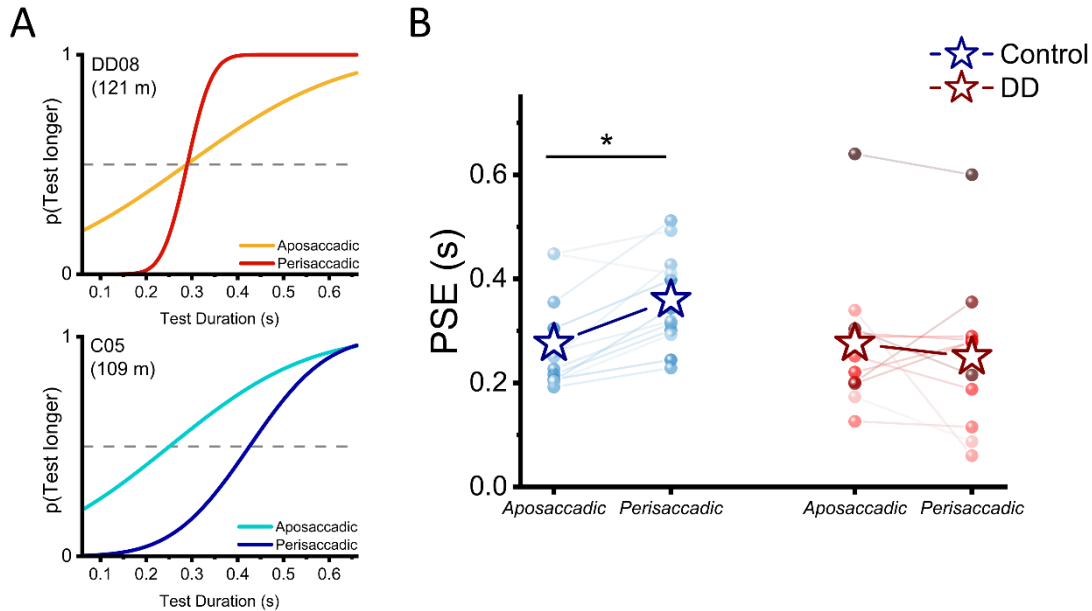


Figure 2.10 Temporal bias during saccadic movements.

A) Sample psychometric curves for two participants, one for each group, with the corresponding age reported in months. Lighter colors indicate performance in the *aposaccadic* condition, while darker color indicate performance in the *perisaccadic* condition. When the inflection points overlap, such as in the participant with DD (upper panel, orange/red curves), saccades did not induce any change in temporal accuracy. However, when the two inflection points are far apart, such as in the control participant (lower panel, cyan/blue curves), saccades determined a significant shift of the PSE and a consequent modification of temporal accuracy. B) PSE measured in both controls and participants with DD, compared between conditions (*aposaccadic* vs. *perisaccadic*). Stars indicate average performance, while each point represent a single participant (*= $p\text{-value}<0.05$).

2007). Post-hoc analysis (after Bonferroni correction for multiple comparisons, adjusting the $p\text{-value}$ and confidence intervals for comparing a family of 6 estimates) highlight no differences in PSE between the *aposaccadic* ($M=0.276$, $SD=0.136$) and *perisaccadic* ($M=0.25$, $SD=0.15$) condition in children with DD ($t_{(10)}=0.877$, $p\text{-value}=1$, 95% CI [-0.052 0.097], Cohen's $d=0.18$). Conversely, the PSE was significantly different between the *aposaccadic* ($M=0.276$, $SD=0.093$) and *perisaccadic* ($M=0.357$, $SD=0.091$) condition in normal-reading participants ($t_{(11)}=-3.168$, $p\text{-value}=0.029$, 95% CI [-0.148 -0.006], Cohen's $d=0.89$). Taken together, these results suggest that saccadic compression of visual temporal information occurred for normal-reading participants, while children with DD failed to shape temporal information at the time of saccades (Figure 2.10B).

Lastly, we investigated the effect of saccadic movements on temporal sensitivity. Thereby, we ran a Two-way repeated measure ANCOVA with within-subject factor Condition (*aposaccadic* vs. *perisaccadic*) and between-subject factor Group (Control vs. Dyslexic) on JNDs, controlling for the effect of the covariate

Age. We found no main effect of Group ($F_{(1,20)}=0.181$, $p\text{-value}=0.675$, $\eta^2_p=0.009$), nor a main effect of Condition ($F_{(1,20)}=0.011$, $p\text{-value}=0.916$, $\eta^2_p<0.001$), as well as no interaction effect between factors ($F_{(1,20)}=0.629$, $p\text{-value}=0.437$, $\eta^2_p=0.031$). Moreover, we found an almost significant effect of the covariate Age ($F_{(1,20)}=3.853$, $p\text{-value}=0.068$, $\eta^2_p=0.162$). Notably, a vast body of literature suggests that temporal sensitivity increases with age (Droit-Volet, 2017; Droit-Volet et al., 2004, 2007), potentially explaining the trend that emerged in our analysis.

Furthermore, in their original research Morrone and colleagues found that temporal sensitivity increases during saccadic movements (Morrone et al., 2005). The authors justified this improvement in temporal abilities considering the functioning of the internal clock, already discussed at the beginning of paragraph 1.1. Since temporal judgments are directly influenced by neural noise, and neural noise is inversely proportional to the ticks produced by the internal clock's pacemaker (Gibbon, 1977), it has been proposed that saccades induce a clock's slowdown so that fewer ticks are delivered during the interval's presentation. Therefore, temporal measurements evaluated at the time of saccades using ticks count should be more precise as fewer ticks are produced. While we do not have a clear, indisputable explanation for the absence of temporal processing improvement observed in our study, we argue that a possible interpretation relies on the intrinsic neural noise present in the child's brain. As neural activity is inherently noisier during development, increased neural noise in specific critical periods might overshadow the potential gain of the lesser number of ticks produced during saccadic movements.

Clinical Relevance of the Study

As emerged from our study, children with DD experience reduced saccadic compression of visual spatial and temporal information compared to normal-reading peers. While these results provide insights on a set of neural mechanisms potentially impaired in DD, they give no useful information from the clinical perspective. Thereby, we tried to relate saccadic compressions to both reading speed and errors, testing whether these two perceptual indices could successfully predict reading impairments using robust linear regression models.

First, we used robust linear regression to test whether Spatial Bias could predict Reading Speed considering all children together, obtaining the following fitted regression model:

$$\text{Reading Speed} = 0.50426 * \text{Spatial Bias} + 1.9094$$

The overall regression was statistically significant ($R^2=0.172$, $F_{(1,32)}=6.64$, $p\text{-value}=0.015$), suggesting that Reading Speed could be predicted using saccadic Spatial Bias (Figure 2.11A).

Then, we used the same model to test whether Temporal Bias could predict Reading Speed. We obtained the following fitted regression model:

$$\text{Reading Speed} = 10.018 * \text{Temporal Bias} + 2.6798$$

The overall regression was statistically significant ($R^2=0.273$, $F_{(1,21)}=7.9$, $p\text{-value}=0.01$), suggesting that Reading Speed could be predicted using saccadic Temporal Bias (Figure 2.11B). Nonetheless, the low R^2 values obtained in both linear fitting procedures hint that the relationship between reading speed and saccadic compressions might be pretty challenging to explain.

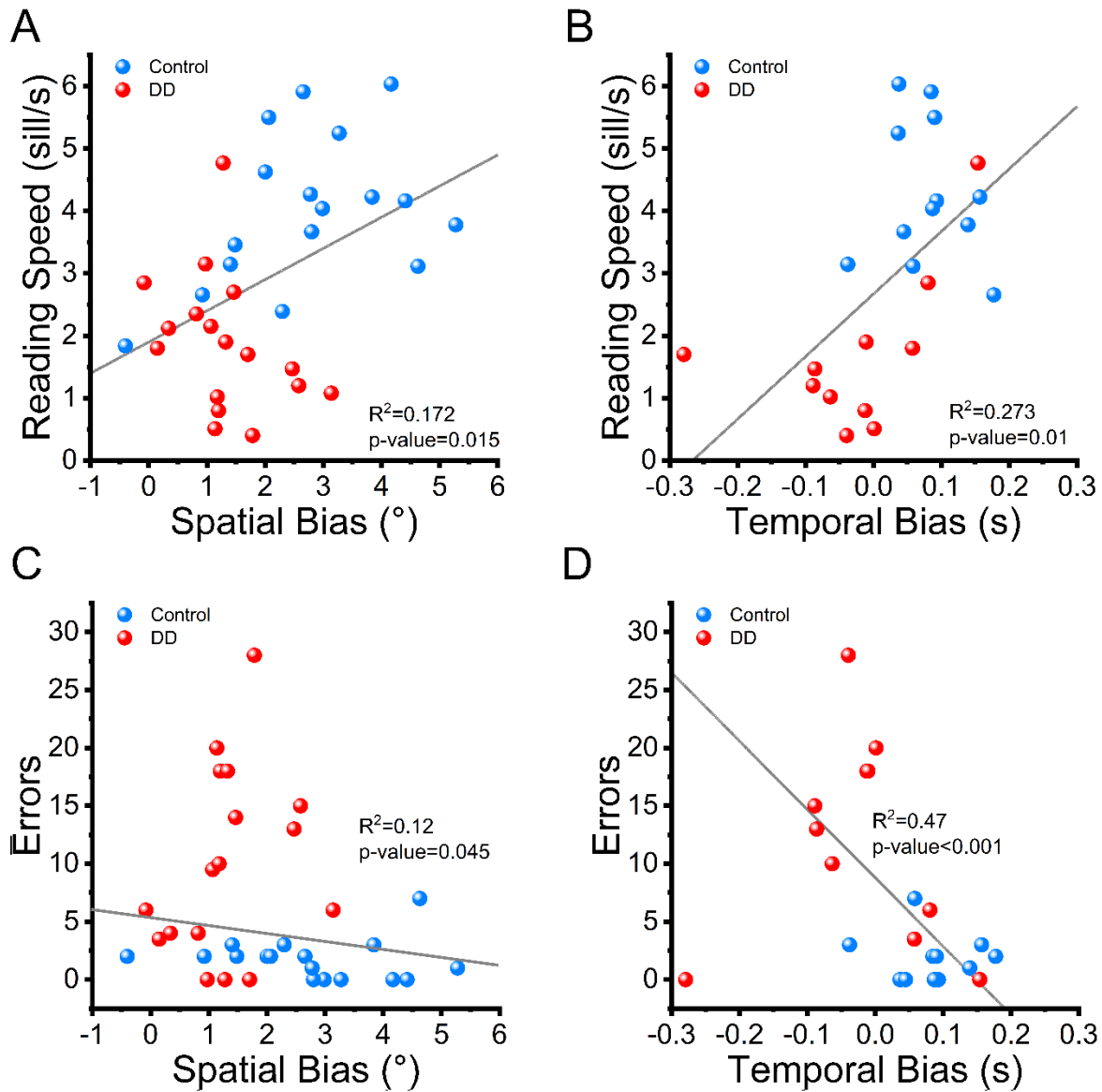


Figure 2.11 Robust linear regressions between saccadic biases and reading abilities.

Robust linear regressions fitted for all participants considering A) Spatial Bias and Reading Speed, B) Temporal Bias and Reading Speed, C) Number of reading Errors and Spatial Bias, and D) Number of reading Errors and Temporal Bias.

As reading speed significantly correlates with both the spatial ($R_{(32)}=0.45$, $p\text{-value}=0.007$) and temporal ($R_{(21)}=0.56$, $p\text{-value}=0.005$) saccadic compression, we argue that it is problematic to define whether saccadic compressions influence reading speed or if there is a third, hidden factor determining coherent oscillations in both variables. Moreover, reading is a complex activity that involves many different components (Cohen et al., 2000; Jobard et al., 2003; Kouider et al., 2007; Paris, 2005; Pugh et al., 1996; Ricketts et al., 2007), thereby it is hard to define a single perceptual index able to highlight, on a one-to-one basis, how well a child can read.

Similarly for what already performed considering reading speeds, we fitted robust linear regressions between saccadic biases and reading errors that occurred during the initial evaluation of reading abilities, considering all children within the same analysis. To test whether Spatial Bias could predict the number of reading errors, we fitted robust linear regression obtaining the following model:

$$\text{Errors} = -0.70702 * \text{Spatial Bias} + 5.4634$$

The overall regression was statistically significant ($R^2=0.12$, $F_{(1, 32)}=4.32$, $p\text{-value}=0.045$), suggesting that children who experienced the highest spatial compression performed few errors (Figure 2.11C).

Lastly, we fitted robust linear regression between Temporal Bias and the number of reading errors, obtaining the following model:

$$\text{Errors} = -59.769 * \text{Temporal Bias} + 8.7873$$

The overall regression was statistically significant ($R^2=0.47$, $F_{(1,21)}=18.6$, $p\text{-value}<0.001$), suggesting that children who experienced the highest temporal compression performed fewer errors while reading (Figure 2.11D).

To further investigate the clinical relevance of saccadic perceptual distortions, we developed a logistic regression model to test whether saccadic compressions could be used to propitiate and support the diagnosis of DD (Figure 2.12).

Logistic regression was performed to ascertain the role of spatial and temporal bias on the likelihood that participants were diagnosed with DD (0=Control, 1=DD). The logistic regression model was statistically significant ($\chi^2_{(20)}=19.981$, $p\text{-value}<0.001$, McFadden $R^2=0.62$), and both spatial and temporal bias were significant predictor variables. Decreasing in spatial (Odds Ratio=0.123, $p\text{-value}=0.042$, 95% CI [-4.119 - 0.079]) and temporal (Odds Ratio<0.001, $p\text{-value}=0.036$, 95% CI [-35.88 -1.164]) saccadic compression was associated with an increase probability to be diagnosed with DD. Indeed, odds ratios suggest that both predictors are inversely related to the dependent variable Group. Notably, the model also shows a strong predictive power, with a sensitivity of 0.9 and a specificity of 0.917.

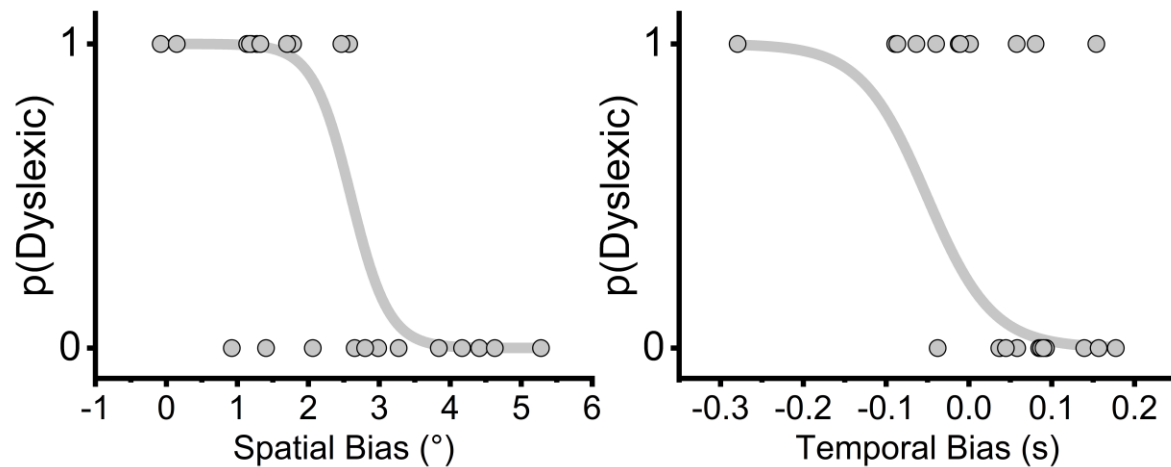


Figure 2.12 Modelling the correct diagnosis probability given saccadic biases.

Logistic regressions on variable Group (probability to correctly classify a child in either the control or the DD group) using as covariates both spatial and temporal bias.

Conclusions

The following study supports once more the notion that magnocellular temporal processing is inefficient in children with DD. Interestingly, we found a reduced efficiency of spatial processing as well, even though children with DD still experienced some degree of spatial compression at the time of saccades (Figure 2.9A). Developing a novel approach, we centered our investigation on the perceptual consequences of saccadic movements rather than focusing on their phenomenological features (such as vergence and accuracy). Nonetheless, few precautions must be discussed to precisely conceptualize the role of magnocellular neurons in determining the absence of saccadic compressions.

For many years, magnocellular neurons have been thought to be unable to provide finely high-frequency or colored information, being considered univocally sensitive to contrast, temporal, and motion information (Livingstone & Hubel, 1988). Since we used colored stimuli on an isoluminant red background, one can argue that magnocellular neurons were not involved when performing the saccadic tasks. Furthermore, red has often been associated with the tonic suppression of magnocellular neurons' excitatory activity (De Monasterio, 1978; Dreher et al., 1976), suggesting that the absence of saccadic compressions observed in DD (precisely, the temporal one) cannot be accounted for considering abnormal magnocellular processing.

Nonetheless, in recent years a significant body of evidence drastically challenged these conceptualizations. Using both electrophysiological and psychophysical techniques, Hugarass and colleagues found that red surrounds do not suppress the magnocellular pathway but that, on the contrary, they even enhance magnocellular sensitivity under certain conditions (Hugarass et al., 2018). Similarly, while isoluminant

stimuli have often been used to silence magnocellular neurons, many studies found activations of magnocellular neurons in response to them (Hubel & Livingstone, 1990; Krüger, 1979; Lee et al., 1988; Lee & Sun, 2009; Peter H. Schiller & Colby, 1983). As a consequence, being able to suppress magnocellular inputs in psychophysical tasks with mere isoluminance is highly questionable (Skottun, 2013). Another interesting aspect to consider is that it is practically impossible to achieve isoluminance at every stimulus location. This is because perceived luminance depends on the responses of different retinal cells whose ratio changes across the retina and on the fact that chromatic aberrations arise at a stimulus' border, which can determine luminance borders (Edwards et al., 2021).

Considering these premises, the absence of saccadic compressions in children with DD is a reasonably intriguing aspect to discuss. In typical adults, the magnocellular visual pathway is selectively suppressed at the time of saccades, as loss of sensitivity for low spatial frequencies modulated in luminance has been extensively observed (Burr et al., 1994). Interestingly, the saccadic suppression of the magnocellular visual pathway seems to follow a developmental trend since adolescents experience higher sensitivity changes at the time of saccades compared to young adults (Bruno et al., 2006), suggesting that some features of magnocellular processing reach maturation in later stages of life (and can potentially fail to reach maturation under particular conditions).

Saccadic spatial compression has been justified considering both the receptive fields' predictive anticipatory remapping, which happens at various levels of information processing (Duhamel et al., 1992; Nakamura & Colby, 2002; Umeno & Goldberg, 1997; Walker et al., 1995), and the fact that the suppression of the magnocellular pathway, which provides the primary input to parietal cortices involved in spatial localization (Mishkin et al., 1983), might determine distortions of internal spatial representations (Ross et al., 1997). Temporal distortions at the time of saccades have been related to similar mechanisms, implying that *perisaccadic* timing processing is selectively modulated by saccade-related neural circuitry (Morrone et al., 2005). Thereby, suppression of the magnocellular pathway should also lead to distortions in the metric of internal representation of time. Furthermore, since magnocellular streams show preferential encoding for transient, rapid-change visual events, it is no surprise that alteration of their functionality determines distortions of perceived durations.

In our study, *perisaccadic* modulations of temporal responses were absent in children with DD, while modulations of spatial responses were significantly reduced, even though still present. In light of these considerations, the absence of saccadic compressions observed in children with DD suggests that their internal spatial and temporal metrics are less adaptable to endogenous, physiological events. This conceptualization is in line with the notion that magnocellular processing is overall less efficient and

flexible in children with DD and, on a more specific scale, with the magnocellular theory of dyslexia (Stein, 2001, 2019; Stein & Walsh, 1997).

Interestingly enough, these results can also be conceptualized within the cross-sensory calibration theory framework as well, since DD is often associated with poor auditory perception (Boets et al., 2007; Menell et al., 1999; Witton et al., 1998, 2002). As already discussed in paragraph 1.2.1, such impairment across development theoretically impacts temporal processing across the whole lifespan. Thereby, our findings suggest that the disruption of hearing inputs in the early stages of life might significantly shape magnocellular processing, hence the absence of saccadic compressions. The link with the cross-sensory calibration theory is further supported by the fact that saccadic compression of temporal information was utterly absent in children with DD, while saccadic compression of spatial information was not (even though its magnitude was significantly reduced compared to normal-reading peers). This suggests that temporal perception in DD is far more flawed than its spatial counterpart, and highlights a selective magnocellular processing impairment tailored around temporal information. Comparing our results with the existing literature, there is a significant overlap with behavioral evidence demonstrating that individuals with DD experience various degrees of generalized temporal deficits (Casini et al., 2018; Gori et al., 2020; Hari et al., 2001; Jaśkowski & Rusiak, 2008).

On a final note, our study highlight also some exciting implications related to the clinical evaluation of DD. On the one hand, we found that saccadic compressions are linked to specific aspects of reading, such as its speed and the number of errors made. While it is undoubtedly hard to reduce reading impairments to a single perceptual parameter, we believe that the absence of saccadic compressions might be a relevant element to consider when investigating DD and its peculiar clinical manifestations. On the other hand, we also found that both spatial and temporal compressions could be combined within the same logistic regression model to support clinical diagnosis. As our logistic model correctly identified more than 90% of the participants as either dyslexic or not, saccadic compression indices might become extremely valuable within clinical contexts. Notably, saccadic compressions indices can become helpful not only to support clinicians' evaluations, but also to foster pre-scholar, early screening intervention as they are obtained through non-semantic testing procedures.

Chapter Three

Portable Psychophysics

In his enthusiastic scientific autobiography, *Tales from both sides of the Brain*, the world-renowned neuroscientist Michael S. Gazzaniga wrote that “The study of Psychophysics proves that it is impossible to bore a German. Thankfully” (Gazzaniga, 2015). Despite this humorous quote, it is undeniable that psychophysical methods are often highly repetitive, time-consuming, and frequently require high-performing setups to be developed appropriately.

Even though psychophysical data collection can sometimes be performed in timely fashions, such as using target tracking (Bonnen et al., 2015), various factors can hinder the evaluation of perceptual abilities. Beyond technical issues related to the needing for overly precise devices, data collection is inherently limited by the possibility to access the facilities in which these devices are held. Undeniably, the recent COVID-19 pandemic outbreak heavily impacted research activities around the globe, limiting such access and making psychophysical data all the more difficult to collect. Nonetheless, even before the pandemic outbreak, accessibility issues have always been relevant in at least two cases. On the one hand, when testing procedures involve participants who cannot reach research facilities due to logistics, or when a specific study is designed around individuals that have limited mobility, such as bed-ridden patients (interestingly, perceptual evaluations have been already linked to conditions that reduce the ability to move (Arrighi et al., 2011)). On the other hand, ease of access must be contemplated when perceptual evaluations are spread across various sessions, as reaching the facility for several days in a row can be seen as a deterrent for many potential participants. This is the case, for example, occurring when implementing perceptual learning protocols, in which the drop-out risk must be considered and – when possible – reduced to contain the experiment’s costs in terms of both time and money.

Here, we challenged both issues by conceptualizing and designing *PsySuite*, an Android APP created to foster a remote, portable, and easy-to-use approach to psychophysical data collection. *PsySuite* was developed to deliver multi-modal (visual, acoustic, and tactile) stimulations with extreme temporal

precision and accuracy. The idea of designing such a novel methodology to perform psychophysical testing was fuelled not only by the COVID-19 contingencies but also by the fact that smartphones can be nowadays highly affordable and practical. Suffice to say that, at the moment in which *PsySuite* was first conceptualized at the beginning of 2020, the number of active mobile subscriptions exceeded the number of people on the planet (World Telecommunication/ICT, 2020). With these considerations in mind, we designed *PsySuite* aiming at satisfying the following requirements:

- ✚ Deliver accurate and precise multi-modal stimulations;
- ✚ Allow participants to perform data collection in an autonomous and flexible way;
- ✚ Collect data on a trial-by-trial basis and send results directly to the experimenter;
- ✚ Develop auto-update routines to correct bugs and administer future implementations.

To support *PsySuite*'s feasibility in fostering remote data collection, we combined two different validation procedures. First, we ran a battery of tests to evaluate the App's hardware performance, measuring stimuli's accuracy and stability across repetitions with an oscilloscope, performing then post-processing signal analyses with custom-made Matlab (v. 2021b) scripts. Second, we compared the results of a simple behavioral experiment collected with a canonical, PC-based setup, with the results in the same experiment obtained using *PsySuite*. We, therefore, opted for testing whether we could elicit the double-flash illusion (DFI) using our App, and whether the magnitude of the effect was comparable to the magnitude of the same effect induced with a classical research apparatus. Furthermore, the DFI was chosen since the illusion can be elicited only when the duration of the stimuli and the temporal distance between them is around a few tens of milliseconds (Keil, 2020). Thereby, such an experimental paradigm represents a solid procedure to validate the App's performance, as the requirement of high temporal resolutions sufficiently stresses *PsySuite*'s hardware and software components. This effectively mimics the hardware overload often needed to perform precise psychophysical measurements.

After assessing both App's validations, we developed a *PsySuite* library specifically designed to evaluate and enhance temporal perceptual thresholds. We tested the possibility to involve the App in psychophysical studies about temporal processing in participants with no sensory or learning disabilities. Then, we used *PsySuite* to investigate altered temporal abilities in deaf individuals and children with DD, further supporting the possibility to implement the App in clinical, other than research, environments.

3.1 Introducing *PsySuite*

Architecture and Implementation

PsySuite was developed within the Android environment as Android smartphones have broader market availability and reduced cost compared to other smartphones brands. Since the App was designed to sustain performance-demanding data collection procedures, we targeted modern smartphones equipped with the most recent versions of Android OS. *PsySuite* was compiled considering an Android SDK with a level of at least 27, corresponding to no less than Android v. 8.1. We used Kotlin as the programming language and AndroidX as library package. Notably, we did not strictly adhere to the MVVM design pattern recommended by Google, even though we considered the separation of concerns between models, views, and business logic.

Experimental Stimuli

Audio stimuli developed within the App were square tone at 1000 Hz, sampled at 48 kHz, encoded in a 16-bit format and stored as .WAV file. Visual stimuli were blue circles with a diameter of 4 cm. Tactile stimuli were phone vibrations delivered at the maximum intensity available. Notably, all stimuli were delivered with the addition of a white noise background. We opted for this decision as vibrations produced by the smartphones' engine were audible, and such incidental auditory information could influence performance in tasks involving the tactile modality. Thereby, white noise signals were used to mask vibrations' related sounds and obtain indices of performance based on pure somatosensory perception. For consistency purposes, white noise backgrounds were added to all stimulations, regardless of the sensory modality involved.

Stimuli Generation Application Programming Interface (API)

Undeniably, the stimuli generation procedure is the core element of the whole app. Psychophysical research involves uni- and multi-modal stimulations that must be conveyed using accurate and precise timing. Specifically, using *PsySuite* we aimed at delivering reliable visual, auditory, and tactile stimulations, both individually and in any of their possible combinations.

Acoustic stimuli have proven to be the most problematic to generate among all sensory modalities involved because the Android Audio Framework is composed of several components that work together, even though they do not guarantee complete determinateness of output latencies (Gokul et al., 2016). The out-of-the-box audio solution developed within Android environments relies on the MediaPlayer API. The MediaPlayer API is a high-level solution able to playback various audio compressed formats, even though

it is difficult to produce low latency output streams following this interface. Thereby, we decided to explore two different, potentially more accurate solutions: the AudioTrack Java API and a C++ native solution executed via the Oboe library (<https://github.com/google/oboe>), which inherently support the development of high-performance audio App on Android OS. We sampled auditory stimuli considering the system's optimal sampling frequency to implement low-latency playback audio streams, encoding them in an uncompressed format. Therefore, audio stimuli were stored in an uncompressed 16-bit PCM format with a sampling rate of 48 kHz and saved as .WAV files. At the beginning of each experimental session, recorded stimuli were preloaded in a dedicated audio buffer and repeatedly played, reducing timing latencies as much as possible. At the end of each experimental session, audio resources were released to generate stimulations.

AudioTrack is a low-level Java API mapping directly into the native code, allowing the reading of each .WAV file's content as ByteArray and copying it into their own object's buffers (ran in static mode). The playback head position is fixed at zero within the static buffer at the end of each auditory presentation. Conversely, the Oboe library is a Google C++ library developed around *ESAudio* (if the SDK level is less than 26) or *AAudio* (if the SDK level is equal to or higher than 27), proposing several optimization routines to reduce input/output timing latencies significantly. Both AudioTrack and the native Oboe solutions were initially considered when producing auditory stimuli, even though, in the end, the latter was chosen due to its more straightforward implementation and slightly superior reliability.

Visual stimuli were created by storing 8-bit PNG drawables within an ImageView component located in a Fragment at the start of each experimental session. Onsets, offsets, and duration of the stimuli were controlled by modifying the component's visualness.

Tactile stimuli were implemented using Android's VIBRATOR_SERVICE, and modeled using the vibrate and cancel methods of the Vibrator inherent class.

3.1.1 Hardware Validation

To validate *PsySuite*'s performance, we ran technical measurements on two different smartphones: a Xiaomi Mi A2, with 3 Gbyte of RAM and a Qualcomm® Snapdragon™ 625 Octa-Core processor running at 2.0 GHz, and a Samsung A40, with 4 Gbyte of RAM and an Octa-Core processor (2x 1.8 GHz Cortex-A73 and 6x 1.6 GHz Cortex-A53). Android v. 10 was installed as an operating system in both smartphones, and both smartphones' refresh rate was 60 Hz.

To measure all different signals produced by *PsySuite*, we used a TDS 2014B Tektronix oscilloscope (Figure 3.1). Visual stimuli were measured through a phototransistor cabled to an external amplifier set at 5V. Tactile stimuli were measured using a brass, disk-shaped piezoelectric sensor with a diameter of 27

mm and a thickness of 0.4 mm. Auditory Stimuli were measured by acquiring the signal directly from the smartphones' 3.5" jack output. All sensors were simultaneously connected via crocodile cables to the oscilloscope across different channels.

The oscilloscope was directly plugged via USB cable to a Lenovo X220 notebook, running MATLAB v. 2013. Each signal was stored within a structure and then evaluated using MATLAB custom-made scripting procedures through post-processing signal analyses. Regardless of the sensory modalities involved, signals were recorded with a 10,000 Hz sampling frequency and measured within a timeframe of ± 125 ms (with 0 being the approximate stimulus' onset by definition), thereby allowing the recording of oscilloscope traces both before and after stimuli delivery.

During post-processing analyses, auditory and tactile signals were smoothed using a Savitzky-Golay filter, fitting subsequent sets of signals' adjacent points with a low-degree polynomial and the linear least-squares method. We scanned for abrupt changes in the signals' traces to mark stimuli's onsets and offsets. Thereby, we evaluated the signals' means and standard deviations before stimuli delivery and considered stimuli's onsets when traces suddenly exceeded a given cutoff, fixed at the averaged signal's value before the stimulus' onset $\pm$ two standard deviations. Using a similar procedure, we evaluated the last traces' points in which the signal exceeded the same cutoff value so that we were able to pinpoint stimuli's offsets as well. Visual signals were smoothed using a low-pass filter with a normalized passband filter of 0.1π rad/sample. We divided the oscilloscope's traces into different partitions to identify abrupt changes. We evaluated the point that minimized the sum of the residual squared error from its local averaged value for each partition. Setting the number of regions as a free-to-vary parameter, we could locate all the significant signals' frames denoting stimuli's onset and offset, i.e., frames in which the signal significantly changed. For all sensory modalities, stimuli durations were evaluated simply by calculating the time difference between stimuli's offset and onset.

To assess *PsySuite*'s feasibility in performing psychophysical experiments, we investigated both its accuracy and precision in delivering uni- and multi-modal stimulations. We performed different recording sessions consisting of 100 subsequent trials for all stimuli durations and sensory modalities combinations.

For each sensory modality or each of their possible combination, we tested and recorded with the oscilloscope the following stimulus durations: 7, 17, 30, 50, and 100 ms. Then, the App's accuracy was tested by evaluating how the produced stimulations matched their corresponding input parameters, i.e., whether onset, offset, and duration respected the values chosen by the experimenter. To obtain an index of accuracy, we calculated the median of measured durations across each recording session. The App's precision was afterward evaluated, testing whether the accuracy of stimulation could be maintained across

prolonged experimental sessions. We thereby calculated the standard deviation of all 100 stimulations measured in each recording session, while expecting a reduced stimulations' variability if *PsySuite* maintained an adequate level of stability over the generation procedure.

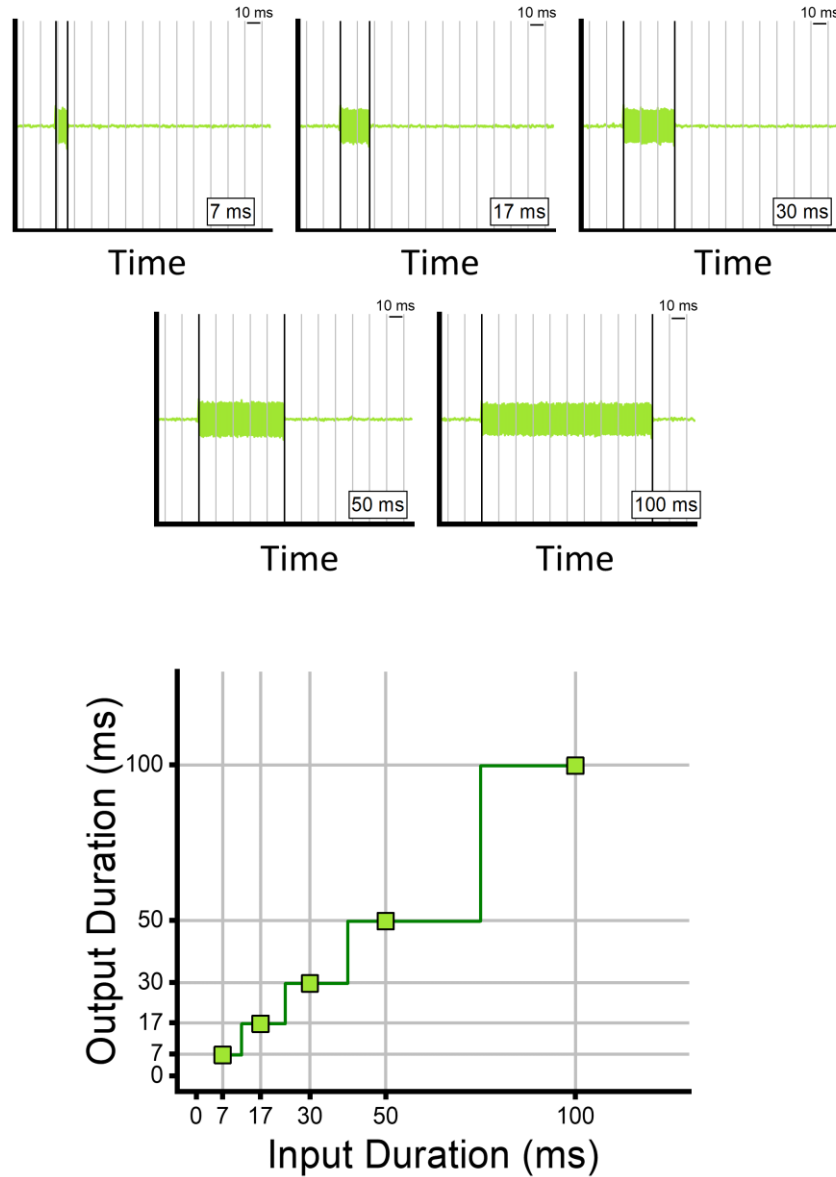
Lastly, we evaluated the minimum temporal distance (i.e., the inter-stimulus interval, ISI) achievable between two stimuli generated with *PsySuite*. To develop proper ISI during recording procedures, we considered the minimum stimulus duration correctly reproduced in the previous tests for each sensory modality. For each possible duration, we applied an ISI that was double the minimum duration considered for that session and assessed whether the App managed to produce both stimuli in sequence. We started considering stimuli with a 7 ms duration (when *PsySuite* managed to produce stimuli as short as that) and an ISI of 14 ms, and then we progressively increased both parameters according to the following formula:

$$(3.1) \text{ ISI} = 2 \cdot \text{stimulus duration}$$

For what concern between-modalities simultaneity accuracy, we evaluated the reciprocal temporal shift considering sensory signals when all three modalities were involved. Such shift is highly dependent on the hardware's and software's intrinsic properties and cannot be changed. Thereby, we evaluated whether stimuli's onsets were temporally misplaced and, eventually, corrected every single modality's onset so that they all occur at the same time. In the following pages, we reported both sample oscilloscope traces and averaged results obtained after stressing the App with 100 trial-recording sessions. When one of the smartphones failed to produce any kind of stimulations (e.g., if the motor engines failed to turn on), we intentionally left the sample traces blank.

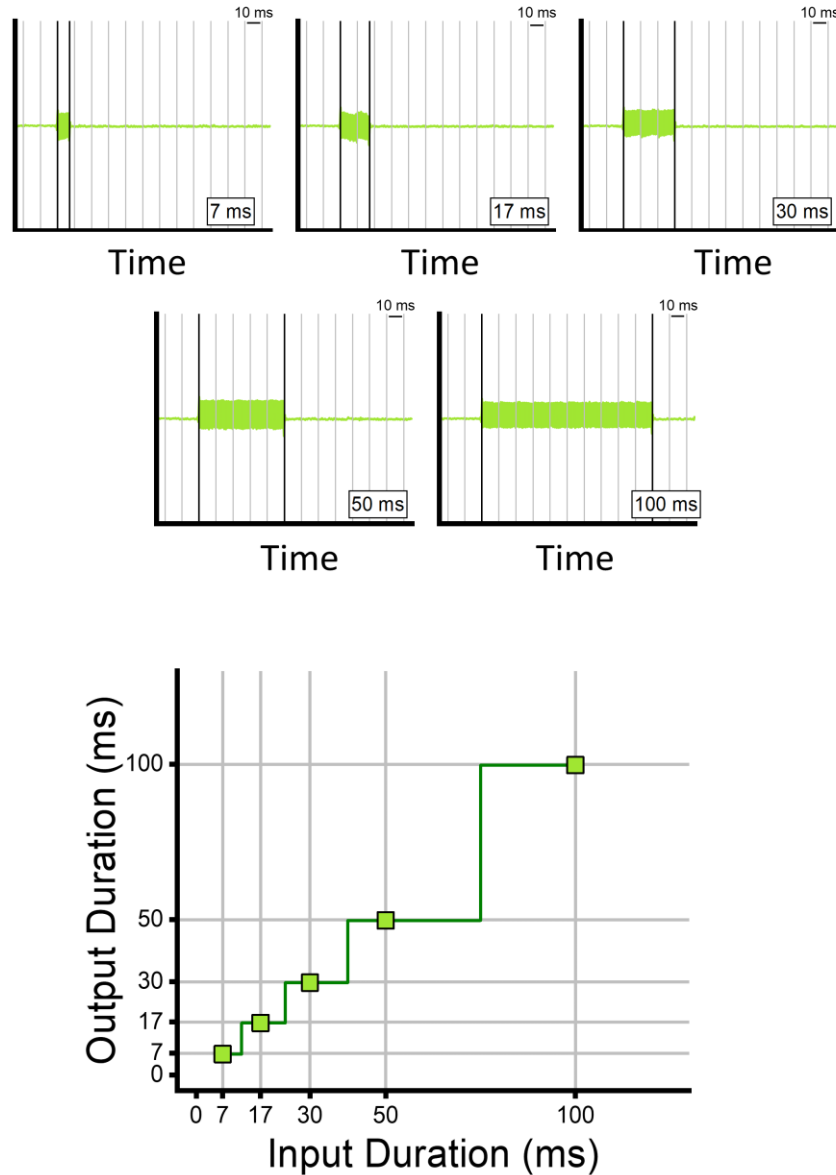
Uni-modal Signals

Uni-modal Stimulations' Accuracy and Precision – Auditory



Xiaomi Mi A2

Figure 3.1 Sample signals' traces, accuracy, and precision for single auditory stimuli delivered using the Xiaomi Mi A2. Sample waveforms measured with the oscilloscope for auditory signals of different durations (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Xiaomi Mi A2 smartphone. In traces graphs, black vertical lines indicate signals' onset and offset marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical signals' durations (output duration) as a function of the durations chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each duration. Both medians and standard deviations were calculated within 100 trials sessions.



Samsung A40

Figure 3.2 Sample signals' traces, accuracy, and precision for single auditory stimuli delivered using the Samsung A40. Sample waveforms measured with the oscilloscope for auditory signals of different durations (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Samsung A40 smartphone. In traces graphs, black vertical lines indicate signals' onset and offset marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical signals' durations (output duration) as a function of the durations chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each duration. Both medians and standard deviations were calculated within 100 trials sessions.

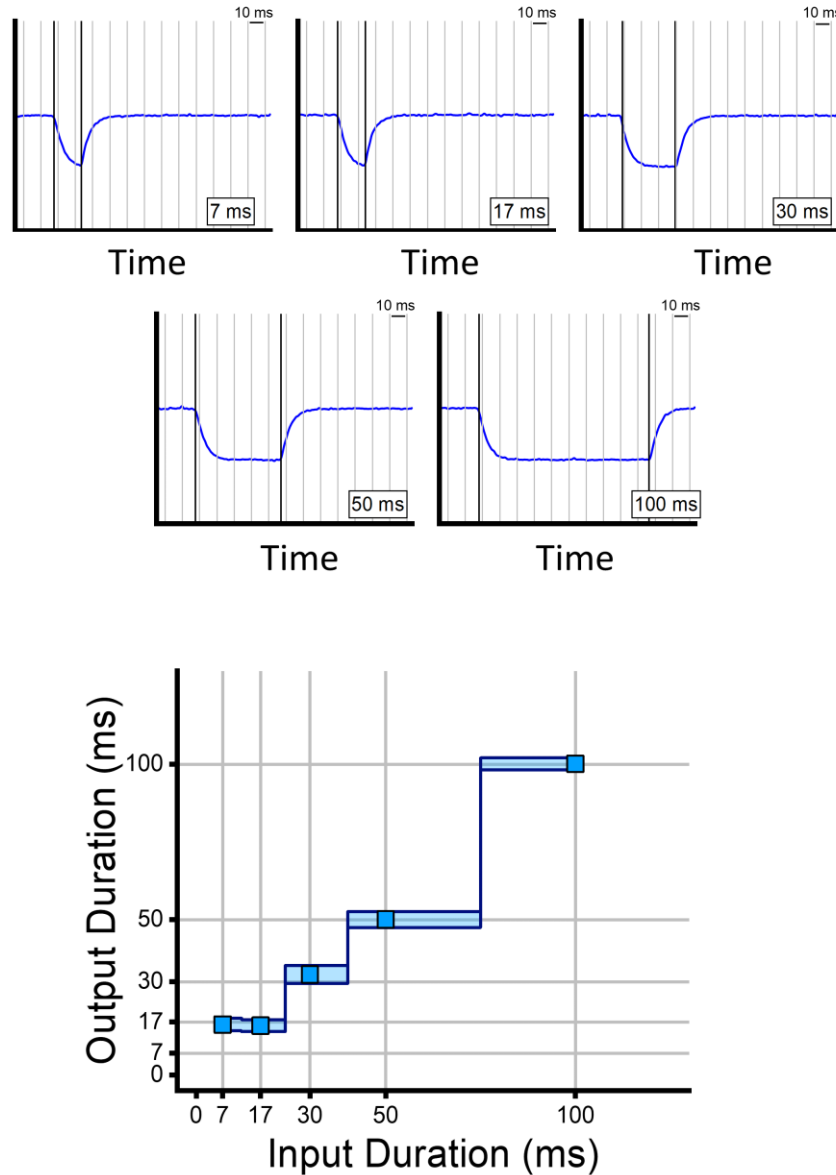
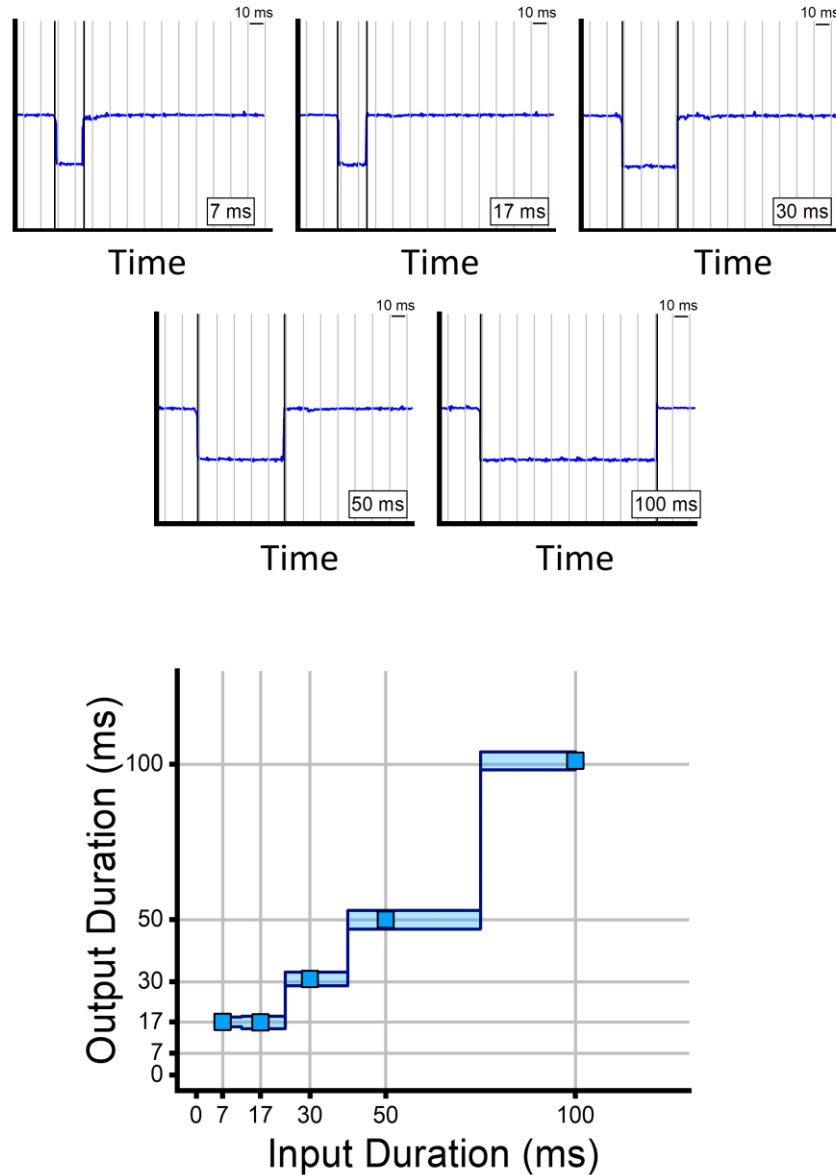
Uni-modal Stimulations' Accuracy and Precision – Visual**Xiaomi Mi A2**

Figure 3.3 Sample signals' traces, accuracy, and precision for single visual stimuli delivered using the Xiaomi Mi A2. Sample waveforms measured with the oscilloscope for auditory signals of different durations (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Xiaomi Mi A2 smartphone. In traces graphs, black vertical lines indicate signals' onset and offset marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical signals' durations (output duration) as a function of the durations chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each duration. Both medians and standard deviations were calculated within 100 trials sessions.



Samsung A40

Figure 3.4 Sample signals' traces, accuracy, and precision for single visual stimuli delivered using the Samsung A40. Sample waveforms measured with the oscilloscope for auditory signals of different durations (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Samsung A40 smartphone. In traces graphs, black vertical lines indicate signals' onset and offset marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical signals' durations (output duration) as a function of the durations chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each duration. Both medians and standard deviations were calculated within 100 trials sessions.

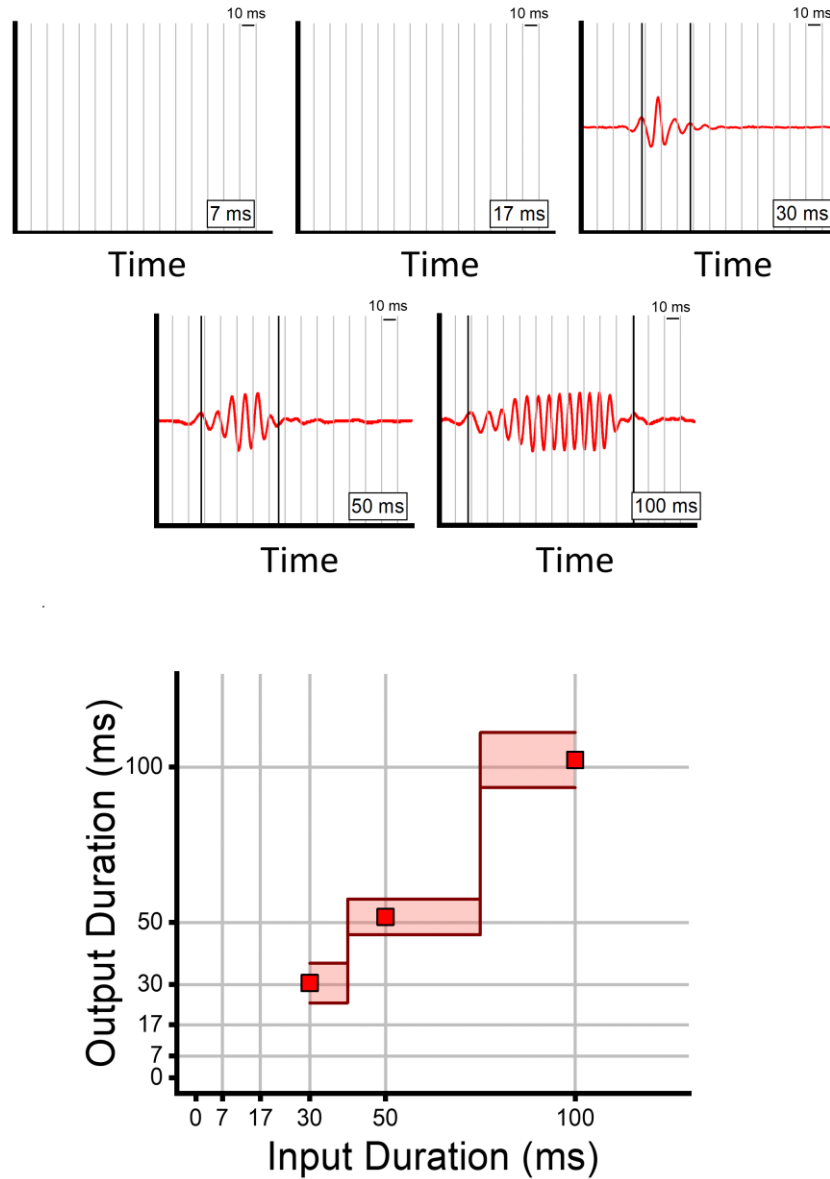
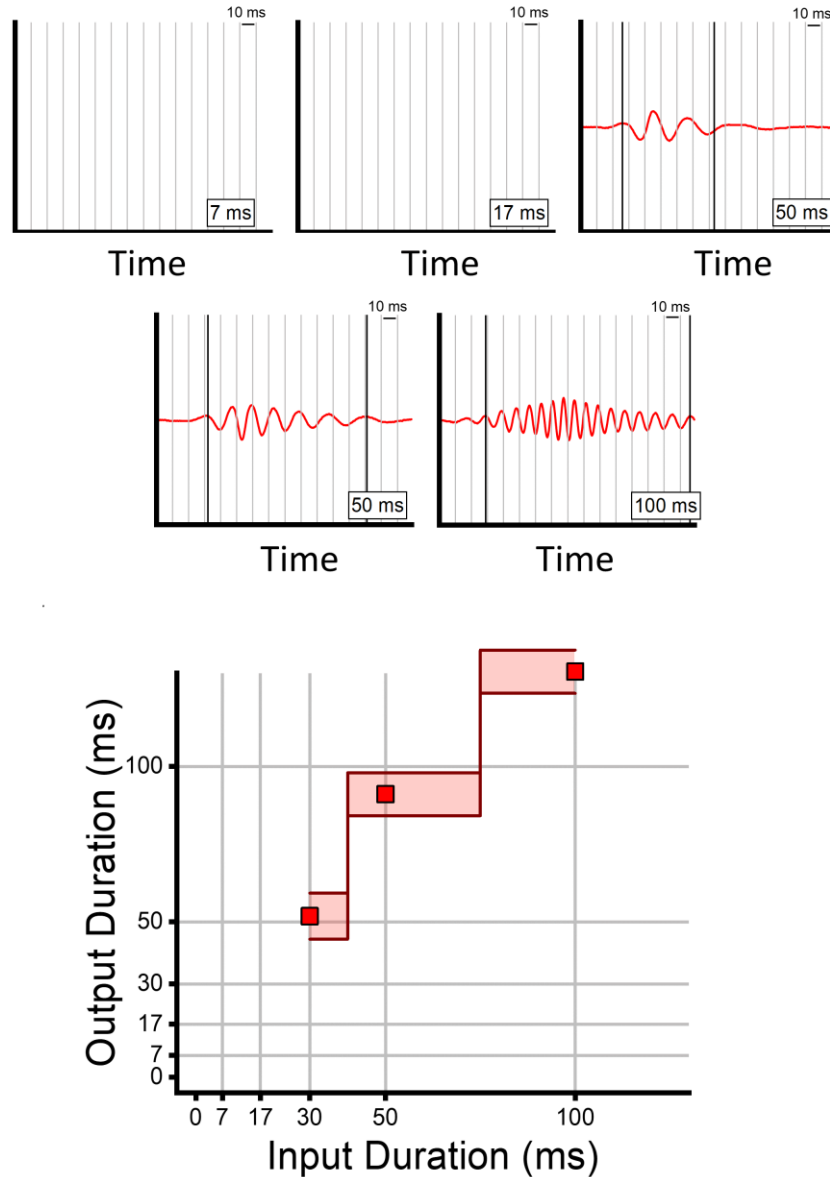
Uni-modal Stimulations' Accuracy and Precision – Tactile**Xiaomi Mi A2**

Figure 3.5 Sample signals' traces, accuracy, and precision for single tactile stimuli delivered using the Xiaomi Mi A2. Sample waveforms measured with the oscilloscope for tactile signals of different durations (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Xiaomi Mi A2 smartphone. In traces graphs, black vertical lines indicate signals' onset and offset marked in the post-processing analysis. Empty traces indicate that the smartphone failed to deliver any stimulation for the chosen duration. Within the scatter plot, we reported medians of the physical signals' durations (output duration) as a function of the durations chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each duration. Both medians and standard deviations were calculated within 100 trials sessions.



Samsung A40

Figure 3.6 Sample signals' traces, accuracy, and precision for single tactile stimuli delivered using the Samsung A40. Sample waveforms measured with the oscilloscope for tactile signals of different durations (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Samsung A40 smartphone. In traces graphs, black vertical lines indicate signals' onset and offset marked in the post-processing analysis. Empty traces indicate that the smartphone failed to deliver any stimulation for the chosen duration. Within the scatter plot, we reported medians of the physical signals' durations (output duration) as a function of the durations chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each duration. Both medians and standard deviations were calculated within 100 trials sessions.

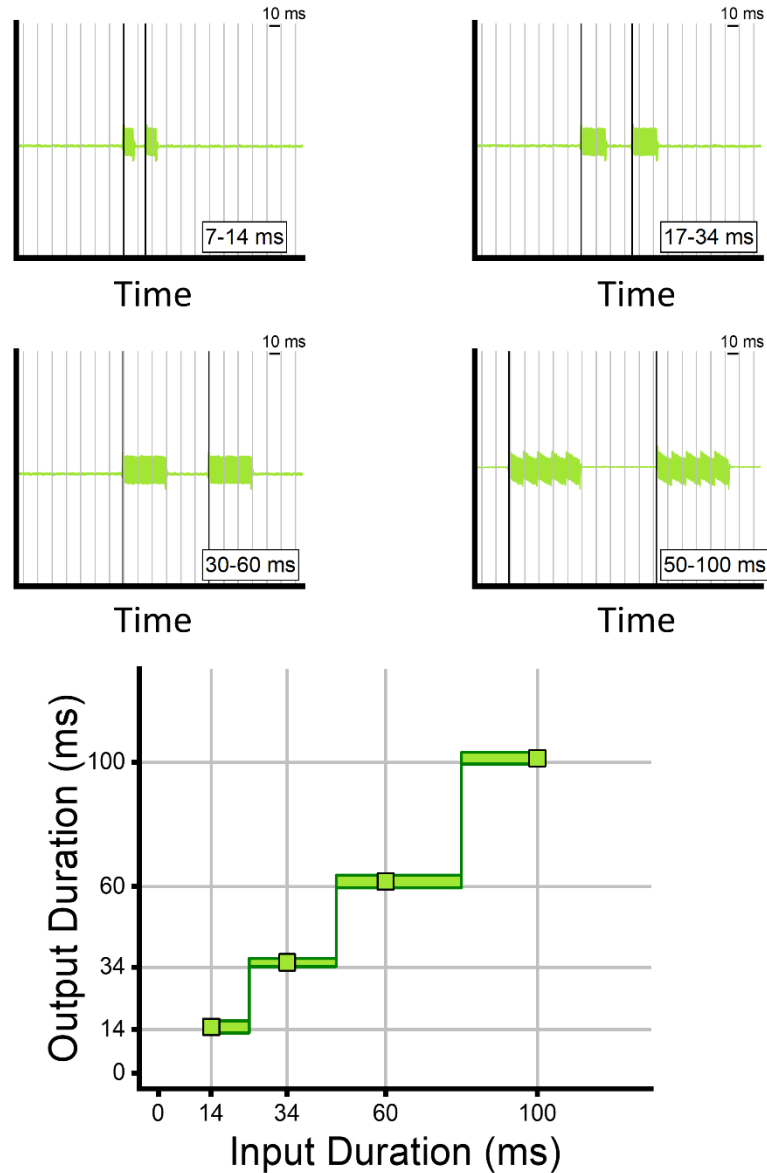
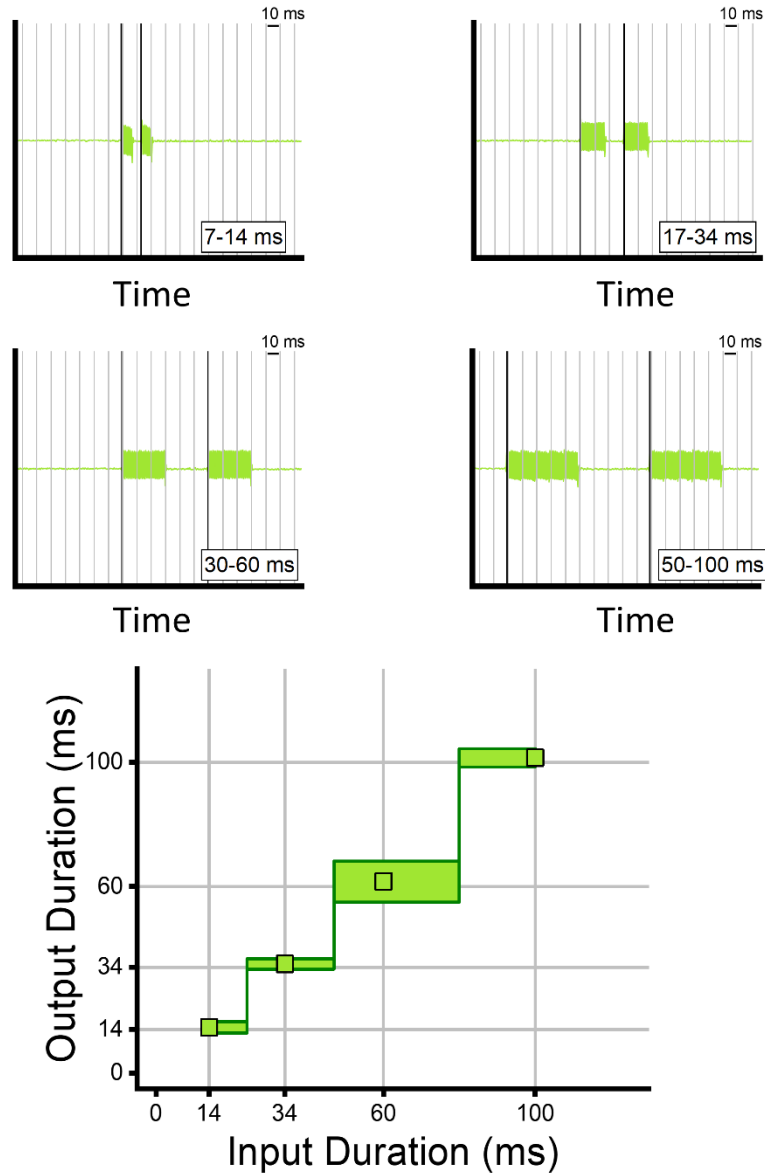
Uni-modal Minimum Temporal Difference – Auditory**Xiaomi Mi A2**

Figure 3.7 Sample signals' traces, accuracy, and precision for paired auditory stimuli delivered using the Xiaomi Mi A2.

Sample waveforms measured with the oscilloscope for paired auditory signals separated by different intervals (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Xiaomi Mi A2 smartphone. In traces graphs, black vertical lines indicate both sequential signals' onsets marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical interval between signals (output duration) as a function of the interval chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each interval. Both medians and standard deviations were calculated within 100 trials sessions.



Samsung A40

Figure 3.8 Sample signals' traces, accuracy, and precision for paired auditory stimuli delivered using the Samsung A40. Sample waveforms measured with the oscilloscope for paired auditory signals separated by different intervals (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Samsung A40 smartphone. In traces graphs, black vertical lines indicate both sequential signals' onsets marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical interval between signals (output duration) as a function of the interval chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each interval. Both medians and standard deviations were calculated within 100 trials sessions.

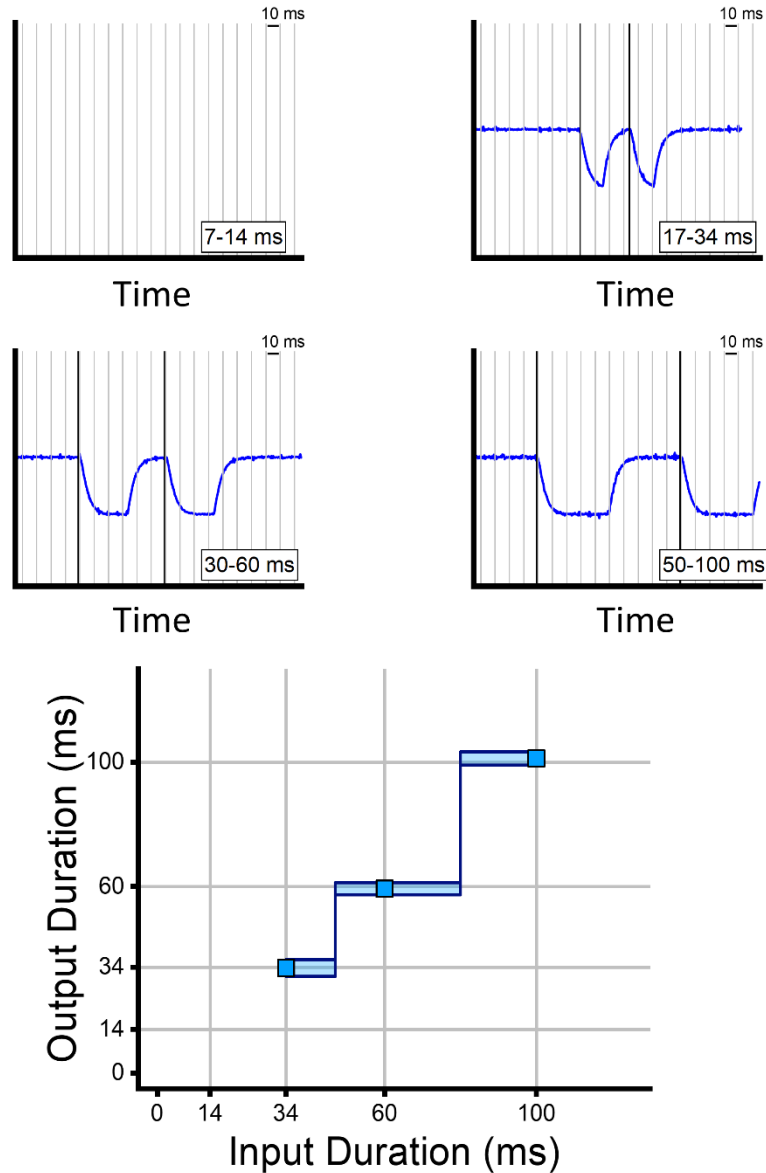
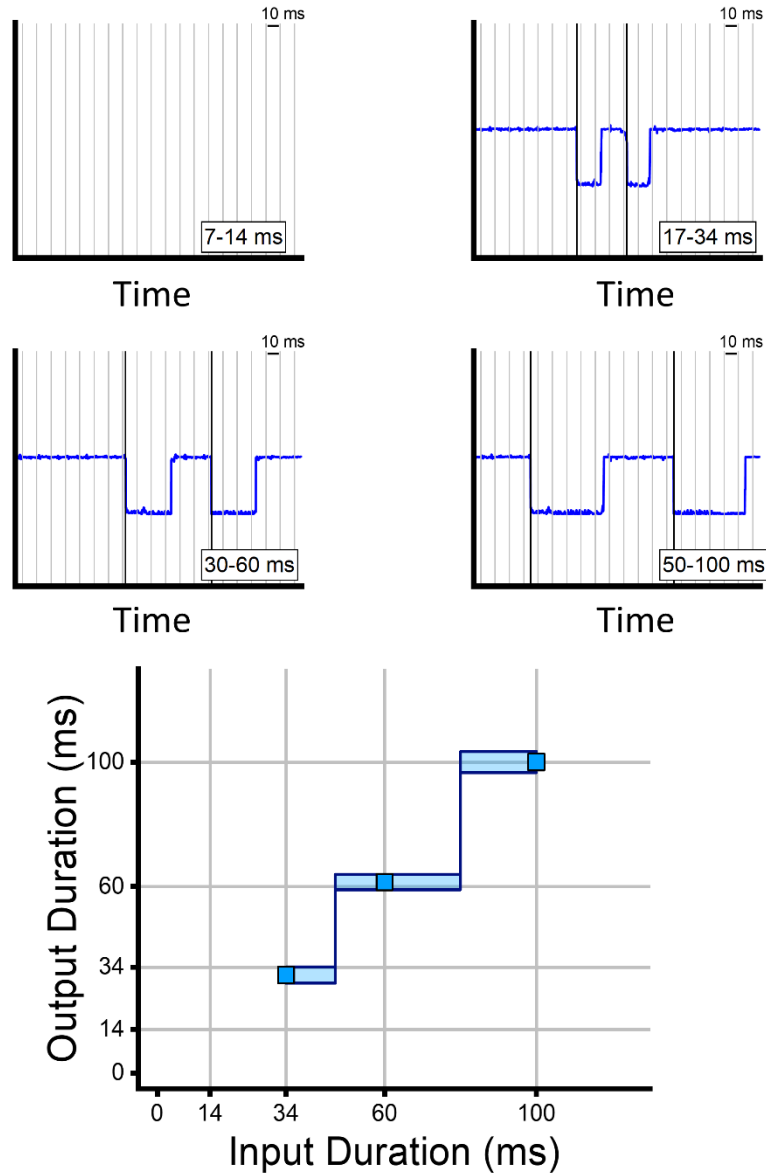
Uni-modal Minimum Temporal Difference – Visual**Xiaomi Mi A2**

Figure 3.9 Sample signals' traces, accuracy, and precision for paired visual stimuli delivered using the Xiaomi Mi A2. Sample waveforms measured with the oscilloscope for paired visual signals separated by different intervals (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Xiaomi Mi A2 smartphone. In traces graphs, black vertical lines indicate both sequential signals' onsets marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical interval between signals (output duration) as a function of the interval chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each interval. Both medians and standard deviations were calculated within 100 trials sessions.



Samsung A40

Figure 3.10 Sample signals' traces, accuracy, and precision for paired visual stimuli delivered using the Samsung A40. Sample waveforms measured with the oscilloscope for paired visual signals separated by different intervals (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Samsung A40 smartphone. In traces graphs, black vertical lines indicate both sequential signals' onsets marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical interval between signals (output duration) as a function of the interval chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each interval. Both medians and standard deviations were calculated within 100 trials sessions.

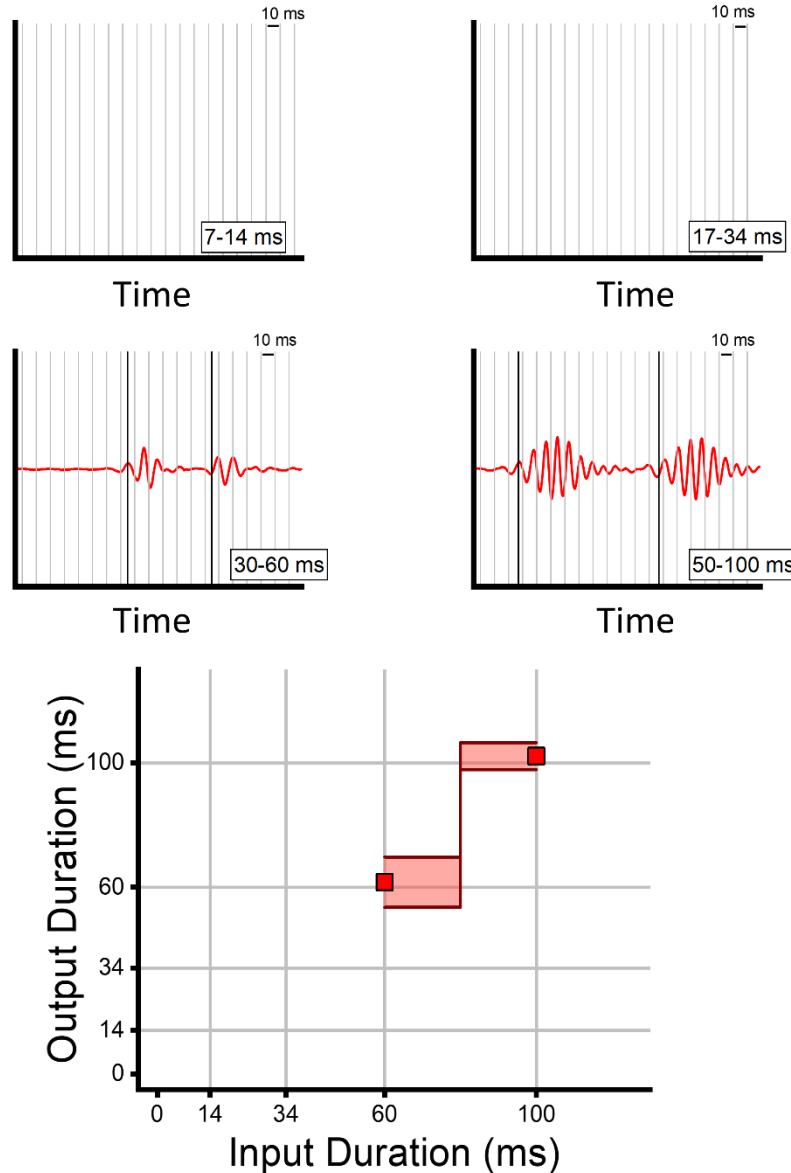
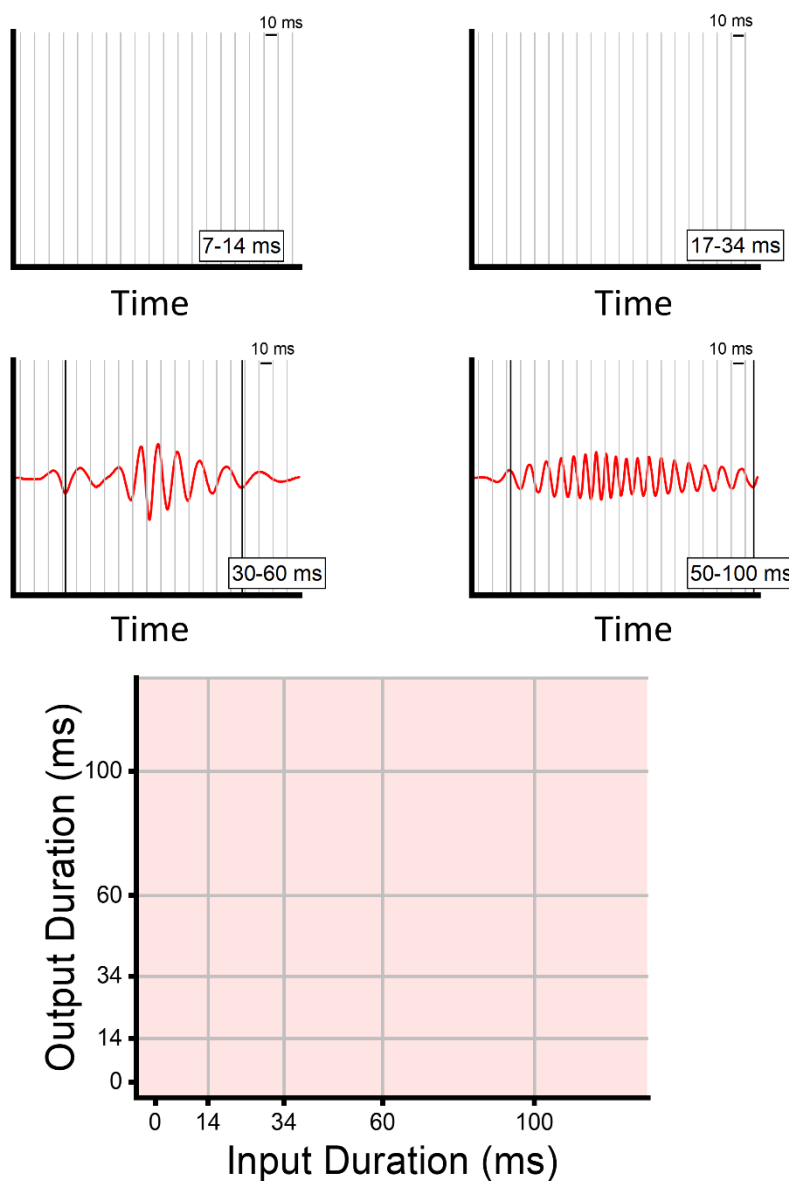
Uni-modal Minimum Temporal Difference – Tactile**Xiaomi Mi A2**

Figure 3.11 Sample signals' traces, accuracy, and precision for paired tactile stimuli delivered using the Xiaomi Mi A2. Sample waveforms measured with the oscilloscope for paired tactile signals separated by different intervals (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Samsung A40 smartphone. In traces graphs, black vertical lines indicate both sequential signals' onsets marked in the post-processing analysis. Empty traces indicate that the smartphone failed to deliver any stimulation for the chosen interval. Within the scatter plot, we reported medians of the physical interval between signals (output duration) as a function of the interval chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each interval. Both medians and standard deviations were calculated within 100 trials sessions.



Samsung A40

Figure 3.12 Sample signals' traces, accuracy, and precision for paired tactile stimuli delivered using the Samsung A40. Sample waveforms measured with the oscilloscope for paired tactile signals separated by different intervals (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Samsung A40 smartphone. In traces graphs, black vertical lines indicate both sequential signals' onsets marked in the post-processing analysis. Notably, the smartphone did not manage to deliver two separate stimulations even when the interval between them was as long as 100 ms. In all tested combinations, the Samsung A40 produced a single wave that overlaps the two stimulations, confirming that it could not reliably deliver paired tactile stimulations suitable to psychophysical testing. The scatter plot was left intentionally blank as it was obviously not possible to measure any interval between the two tactile stimuli.

Multi-modal Signals

Between-modalities simultaneity accuracy

We first produced simultaneous tri-modal stimulations and calculated the reciprocal shifts between auditory, visual, and tactile signals.

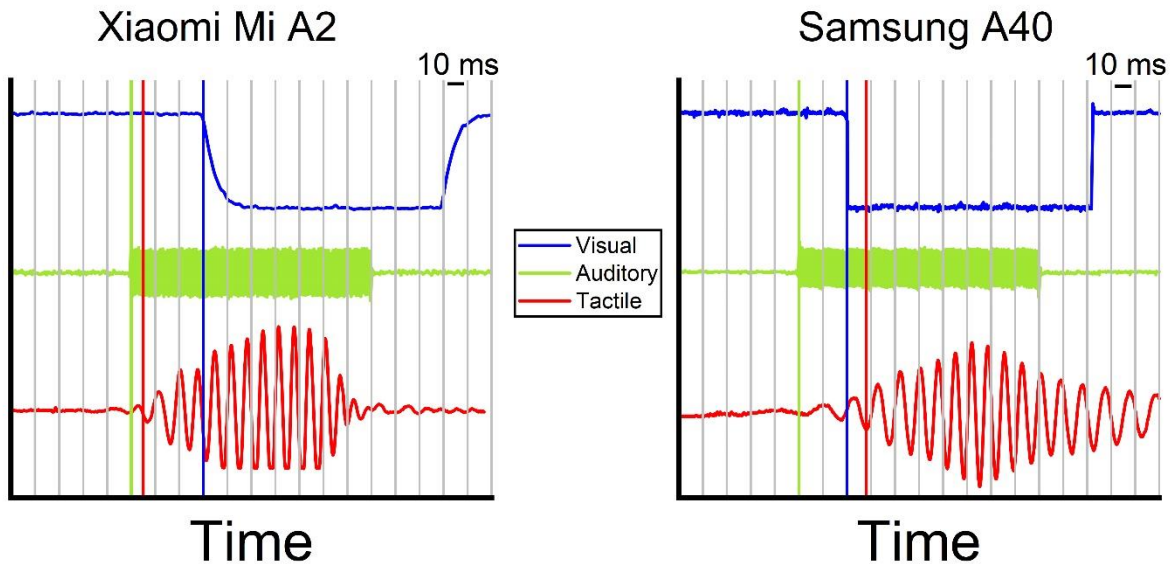


Figure 3.13 Uncorrected between-modalities simultaneity for both smartphones. Vertical colored lines represent stimuli onsets for the corresponding color-coded modality.

Overall, the Xiaomi vibrators engine was much faster when compared to the Samsung engine, even though tactile stimuli production was generally slightly slower than auditory stimuli production. Conversely, visual faster responses were observed using the Samsung smartphone, in line with previous measurements observed when delivering uni-modal stimuli. Samsung's faster performance in delivering visual stimulations resulted in shorter onset delays when compared to the Xiaomi's. A slight temporal difference of ~5 ms could indeed be observed when comparing visual signals produced by the two devices (Figure 3.4 and Figure 3.5, upper panels). Stimuli delays, with 0 being the faster (i.e., auditory) signals produced by definition, were the following:

	Auditory	Tactile	Visual
Mi A2	0	5	30
A40	0	28	20

Table 3.1 Onset delays, expressed in milliseconds, measured delivering multi-modal stimuli with both smartphones.

Temporal delays were subsequently stored in a data structure and applied through an online, run-time procedure executed during each trial. The module that managed stimuli delivery was equipped with a set of accessory functions able to identify modality combinations, calculate the specific delay among the onset of each stimulus, and then call the single primitive method. Such a method uses the `Handler.postDelayed` routine to enqueue single uni-modal calls in the UI thread's `MessageQueue` of the smartphone's OS. For example, assuming that the temporal difference between visual and auditory stimulations had a fixed delay of T_{AV} , each time audio and visual stimuli are simultaneously displayed, the code started the first stimulus considering a delay of T_{AV} ms before delivering the second one, with the faster stimulus being delivered as first.

After applying adjustments based on the observed onset delays, simultaneous delivery of signals forming tri-modal stimulations was successfully generated (Figure 3.15).

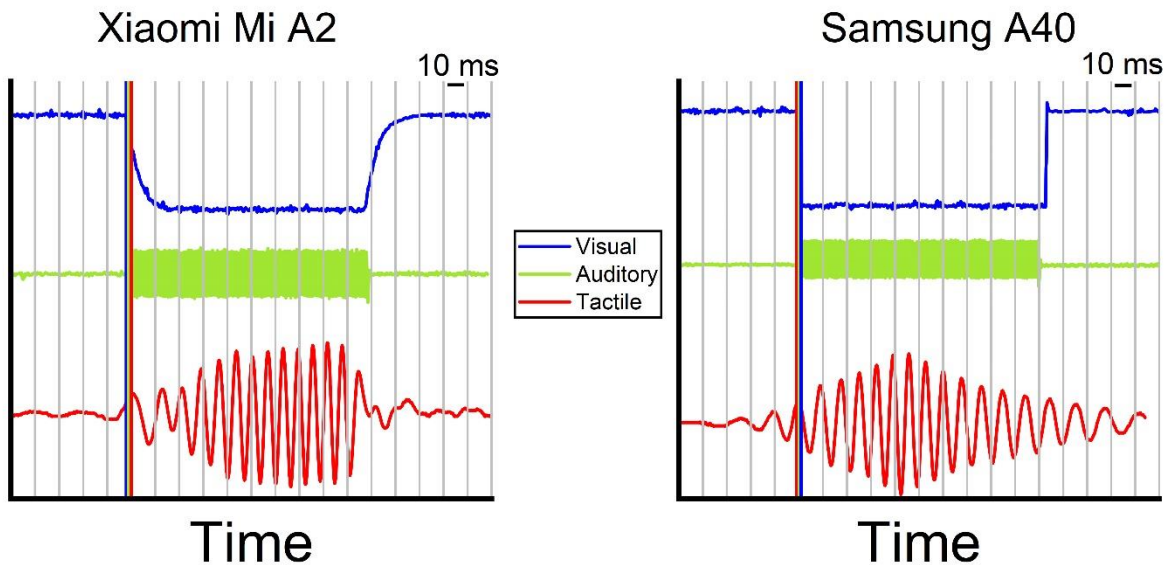


Figure 3.14 Corrected between-modalities simultaneity for both smartphones.
Vertical colored lines represent stimuli onsets for the corresponding color-coded modality.

Delays corrections were equally implemented when multi-modal stimulations were delivered, regardless of the sensory combinations involved. This is because delays are mainly determined by hardware components, and are likely similar when either bi- or tri-modal stimuli are chosen.

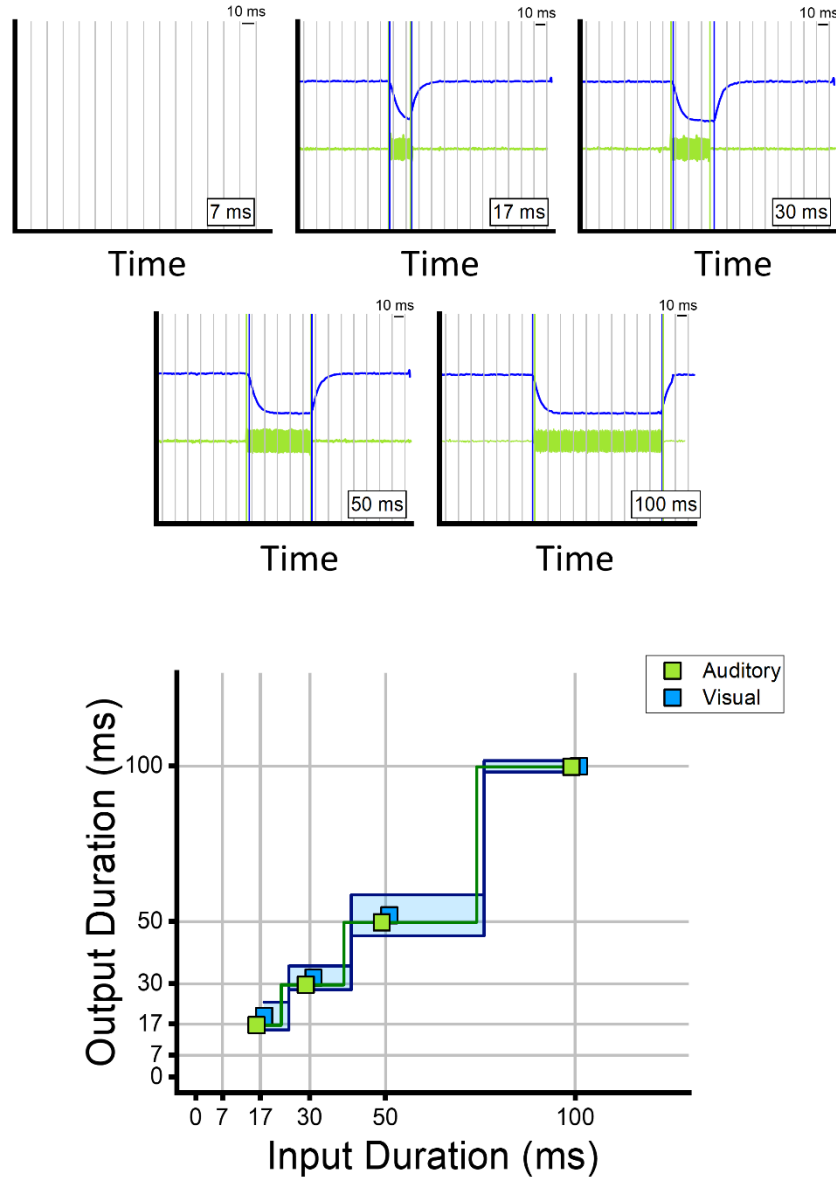
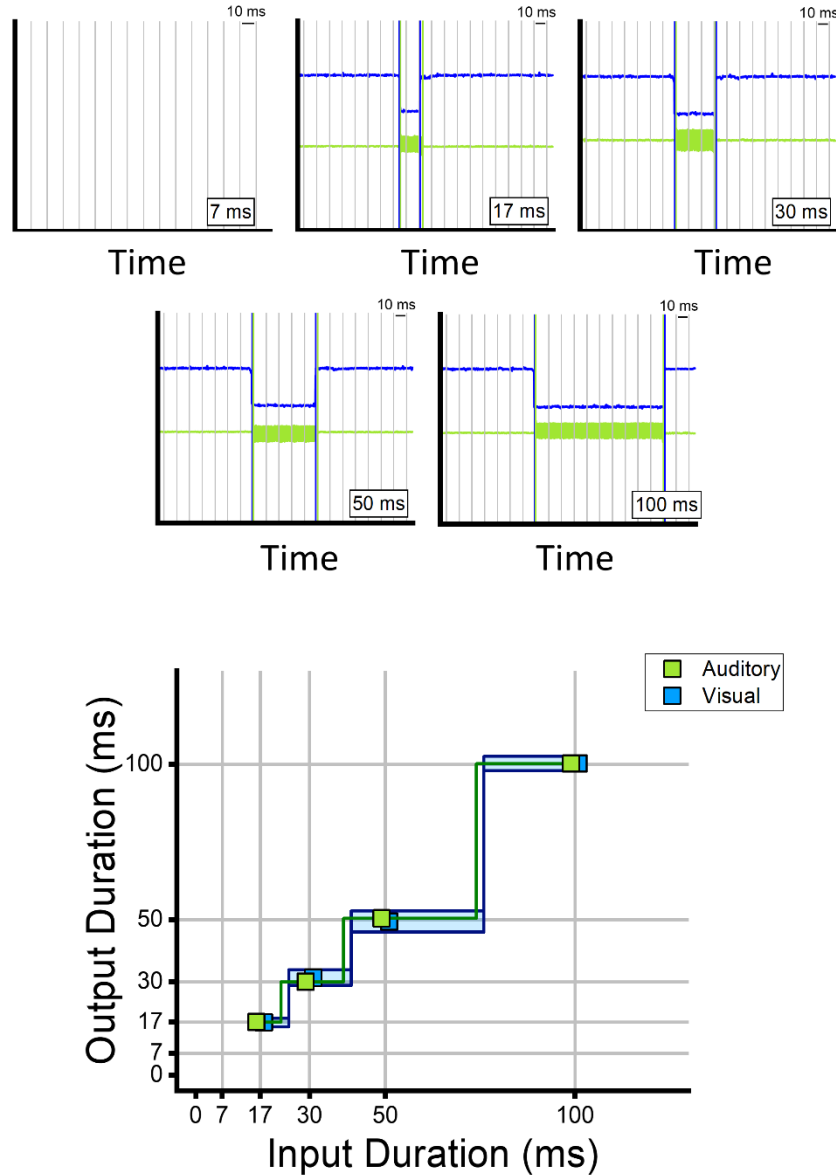
Multi-modal Stimulation's Accuracy and Precision – Audiovisual**Xiaomi Mi A2**

Figure 3.15 Sample signals' traces, accuracy, and precision for single audiovisual stimuli delivered using the Xiaomi Mi A2.

Sample waveforms measured with the oscilloscope for simultaneous audiovisual signals for different durations (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Xiaomi Mi A2 smartphone. In traces graphs, colored vertical lines indicate signals' onset and offset marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical signals' durations (output duration) as a function of the durations chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each duration. Both medians and standard deviations were calculated within 100 trials sessions.



Samsung A40

Figure 3.16 Sample signals' traces, accuracy, and precision for single audiovisual stimuli delivered using the Samsung A40.

Sample waveforms measured with the oscilloscope for simultaneous audiovisual signals for different durations (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Samsung A40 smartphone. In traces graphs, colored vertical lines indicate signals' onset and offset marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical signals' durations (output duration) as a function of the durations chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each duration. Both medians and standard deviations were calculated within 100 trials sessions.

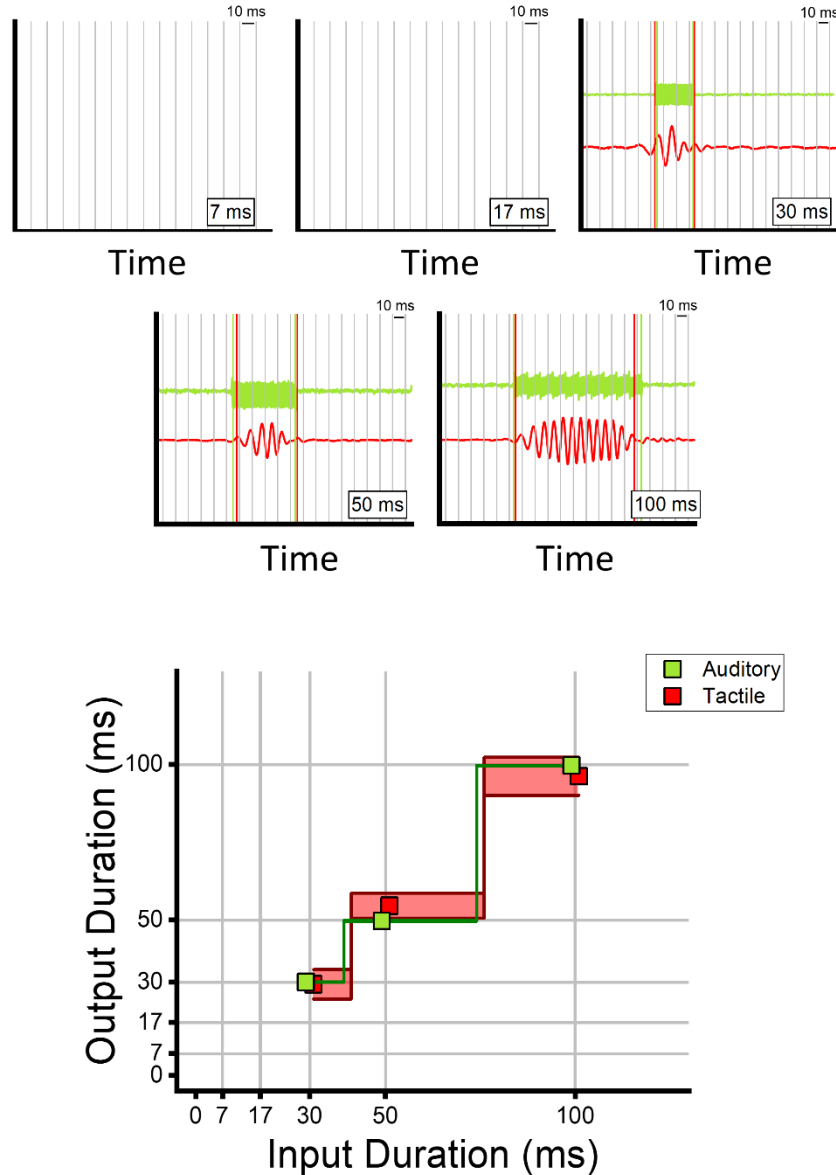
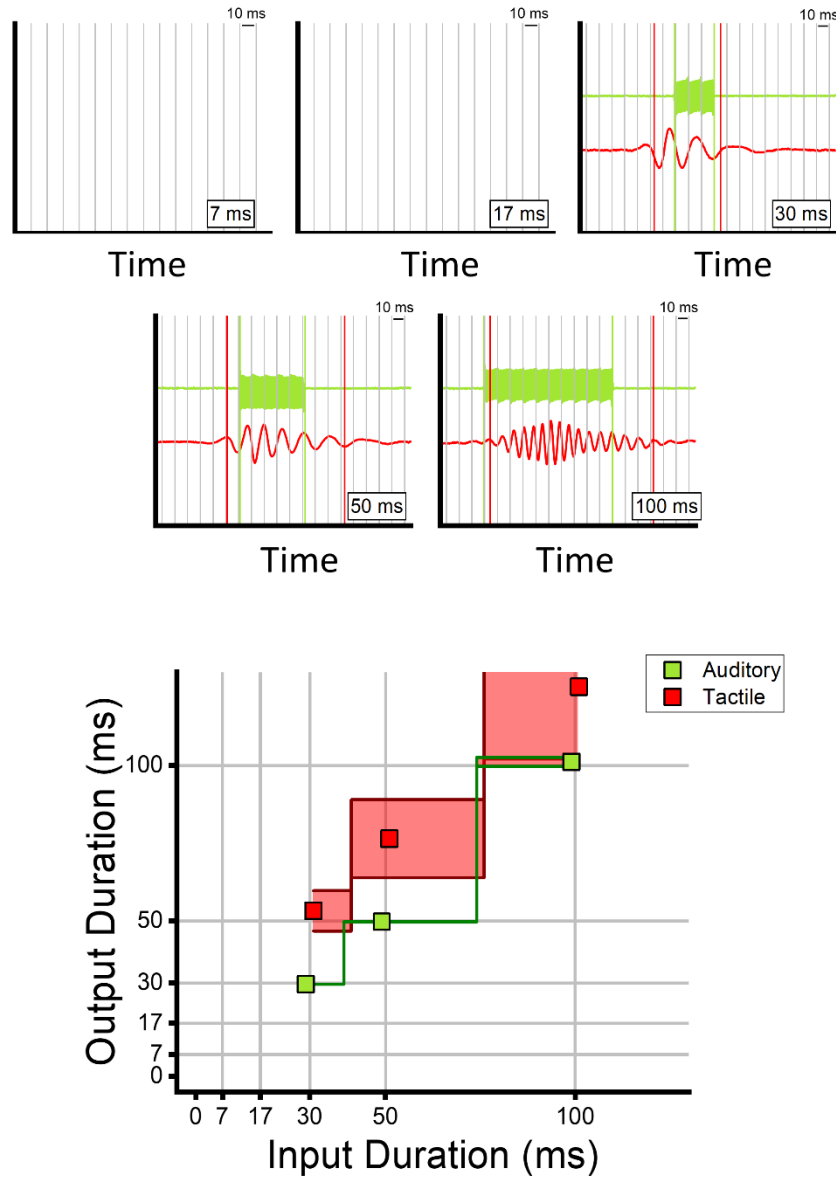
Multi-modal Stimulation's Accuracy and Precision – Audiotactile**Xiaomi Mi A2**

Figure 3.17 Sample signals' traces, accuracy, and precision for single audiotactile stimuli delivered using the **Xiaomi Mi A2**.

Sample waveforms measured with the oscilloscope for simultaneous audiotactile signals for different durations (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Xiaomi Mi A2 smartphone. In traces graphs, colored vertical lines indicate signals' onset and offset marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical signals' durations (output duration) as a function of the durations chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each duration. Both medians and standard deviations were calculated within 100 trials sessions.



Samsung A40

Figure 3.18 Sample signals' traces, accuracy, and precision for single audiotactile stimuli delivered using the Samsung A40.

Sample waveforms measured with the oscilloscope for simultaneous audiotactile signals for different durations (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Samsung A40 smartphone. In traces graphs, colored vertical lines indicate signals' onset and offset marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical signals' durations (output duration) as a function of the durations chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each duration. Both medians and standard deviations were calculated within 100 trials sessions.

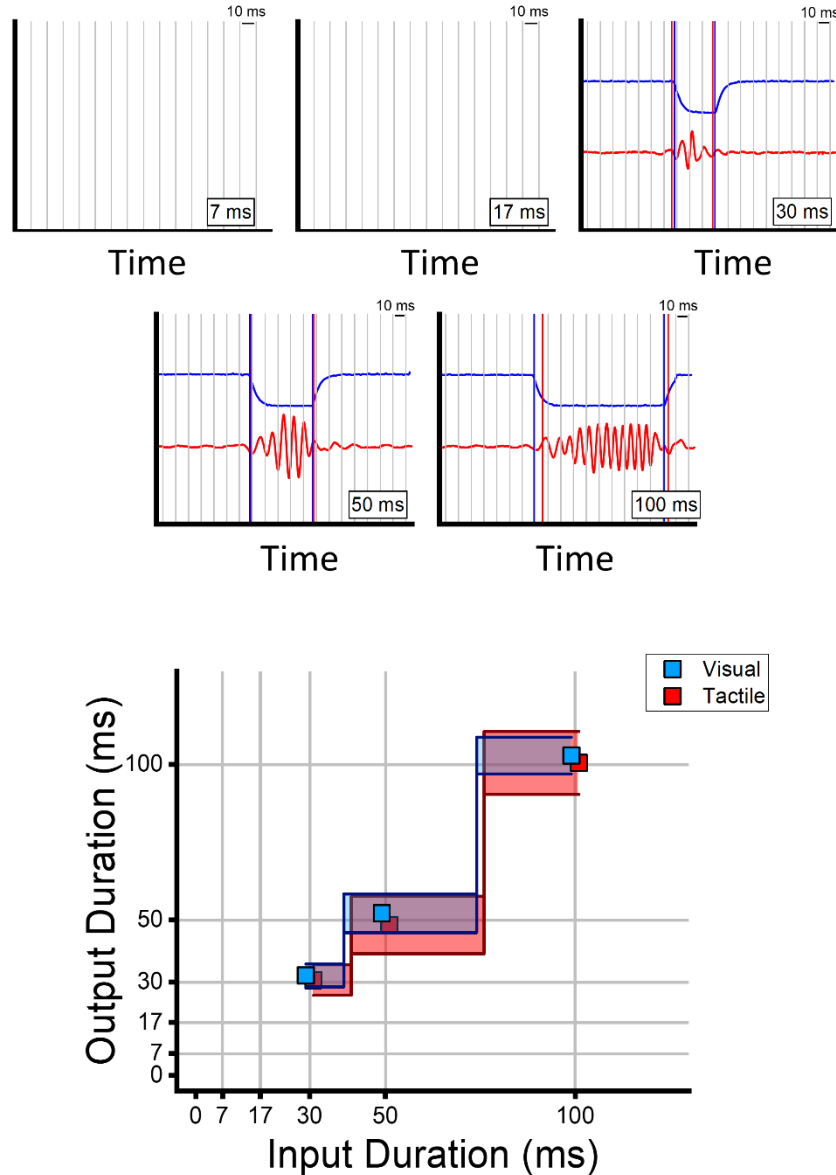
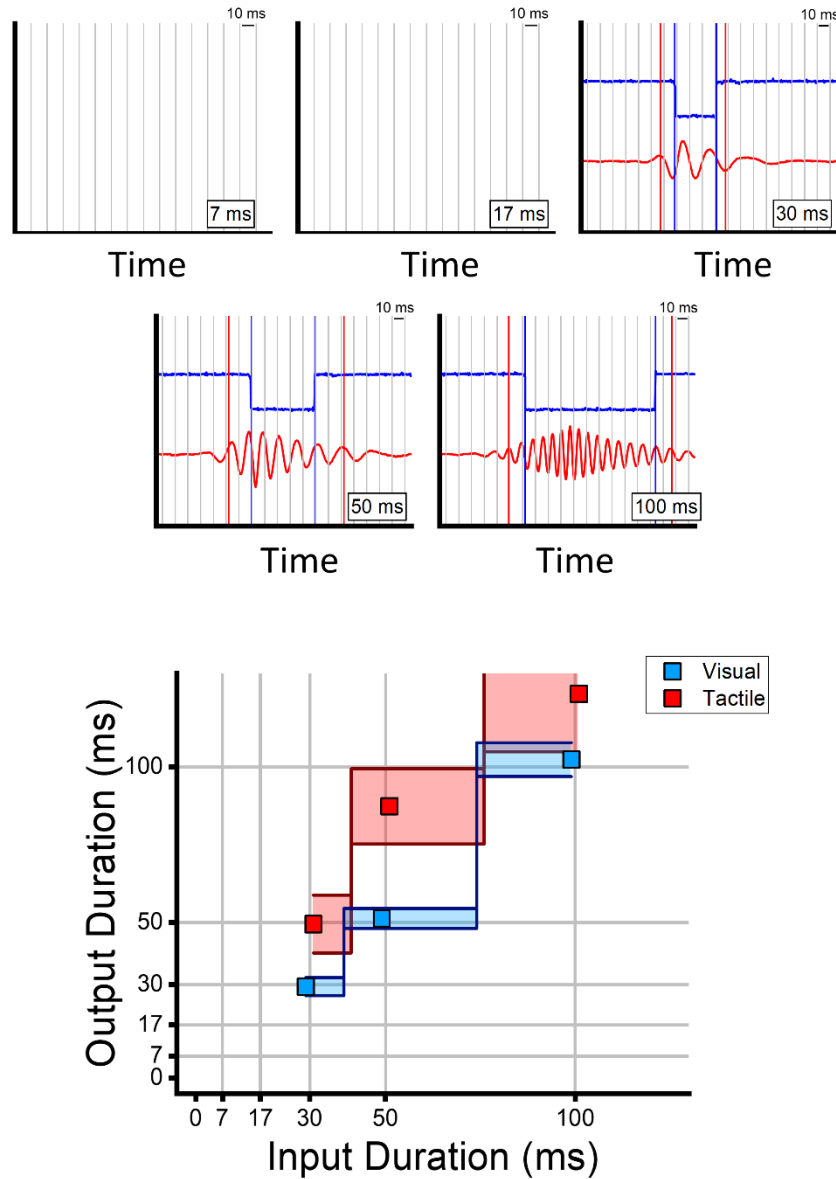
Multi-modal Stimulation's Accuracy and Precision – Visuotactile**Xiaomi Mi A2**

Figure 3.19 Sample signals' traces, accuracy, and precision for single visuotactile stimuli delivered using the Xiaomi Mi A2.

Sample waveforms measured with the oscilloscope for simultaneous visuotactile signals for different durations (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Xiaomi Mi A2 smartphone. In traces graphs, colored vertical lines indicate signals' onset and offset marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical signals' durations (output duration) as a function of the durations chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each duration. Both medians and standard deviations were calculated within 100 trials sessions.



Samsung A40

Figure 3.20 Sample signals' traces, accuracy, and precision for single visuotactile stimuli delivered using the Samsung A40.

Sample waveforms measured with the oscilloscope for simultaneous visuotactile signals for different durations (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Samsung A40 smartphone. In traces graphs, colored vertical lines indicate signals' onset and offset marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical signals' durations (output duration) as a function of the durations chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each duration. Both medians and standard deviations were calculated within 100 trials sessions.

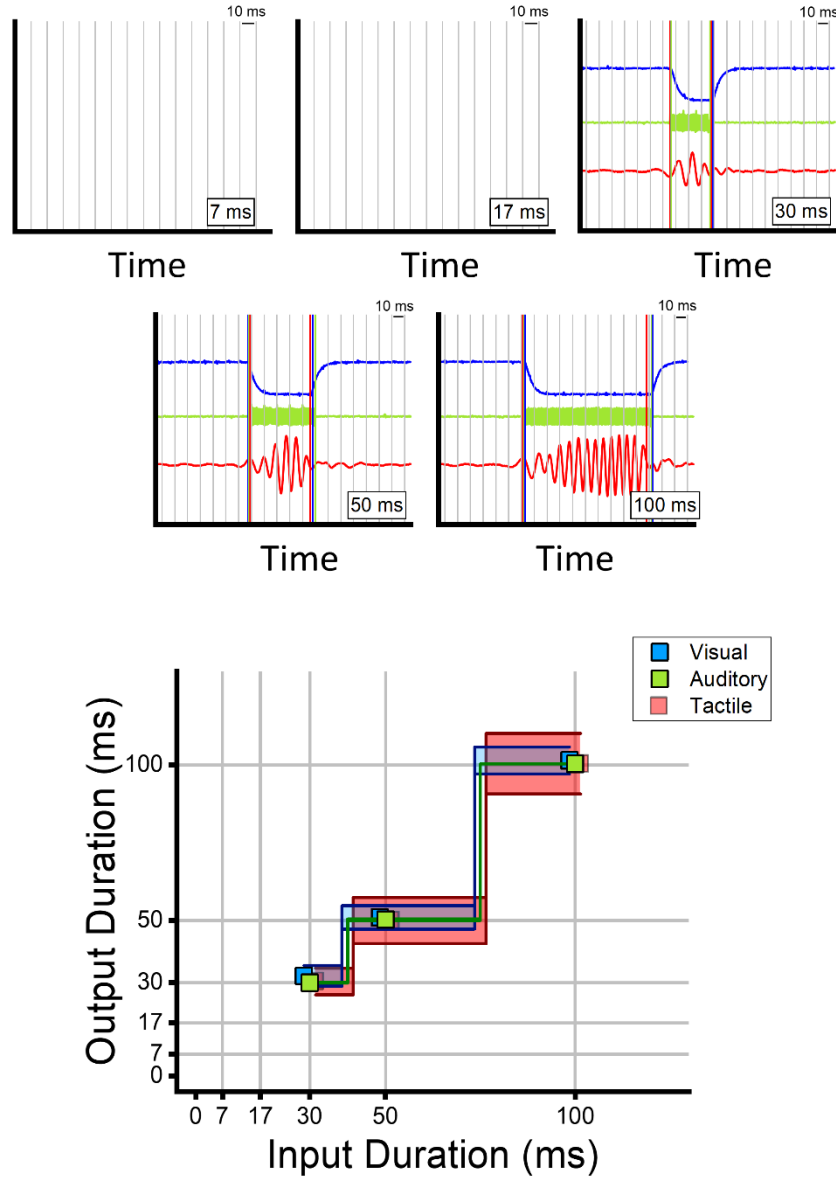
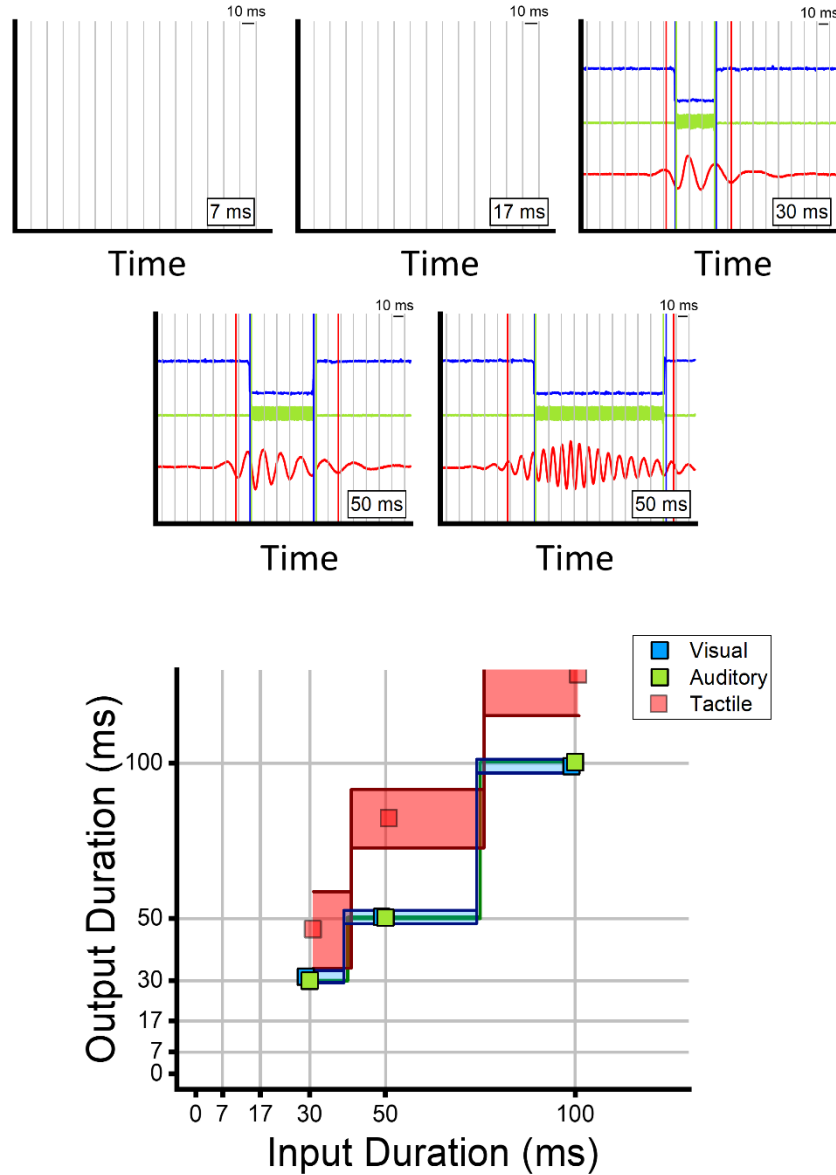
Multi-modal Stimulation's Accuracy and Precision – Tri-modal**Xiaomi Mi A2**

Figure 3.21 Sample signals' traces, accuracy, and precision for single tri-modal stimuli delivered using the Xiaomi Mi A2.

Sample waveforms measured with the oscilloscope for simultaneous tri-modal signals for different durations (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Xiaomi Mi A2 smartphone. In traces graphs, colored vertical lines indicate signals' onset and offset marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical signals' durations (output duration) as a function of the durations chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each duration. Both medians and standard deviations were calculated within 100 trials sessions.



Samsung A40

Figure 3.22 Sample signals' traces, accuracy, and precision for single tri-modal stimuli delivered using the Samsung A40.

Sample waveforms measured with the oscilloscope for simultaneous tri-modal signals for different durations (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Samsung A40 smartphone. In traces graphs, colored vertical lines indicate signals' onset and offset marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical signals' durations (output duration) as a function of the durations chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each duration. Both medians and standard deviations were calculated within 100 trials sessions.

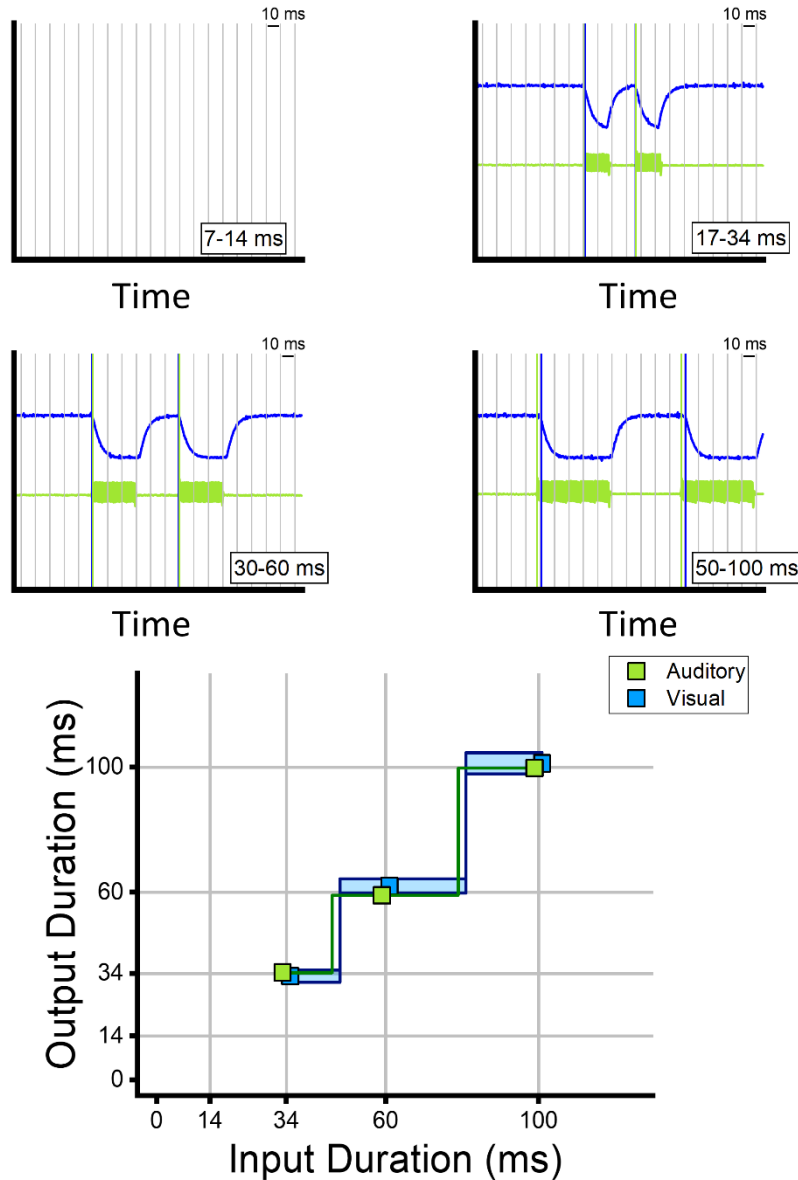
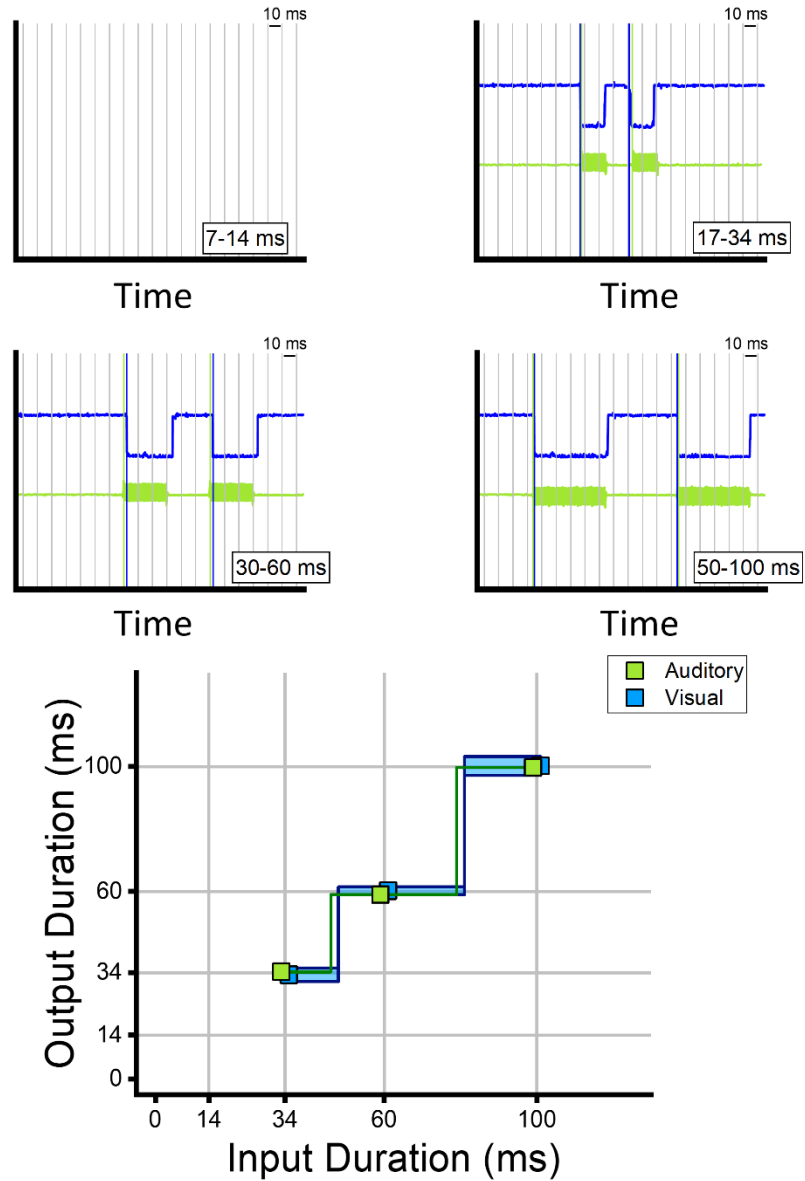
Multi-modal Minimum Temporal Difference – Audiovisual**Xiaomi Mi A2**

Figure 3.23 Sample signals' traces, accuracy, and precision for paired audiovisual stimuli delivered using the **Xiaomi Mi A2**.

Sample waveforms measured with the oscilloscope for paired audiovisual signals separated by different intervals (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Xiaomi Mi A2 smartphone. In traces graphs, colored vertical lines indicate sequential signals' onsets marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical interval between signals (output duration) as a function of the interval chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each interval. Both medians and standard deviations were calculated within 100 trials sessions.



Samsung A40

Figure 3.24 Sample signals' traces, accuracy, and precision for paired audiovisual stimuli delivered using the Samsung A40.

Sample waveforms measured with the oscilloscope for paired audiovisual signals separated by different intervals (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Samsung A40 smartphone. In traces graphs, colored vertical lines indicate sequential signals' onsets marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical interval between signals (output duration) as a function of the interval chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each interval. Both medians and standard deviations were calculated within 100 trials sessions.

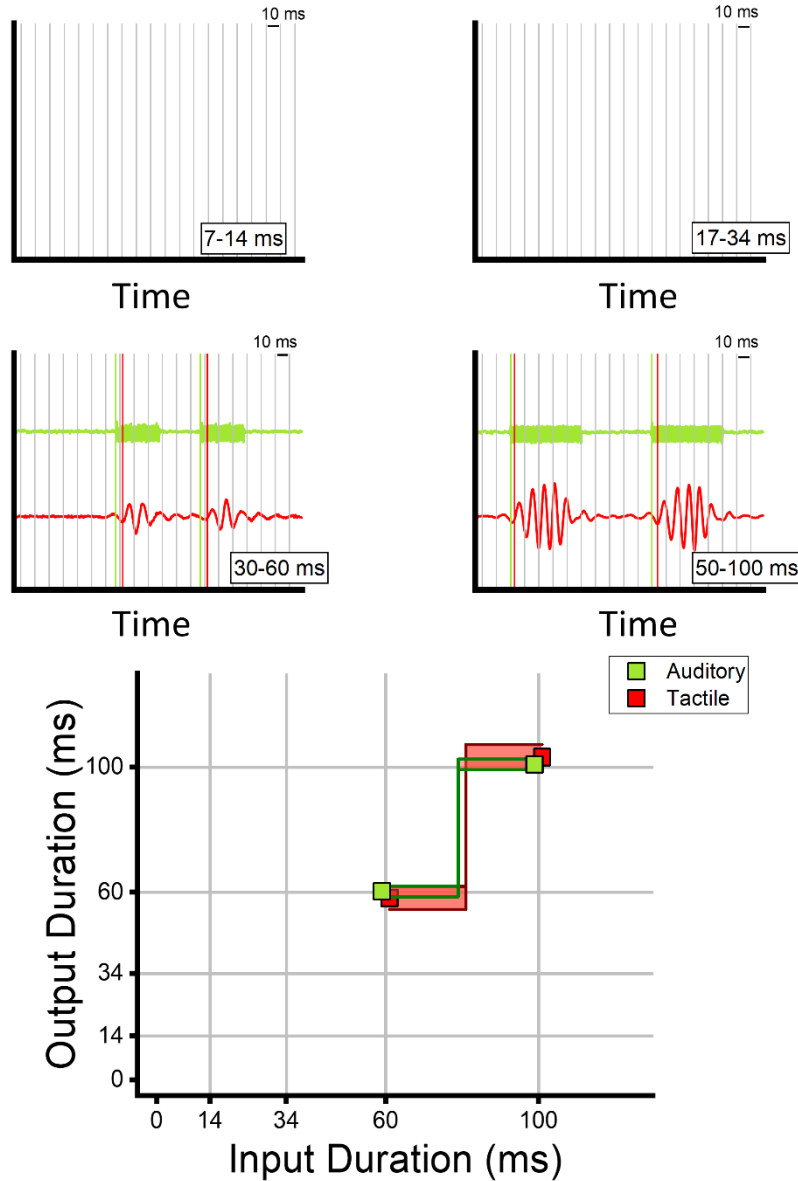
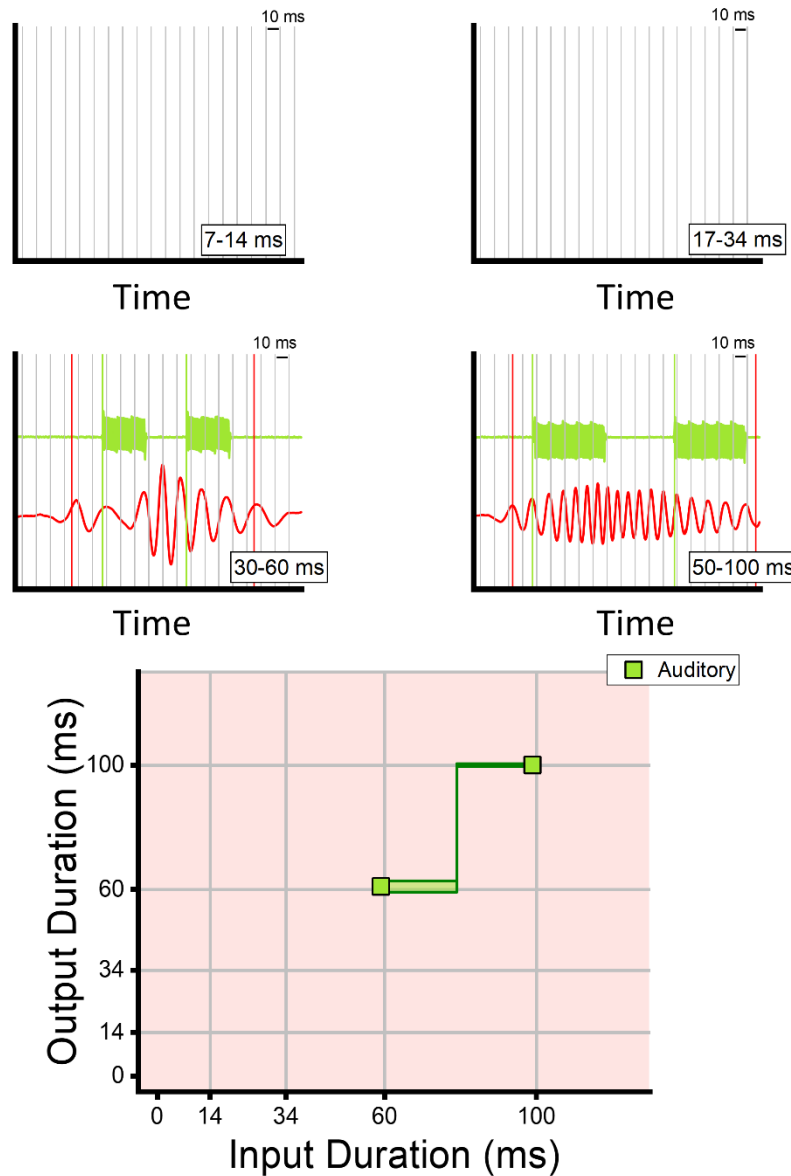
Multi-modal Minimum Temporal Difference – Audiotactile**Xiaomi Mi A2**

Figure 3.25 Sample signals' traces, accuracy, and precision for paired audiotactile stimuli delivered using the Xiaomi Mi A2.

Sample waveforms measured with the oscilloscope for paired audiotactile signals separated by different intervals (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Xiaomi Mi A2 smartphone. In traces graphs, colored vertical lines indicate sequential signals' onsets marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical interval between signals (output duration) as a function of the interval chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each interval. Both medians and standard deviations were calculated within 100 trials sessions.



Samsung A40

Figure 3.26 Sample signals' traces, accuracy, and precision for paired audiotactile stimuli delivered using the Samsung A40.

Sample waveforms measured with the oscilloscope for paired audiotactile signals separated by different intervals (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Samsung A40 smartphone. In traces graphs, colored vertical lines indicate sequential signals' onsets marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical interval between signals (output duration) as a function of the interval chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each interval. Both medians and standard deviations were calculated within 100 trials sessions. In all tested combinations, the Samsung A40 managed to reliably produce auditory stimuli in a consistent manner. However, when delivering tactile stimulations the smartphone produced a single wave, confirming that it could not reliably deliver paired tactile stimulations suitable to psychophysical testing.

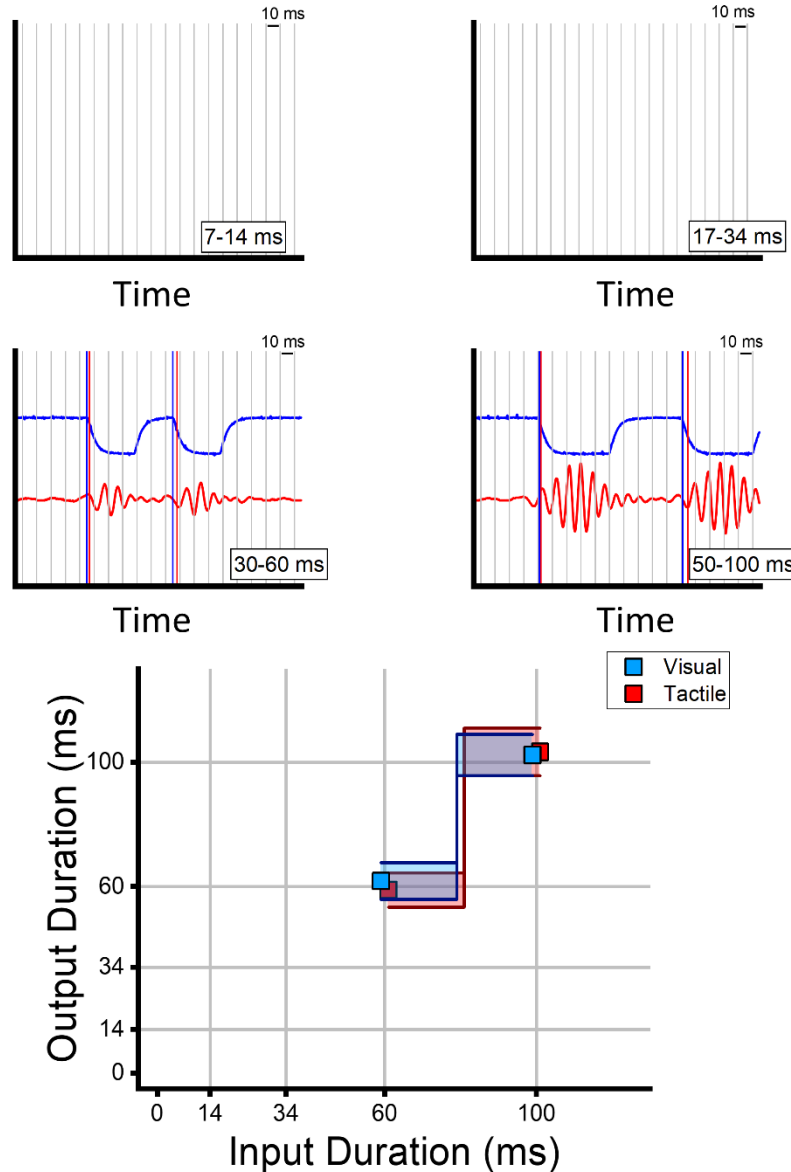
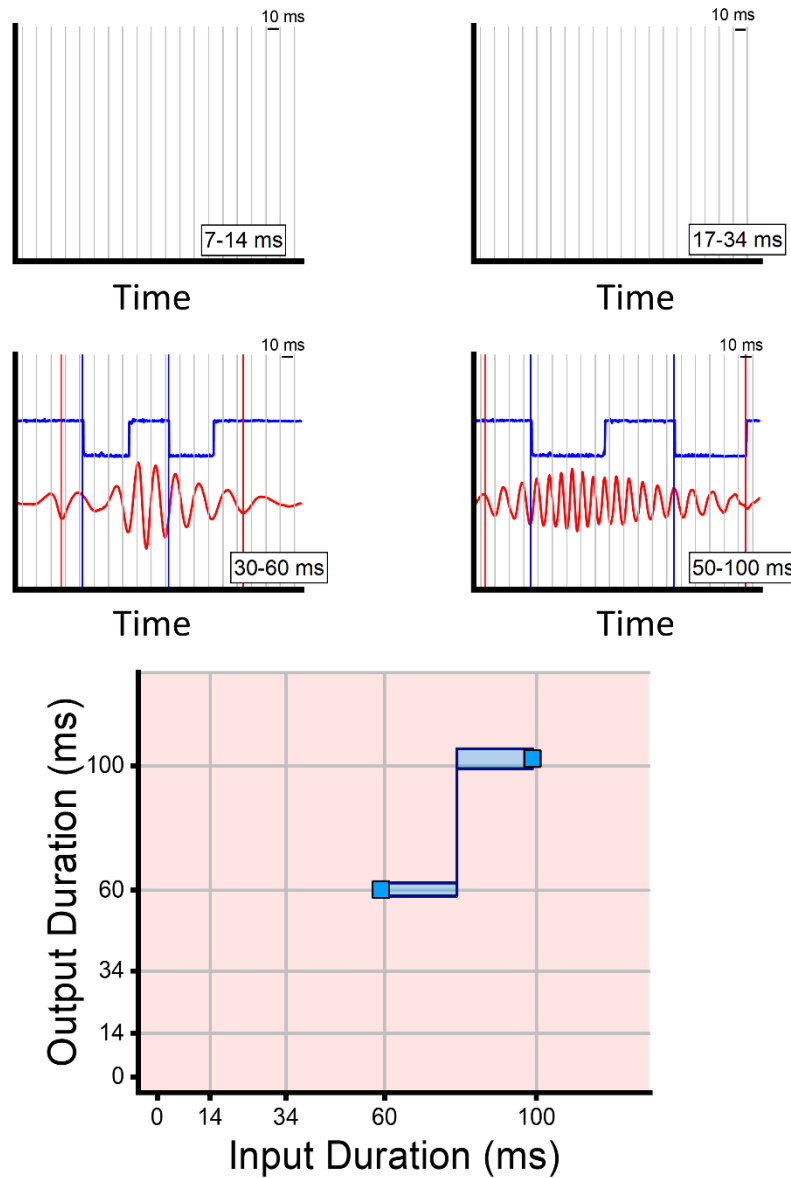
Multi-modal Minimum Temporal Difference – Visuotactile**Xiaomi Mi A2**

Figure 3.27 Sample signals' traces, accuracy, and precision for paired visuotactile stimuli delivered using the Xiaomi Mi A2.

Sample waveforms measured with the oscilloscope for paired visuotactile signals separated by different intervals (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Xiaomi Mi A2 smartphone. In traces graphs, colored vertical lines indicate sequential signals' onsets marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical interval between signals (output duration) as a function of the interval chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each interval. Both medians and standard deviations were calculated within 100 trials sessions.



Samsung A40

Figure 3.28 Sample signals' traces, accuracy, and precision for paired visuotactile stimuli delivered using the Samsung A40.

Sample waveforms measured with the oscilloscope for paired visuotactile signals separated by different intervals (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Samsung A40 smartphone. In traces graphs, colored vertical lines indicate sequential signals' onsets marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical interval between signals (output duration) as a function of the interval chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each interval. Both medians and standard deviations were calculated within 100 trials sessions. In all tested combinations, the Samsung A40 managed to reliably produce visual stimuli in a consistent manner. However, when delivering tactile stimulations the smartphone produced a single wave, confirming that it could not reliably deliver paired tactile stimulations suitable to psychophysical testing.

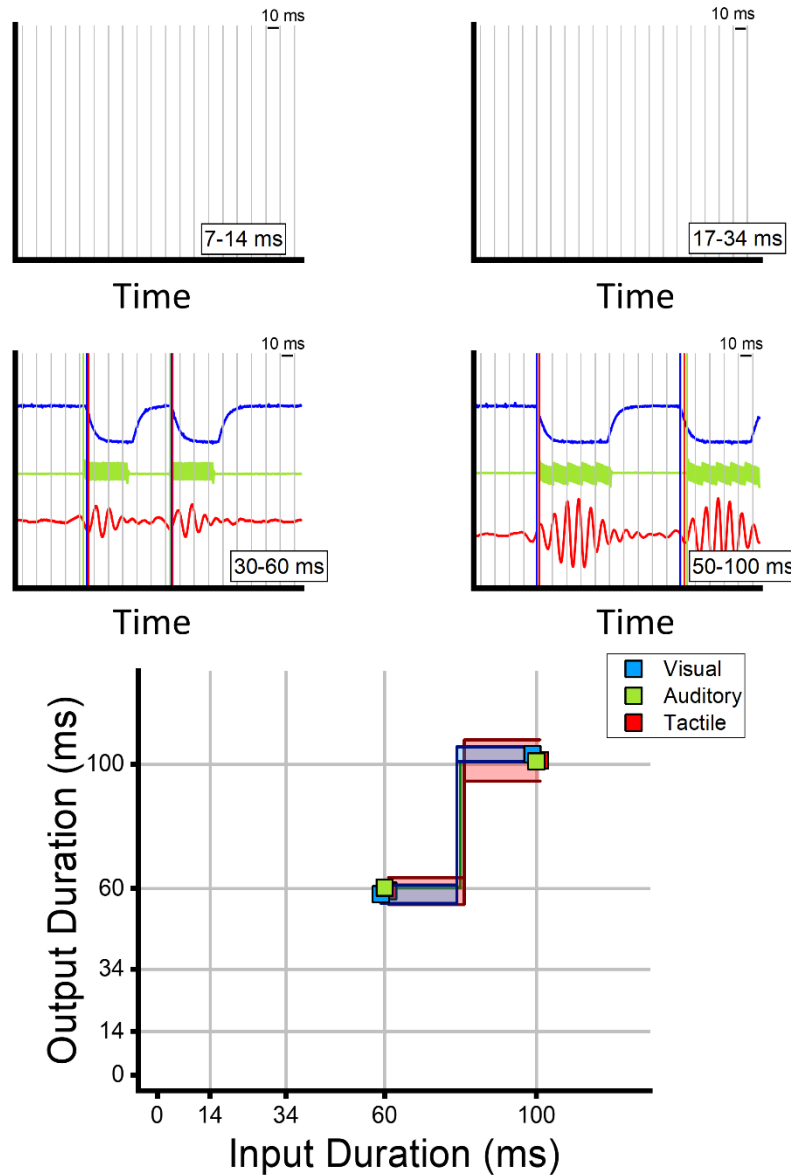
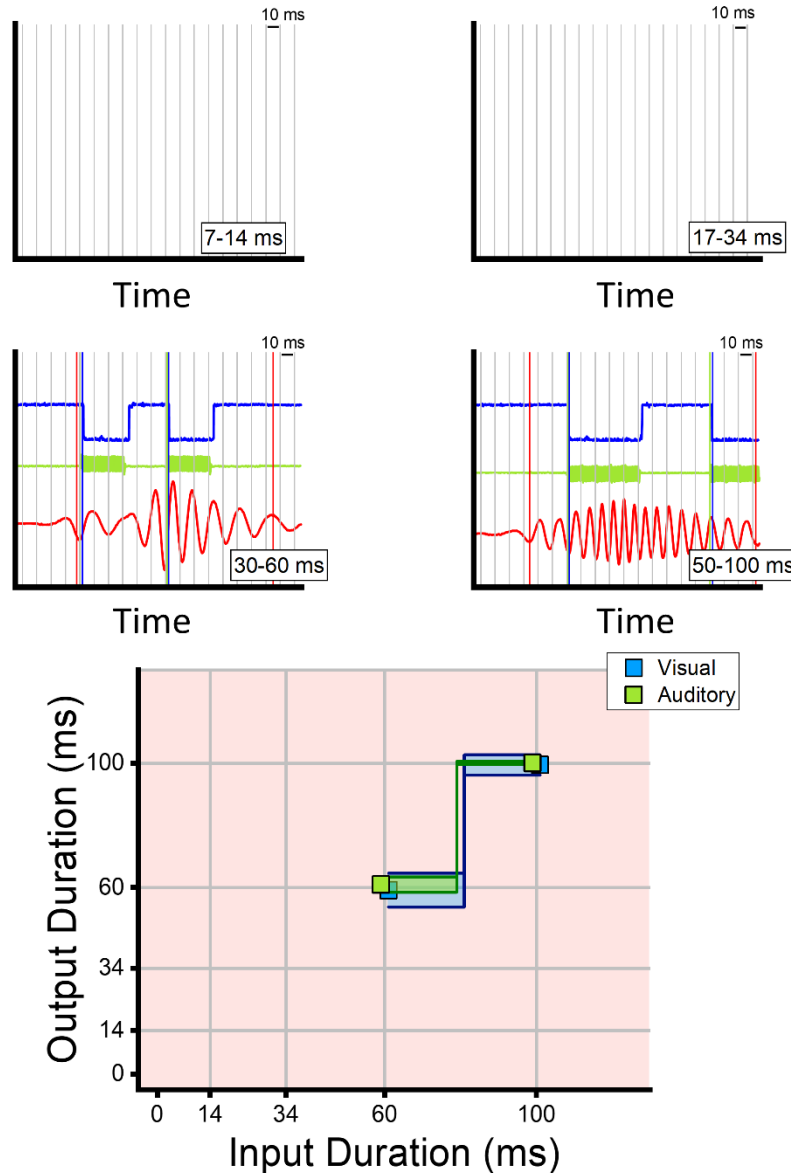
Multi-modal Minimum Temporal Difference – Tri-modal**Xiaomi Mi A2**

Figure 3.29 Sample signals' traces, accuracy, and precision for paired tri-modal stimuli delivered using the Xiaomi Mi A2.

Sample waveforms measured with the oscilloscope for paired tri-modal signals separated by different intervals (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Xiaomi Mi A2 smartphone. In traces graphs, colored vertical lines indicate sequential signals' onsets marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical interval between signals (output duration) as a function of the interval chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each interval. Both medians and standard deviations were calculated within 100 trials sessions.



Samsung A40

Figure 3.30 Sample signals' traces, accuracy, and precision for paired tri-modal stimuli delivered using the Samsung A40.

Sample waveforms measured with the oscilloscope for paired tri-modal signals separated by different intervals (upper panels), with the corresponding evaluation of *PsySuite*'s accuracy and precision (lower panel), for the Xiaomi Mi A2 smartphone. In traces graphs, colored vertical lines indicate sequential signals' onsets marked in the post-processing analysis. Within the scatter plot, we reported medians of the physical interval between signals (output duration) as a function of the interval chosen by the experimenter (input duration). Shaded areas' height indicate the standard deviation measured for each interval. Both medians and standard deviations were calculated within 100 trials sessions. In all tested combinations, the Samsung A40 managed to reliably produce both auditory and visual stimuli in a consistent manner. However, when delivering tactile stimulations the smartphone produced a single wave, confirming that it could not reliably deliver paired tactile stimulations suitable to psychophysical testing.

Conclusions

Through systematic and accurate hardware validation, we assessed *PsySuite*'s feasibility in delivering stimuli suitable for psychophysical testing. We also compared the technical performances of both a Xiaomi Mi A2 and a Samsung A40 devices, aiming to find the most appropriate smartphone to foster remote data collection procedures.

To test the App stability, we considered three different parameters: the stimulations' accuracy, the stimulation's precision, and the minimum temporal difference between two stimuli sequentially delivered. An additional index, the between-modalities simultaneity accuracy, was initially evaluated to investigate whether the App could reliably produce appropriate multi-modal stimulations. We thus first measured the temporal difference between stimuli onsets when multi-modal signals were displayed (Figure 3.14) and proceeded to correct the onset for each sensory modality (considering the onset of the auditory stimulation as 0 by default) to achieve simultaneity of stimulation (Figure 3.15). The evaluation of this parameter was mandatory to deliver proper multi-modal stimulations, and delays were easily fixed by introducing a temporal jitter to reduce the difference between onsets (Table 3.1).

When delivering uni-sensory stimulations, significant differences in terms of performance between the Xiaomi Mi A2 and the Samsung A40 smartphones emerged. Interestingly, both devices' reached optimal levels of precision and accuracy when producing either auditory or visual stimulations. Nonetheless, performance significantly differed between smartphone models when considering vibratory stimuli, with one of the two performings notably worse than the other.

For auditory stimulations, no differences in produced durations between the two smartphones were found (Figures 3.1 and 3.2). The Oboe native solution, which was ultimately chosen to deliver auditory stimulations, correctly played all .WAV files for their exact duration, and transitions from onsets and offsets were immediate and consistent with signal frequency.

For visual stimulations, the two smartphones' behavior was slightly different (Figures 3.3 and 3.4). Even though both devices could systematically reproduce durations from 17 to 100 ms, transition speeds were moderately dissimilar. The Samsung A40 smartphone was faster, with transitions within the order of one millisecond, while the Xiaomi Mi A2 showed slower transitions, up to five milliseconds. Thereby, Samsung's waveforms were closer to a square signal when compared to Xiaomi's ones. Unsurprisingly, durations shorter than 17 ms were not reproducible by any of the smartphones due to the monitors' refresh rate, fixed at 60 Hz (allowing a minimum duration of $1/60=0.017$ sec).

When delivering tactile stimulations, however, smartphones' behavior was overall less reliable, as well as significantly different. On the one hand, the Xiaomi Mi A2 managed to successfully produce tactile

stimulations as short as 30 ms, showing a slightly lower precision when compared to the optimal values found in the other modalities (Figure 3.5). On the other hand, the Samsung A40 failed to reproduce accurate tactile stimulations (Figure 3.6), even when trying to deliver the longest stimulus possible (as setting an input duration of 100 ms led to vibrations lasting more than 125 ms). Waveforms produced by the Samsung device were significantly longer in all conditions (30, 50, and 100 ms), denoting an unstable control of vibrators engines. Altogether, the Xiaomi Mi A2 drastically outclassed the Samsung A40 in terms of both accuracy and precision. On a final note, tactile signal amplitude comparisons were pretty challenging to carry on, as amplitude measurements were dependent on the position of the sensor over the smartphone's casing. To overcome this technical issue, when performing psychophysical testing with *PsySuite* we asked participants to firmly hold the smartphone in their hand instead of letting them place one of their fingers over a specific smartphone's point.

When considering the minimum temporal difference achievable between two stimulations, similar patterns were highlighted considering the two smartphones, consistently with measurements obtained via single stimuli generation. Both devices appropriately performed when delivering pairs of either auditory (Figures 3.7 and 3.8) or visual (Figures 3.9 and 3.10) stimulations, while the Xiaomi Mi A2 drastically outclassed the Samsung A40 when producing pairs of tactile stimulations (Figures 3.11 and 3.12). While the former could reliably produce pairs of 30 ms tactile stimuli whose ISI was as short as 60 ms, the Samsung A40 always produced a single wave lasting about 125 ms. Consequently, the Samsung A40 device was not able to generate two distinct, separate waves when following the simple separation rule defined in equation 3.1, proving once more to be unfitting for psychophysical testing in the tactile domain.

Interestingly, multi-modal stimuli generation procedures followed a trend similar to the one observed when producing uni-sensory stimulations. In all possible combinations of sensory modalities, the Xiaomi Mi A2 showed higher accuracy and precision compared to the Samsung A40, which failed to deliver vibrations of the proper duration (Figures 3.15-3.30). Even though the Samsung maintained slightly faster transition speeds for visual stimuli, its performance was generally less stable, becoming completely unreliable when tactile stimulations were involved.

Taken together, these results suggest that the Xiaomi Mi A2 was able to control the duration of the produced stimuli efficiently, regardless of the stimuli generated, while the Samsung A40 did not meet all the stability requirements to be suitable for remote data collection. Furthermore, stimuli generated with the Xiaomi Mi A2 were extremely accurate and precisely reproduced, with the only limitations being tied to the refresh rate of the monitor (that did not allow the generation of visual stimuli shorter than 17 ms) and the slow response of the vibrator engines (that did not allow the generation of tactile stimuli shorter than 30 ms).

Nonetheless, the lack of significant delays in stimuli reproduction and the overall solidity shown by *PsySuite* suggest that our App is potentially a befitting tool for remote psychophysical testing.

Since the Xiaomi Mi A2 drastically outclassed the Samsung A40 in terms of hardware performance and stimuli generation, in all testing procedures developed after the hardware validation only the former model was involved.

3.1.2 Behavioral Validation

In paragraph 3.1.1, we evaluated *PsySuite*'s reliability when generating and delivering uni- and multi-modal stimulations. Even though the App proved itself to be a valid tool to generate appropriate sensory stimulations, as generation procedures stability was optimal, we wanted to ensure that data collected with a smartphone could be genuinely comparable to data obtained with classic setups. Thereby, we developed a portable version of a DFI-inducing experimental paradigm to assess whether psychophysical data collection could be efficiently performed using *PsySuite*. The DFI is a visual illusion when a different number of auditory and visual stimuli are presented to an observer. In such a scenario, the influence of the auditory information determines the visual illusion, through which a different number of flashes is perceived. Presenting two auditory stimuli concurrently with one visual stimulus, for example, often leads to the illusion that two visual stimuli were instead displayed (Keil, 2020; McCormick & Mamassian, 2008; Shams et al., 2000). Even though it has been demonstrated that touch can induce flash-illusions as well (Lange et al., 2011; Violentyev et al., 2005), to perform *PsySuite*'s behavioral validation we focused only on sound-induced changes in visual perception.

To evaluate *PsySuite*'s feasibility in performing behavioral testing, we opted for implementing a DFI paradigm as the illusion is elicited only when stimuli durations and temporal displacements between stimuli are short enough (within the order of tens of milliseconds). Thereby, high temporal resolution is required for the illusion to occur, and such resolution can be directly assessed by evaluating observers' performance (i.e., whether or not participants experience the visual illusion). Furthermore, both *PsySuite*'s software and hardware components were highly stressed while performing the paradigm due to the strict time frames needed to elicit the visual illusion. Because of this, the DFI was considered an appropriate paradigm to evaluate the App's ability to perform reliable data collection procedures.

To test whether *PsySuite* could be a valuable tool to foster remote approaches to psychophysical research, we elicited DFI in participants directly using the App. Then, we compared the magnitude of the DFI obtained with *PsySuite* with the magnitude of a similar effect obtained with a more classic PC-based setup. If *PsySuite* can be successfully used to collect behavioral parameters by remote, we expect to witness two

different results: first, we expect that observers experience the illusion when using the smartphone; second, we also expect that the magnitude of the effects between the two setups is comparable.

Participants

A total of 10 participants (4M, Age: $M=30.4$ y, $SD=5.4$ y) were recruited to assess *PsySuite*'s capabilities in performing accurate behavioral testing. All participants had normal or corrected-to-normal vision and no history of neurological disease. All participants were naïve to the purpose of the study and gave informed consent prior the participation in the experimental procedure. Data collection was performed either at the Istituto Italiano di Tecnologia, in Genova, or directly at participants' homes when tested using *PsySuite*. Testing procedures were developed following Helsinki's declaration and were approved by the local ethical committee (Comitato Etico ASL3, Genova).

Apparatus and Stimuli

Stimuli delivered with *PsySuite* are described in paragraph 3.1. For the DFI elicited through the PC-based setup, stimuli were generated using the MSI-caterpillar (Gori et al., 2019), a custom-made device plugged via USB cable to a tower PC, directly controlled with MATLAB v. 2020b. Such a device is tailored explicitly for multi-modal stimulation, as it reliably delivers stimuli in the auditory, visual, and tactile modalities. During the procedure, participants sat at a 57 cm viewing distance from a 24" Asus VG248QE LCD monitor with a resolution of 1920 x 1080 pixels and a refresh rate of 100 Hz. The monitor was used to display a red fixation point on an otherwise black screen, at which participants stared for the whole duration of the procedure, while the MSI caterpillar was placed two degrees of visual angle under it. Visual stimuli generated with the MSI caterpillar were 17 ms blue flashes subtending two degrees of visual angle, while auditory stimuli were 1k Hz pure tone bursts lasting 7 ms. To control for possible learning interference, the order of setups was counterbalanced across participants, which either first performed the task with *PsySuite* or with the PC-based setup.

Experimental Procedure

Similar experimental procedures were implemented using both *PsySuite* and the classic PC-based setup. Four different trial conditions were developed (Figure 3.31): a set of trials in which one single visual stimulus was delivered (single uni-modal condition), a set of trials in which two visual stimuli were sequentially delivered (double uni-modal condition), a set of trials in which one visual and one auditory stimuli were delivered (single bi-modal condition), and a set of trials in which one visual stimulus and two auditory stimuli were delivered, i.e., the trial condition in which we would expect the illusion to occur (double bi-modal condition). Each type of trial was repeated 20 times, leading to a total of 80 trials that

were presented to participants in random order. The delay between stimuli onsets was fixed at 30 ms, so that the shortest kind of trial (single uni-modal) lasted 17 ms, and the longest kind of trial (double uni-modal/double bi-modal conditions) lasted 67 ms. At the end of each trial, participants reported how many visual flashes were displayed.

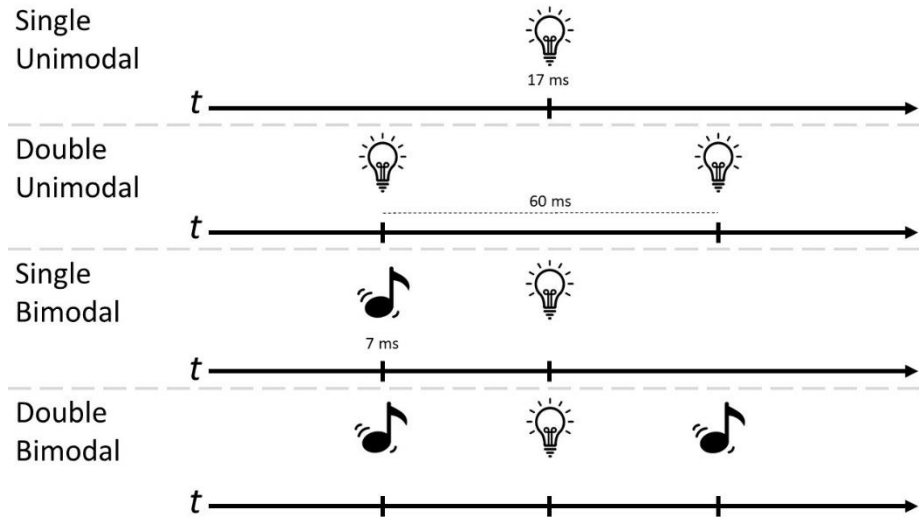


Figure 3.31 Trial classification for the DFI task.

Different trial conditions developed to evaluate the DFI using both *PsySuite* and a PC-based setup.

Data Analysis

To assess *PsySuite*'s feasibility in performing efficient behavioral data collection, we first calculated the proportion of correct responses for both the single uni-modal and the double bi-modal condition obtained with *PsySuite* and the classic PC-based setup, respectively. Then, to evaluate whether we successfully elicited the DFI using *PsySuite* stimuli presentation, we compared proportions of correct responses between the two trials conditions of interest obtained when participants performed the task using the App. Lastly, to compare DFI's magnitude observed within the two different setups, we compared the proportion of correct responses in the double bi-modal condition measured using *PsySuite* and the classic PC-based setup.

Quantification and Statistical Analysis

All statistical procedures were conducted using JASP v. 0.14 (Love et al., 2019). In the current work, we used parametric statistical tests (Dependent t-test for two samples) since all samples met normality and homogeneity assumptions (evaluated using Shapiro Wilk and Levene's test, respectively). Statistical significance was defined considering p-values lower than 0.05. No participant was excluded from the final analysis.

Results

First, we evaluated the difference in proportion of correct responses between the single uni-modal and double bi-modal conditions. Our analysis indicated that the proportion of correct responses in the single uni-modal condition (M: 0.97, SD: 0.034) was statistically higher ($t_{(9)}=15.06$, $p\text{-value}<0.001$, 95% CI [0.686 0.929], Cohen's $d=6.22$) than the proportion of correct responses in the double bi-modal condition (M: 0.172, SD: 0.178), suggesting that participants tended to give the wrong answer when two sounds and one flash were delivered (Figure 3.32A). Then, we compared the DFI measured with *PsySuite* with the effect found using the canonical PC-based setup. We found that the magnitude of the DFI induced with both the App and the PC (M: 0.168, SD: 0.1) did not differ in a statistically significant manner ($t_{(9)}=-0.028$, $p\text{-value}=0.978$, 95% CI [-0.086, 0.084], Cohen's $d=0.03$), suggesting that the illusion was equally elicited when performing the task, regardless of the setup involved (Figure 3.32B).

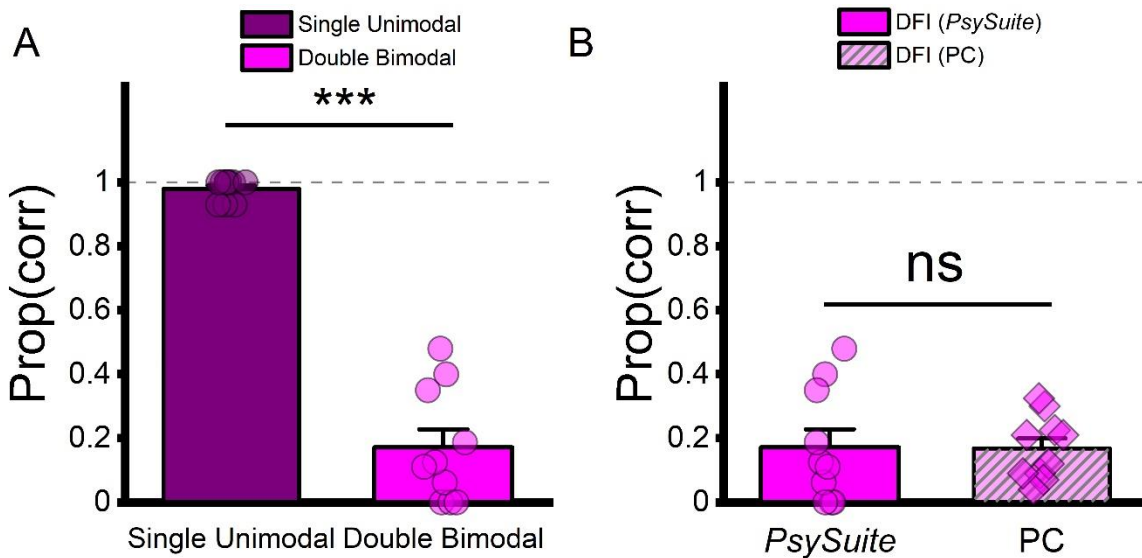


Figure 3.32 DFI elicited with *PsySuite* and a classic PC-based setup.

A) Proportion of correct responses for the single uni-modal (one flash displayed) and the double bi-modal (one flash and two sounds delivered) conditions, tested using *PsySuite*. B) Proportion of correct responses in the double bi-modal condition measured with both *PsySuite* and a classic PC-based setup. In both graphs, single points indicate individual participants, dashed line indicates ceiling performance, and error bars indicate $\pm$ SEM (**= $p\text{-value}<0.01$, ns= $p\text{-value}>0.05$).

Conclusions

Through the DFI, a classic illusion widely studied within psychophysical research, we validated the use of *PsySuite* considering behavioral performance measured with the App. If *PsySuite* was not suitable to sustain heavily demanding testing procedures in terms of both hardware and software requirements, eliciting the DFI with it should have been almost impossible. This is because the illusion itself requires short and accurate presentations timing that inevitably stresses the App's components. Thereby, eliciting the DFI with

the App proves that the DFI, one of the most timing-dependent visual illusions, is inducible also using devices not inherently designed for research, such as smartphones.

The results of the performed behavioral validation are twofold. On the one hand, we managed to induce the DFI in all participants using *PsySuite*'s testing procedures, as their proportions of correct responses significantly dropped when two auditory stimuli and one visual stimulus were concurrently delivered. On the other hand, DFI magnitudes elicited with the App were equal to DFI magnitudes elicited with the classic PC-based setup, as the reduced proportion of correct responses in the double bi-modal condition did not differ between setups.

Taken together, these findings support *PsySuite*'s feasibility in performing remote and reliable psychophysical testing within the temporal domain, using short-timed auditory and visual stimuli. While *PsySuite*'s efficiency in delivering highly accurate and precise stimulations was already supported by the hardware validation described in paragraph 3.1.1, behavioral validation confirmed that *PsySuite* is a powerful tool through which collect behavioral data. Notably, behavioral validation was developed to control the influence of factors potentially interfering with results collected when using smartphones to deliver psychophysical testing procedures. To name but a few examples, behavioral results could be influenced by the fact that data collection was performed in an environment known by the participant (e.g., their living room) or that the experimenter was not nearby the participant during the procedure.

Overall, *PsySuite* validations demonstrated that obtaining psychophysical measurements does not require participants to go to research facilities. Data collection can be safely and remotely performed at their own houses with just an everyday, easy-to-use device such as a smartphone.

3.2 Portable Evaluation and Enhancement of Temporal Sensitivity

In paragraphs 3.1.1 and 3.1.2, we assessed *PsySuite*'s capability to deliver accurate and precise uni- and multi-modal stimulations, as well as its feasibility in performing behavioral data collection when allowing participants to use it autonomously. Both hardware and behavioral validations suggested that through the App it was possible to efficiently collect data that were qualitatively comparable to measurements obtained with more classical PC-based setups.

After witnessing *PsySuite*'s suitability in delivering testing procedures requiring high temporal resolutions, such as the DFI-inducing task, we developed *Temporal Interval Discrimination (TID)*, a *PsySuite* library designed to evaluate and enhance temporal perceptual thresholds in the auditory and tactile domains. We specifically decided to involve the auditory and the tactile modalities as they were the best and worst performant, respectively. Within *TID*, we developed a portable version of a Two-Alternatives Forced-

Choice task (2AFC), a classic psychophysical paradigm extensively used to evaluate perceptual skills in behavioral research (Matthews & Meck, 2014). In a 2AFC task, perception is evaluated through the presentation of two alternative stimuli that differ in magnitude for one or more perceptual features (e.g., their durations) and then forcing participants to choose one of them according to the task (e.g., selecting the stimulus that lasted longer between the two). Notably, participants cannot avoid choosing one of the stimuli, nor can they choose both (hence, the paradigm's name). Forcing participants to pick one of the stimuli is a procedure that allows the evaluation of perceptual thresholds as it pinpoints the perceptual magnitudes at which the two stimuli are perceived as equal (i.e., the PSE) as well as the minimum level of change in stimulation that is detectable 50% of the time (i.e., perceptual thresholds, or JND). Within *TID*, we developed a temporal 2AFC task in which stimuli differ in duration, and participants had to choose the longer one.

As we wanted to assess if *TID* was an effective tool for measuring temporal abilities, we first evaluated whether we could obtain a reliable assessment of temporal thresholds using the App. To do so, we tested adults with the temporal 2AFC task implemented within *TID*, delivering either auditory or tactile stimulations in separate sessions. Then, we compared measurements obtained with *TID* with results already available in the literature acquired using similar tasks, but collected via classic PC-based approaches. Lastly we also investigated whether temporal abilities could be enhanced by developing a temporal perceptual learning protocol, asking participants to use *TID* for four days and then comparing temporal performances before and after the training with the App (Domenici et al., 2021).

Participants

A total of 12 participants (5M, Age: $M=28.1$ y, $SD=1.21$ y) were recruited to assess *TID*'s potential. All participants had normal or corrected-to-normal vision and no history of neurological diseases. All participants were naïve to the purpose of the study and gave informed consent prior the participation in the experimental procedure. Testing procedures were developed following Helsinki's declaration and were approved by the local ethical committee (Comitato Etico ASL3, Genova). Data collection was directly performed at participants' homes, as they were given smartphones to either evaluate temporal thresholds or perform the temporal training. Temporal thresholds in both auditory and tactile modalities were evaluated among all participants involved in the study, while temporal trainings were conducted by dividing them into two groups of equal number. Six participants (3M, Age: $M=27.75$ y, $SD=0.5$ y) trained for four days using the 2AFC auditory task, while the other six participants (2M, Age: $M=27.83$ y, $SD=1.47$ y) trained for four days using the 2AFC tactile task.

Apparatus and Stimuli

Stimuli delivered were empty intervals delimited either by 50 ms phone vibrations (in the tactile 2AFC task) or by 50 ms 1 kHz sounds (in the auditory 2AFC task), separated by an inter-stimulus interval of 500 ms.

Experimental Procedure

In both 2AFC tasks developed with TID, participants had to discriminate between two sequentially delivered intervals, indicating which one lasted longer at the end of each trial (Figure 3.33). Stimuli to be compared were a *Reference* interval, whose duration was fixed across the whole procedure and lasted 200 ms, and a *Test* interval, whose duration changed across trials and was chosen among one of eight pre-configured durations (100, 128, 157, 185, 214, 242, 271, or 300 ms). Each duration was randomly displayed eight times so that a whole experimental block consisted of 64 trials and lasted approximately 5 minutes. We analyzed performance to evaluate temporal thresholds, asking participants to complete only one block. As already reported in paragraph 3.1, testing procedures were run adding a white noise background to mask the vibrator's engines sound to ensure that participants relied on tactile cues only when needed. For consistency purposes, we added a white noise background in the auditory task as well, so participants were required to wear headphones while performing the experiment – regardless of the sensory modality involved.

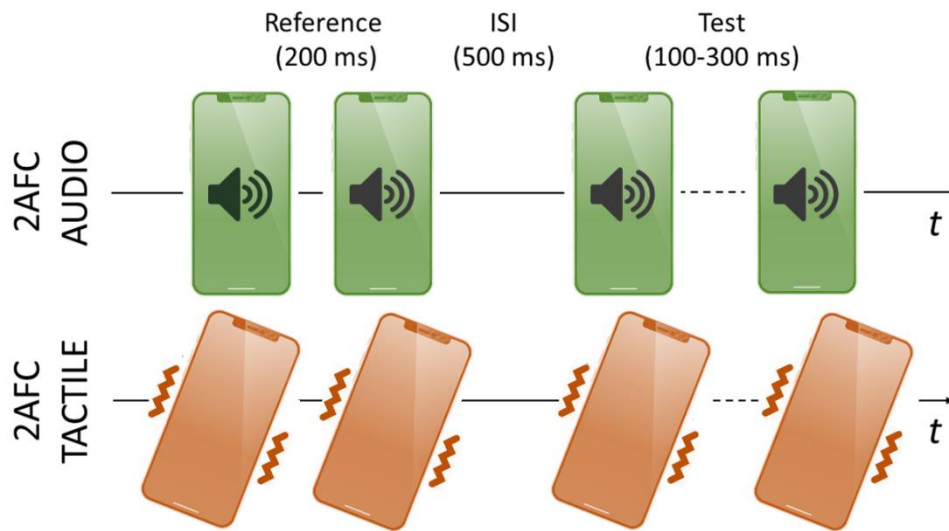


Figure 3.33 2AFC tasks included within TID.

Schematic representations of both auditory and tactile 2AFC task. Dashed lines between test's onsets and offsets indicate that the duration of the Test changed across trials, while all other intervals were kept constant.

To assess whether participants' temporal abilities could be enhanced by involving just a smartphone, we asked them to use TID for four consecutive days, training with the corresponding sensory modality to which

they were assigned (performing the training either with the auditory or the tactile task). During each training session, participants performed three experimental blocks for a total of 192 trials. Overall, training sessions were completed in around 15 minutes and were performed around the same time by every participant (between 8 PM and 10 PM). While completing training experimental blocks, TID provided participants with response feedback at the end of each trial. If participants succeeded in individuating the longer interval between the two, a green checkmark appeared on the display to notify the correctness of the response. In case of a wrong answer, a red cross was otherwise displayed. Feedback was provided during training blocks as reinforcement from internal rewards increases learning rates (Sasaki et al., 2010). The day after the training was completed, participants' temporal abilities were re-evaluated in both the auditory and tactile domains, using just one experimental block per sensory modality. Then, for each participant, temporal performance in the post-training sessions was compared to the performance observed in the pre-training sessions, testing whether training perceptual learning occurred using *TID*.

Data Analysis

We fitted psychometric functions into individual participants' data to evaluate temporal performance, similar to what was already done in paragraph 2.2 for a previously discussed study, using the formula reported in equation 2.8. We then evaluated the JND, which identifies temporal perceptual thresholds and is an index of temporal sensitivity. To better compare performances across modalities, as well as with data available in the existing literature, we decided to define performance using Weber's Fraction (WF), evaluated through the following formula:

$$(3.2) WF = \frac{\Delta\phi}{\phi}$$

where $\Delta\phi$ is the incrementing thresholds for detecting a perceptual difference (i.e., the JND) and ϕ is the physical intensity of the reference stimulation. Notably, WF is a dimensionless parameter, therefore being remarkably indicated when comparing perceptual sensitivities across modalities and tasks. As a rule of thumb, the lower the WF, the higher the perceptual sensitivity since WF is directly proportional to the JND.

Quantification and Statistical Analysis

All statistical procedures were conducted using JASP v. 0.14 (Love et al., 2019). We used classic parametric statistical tests (Two-way repeated measure ANOVA, dependent t-test for two samples, and one sample t-test), since all samples met normality and homogeneity assumptions (evaluated using Shapiro Wilk and Levene's test, respectively). Statistical significance was defined considering p-values lower than 0.05. No participant was excluded from the final analysis.

Results

To evaluate whether thresholds measured using *TID* could be considered a reliable indicator of participants' temporal abilities, we compared them with similar temporal thresholds already reported in the existing literature evaluated with classic psychophysical setups (Domenici et al., 2021; Treisman, 1963). Thereby, we performed One sample t-tests on WF measured with *TID* considering literature values as population means (WF: Auditory=0.132, Tactile=0.154). Then, we compared WF across the two sensory modalities using a dependent samples t-test, as we expected WF in the auditory modality to be lower than WF in the tactile modality (Merchel & Altinsoy, 2020), in accordance with the *Modality Appropriateness Hypothesis* (Welch & Warren, 1980).

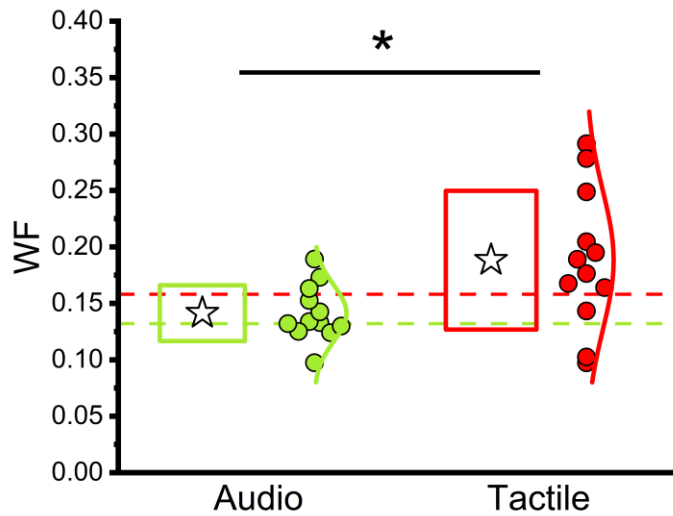


Figure 3.34 Auditory and tactile WF measured with *TID*.

Estimated WF using *TID*. Dashed lines represent population values for auditory (green) and tactile (red) temporal perception, measured in Treisman 1963, and Domenici et al., 2020, respectively. Symbols indicate individual data, while stars indicate averaged values. Box plots extend up to $\pm$ one standard deviation.

Our analyses highlighted that WF measured using *TID* (Auditory: $M=0.14$, $SD=0.02$; Tactile: $M=0.18$, $SD=0.06$) did not differ from populations values neither in the auditory ($t_{(11)}=1.308$, $p\text{-value}=0.22$, 95% CI $[-0.006\ 0.025]$, Cohen's $d=0.75$) nor in the tactile ($t_{(11)}=1.93$, $p\text{-value}=0.08$, 95% CI $[-0.005\ 0.073]$, Cohen's $d=0.33$) sensory modality (Figure 3.34). Then, we compared WF observed with *TID* across sensory modalities, founding that WF measured in the auditory task was significantly lower than WF observed in the tactile task ($t_{(11)}=-2.882$, $p\text{-value}=0.014$, 95% CI $[-0.083\ -0.011]$, Cohen's $d=0.89$), following perceptual trends already emerged in previous studies (Merchel & Altinsoy, 2020).

To assess whether perceptual learning could be fostered using *TID*, we compared WF measured before and after the four-days training. Therefore, we ran a Two-way repeated measure ANOVA with within-subject factor Session (Pre-training vs. Post-training) and between-subject factor Training Modality (Auditory vs. Tactile) on WFs for the trained task (i.e., considering intra-modal effects). We found a main effect of the

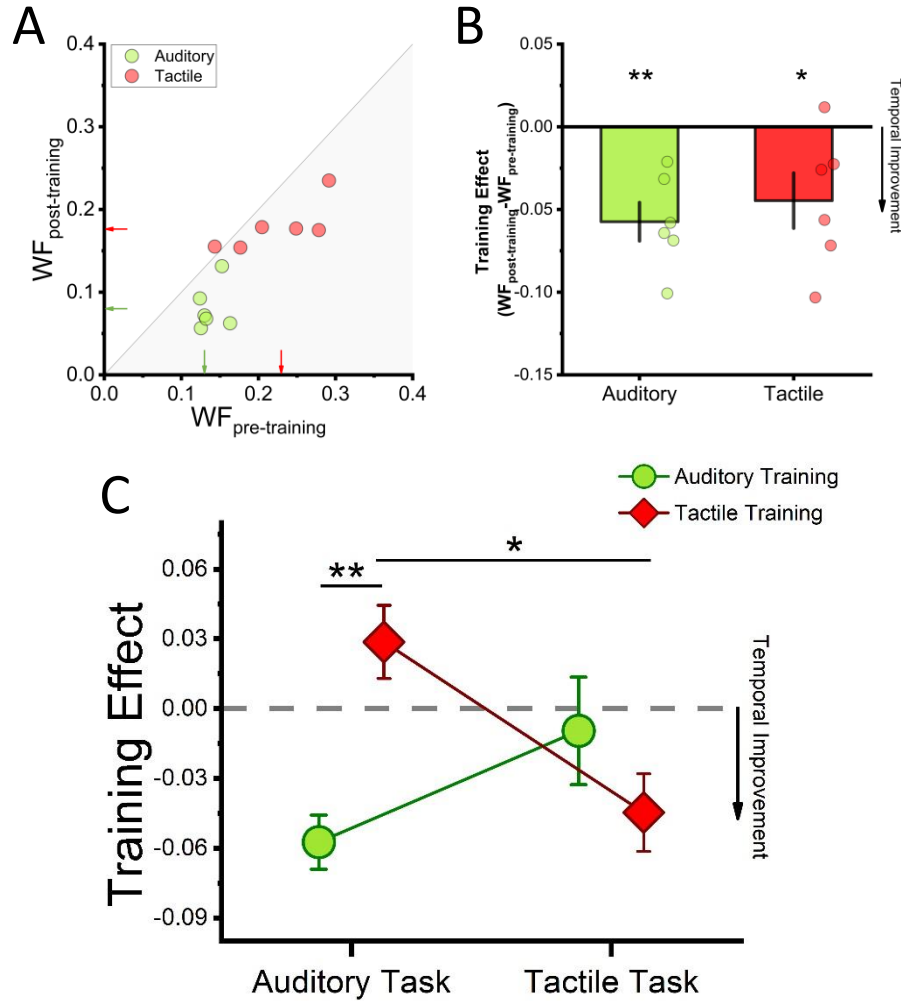


Figure 3.35 Intra- and cross-modal training effects.

A) Intra-modal individual post-training WFs plotted as a function of pre-training WFs for each participant. Green symbols indicate participants that trained using the auditory task, while red symbols indicate participants that trained using the tactile task. Symbols under the oblique line represent participants whose performance improved after the training in the trained sensory modality. Arrows nearby both axes indicate group averages. B) WF difference between post- and pre-training sessions. Both groups showed a significant reduction of WF in the post-training session, as the difference observed was significantly higher than zero. Symbols indicate individual participants' data. C) Effect of training on both untrained and trained sensory modalities. While the gray, dashed line indicates no effect of the training whatsoever, values lower than zero highlight a significant training effect (In both panel B and C error bars indicate $\pm$ SEM; **= p -value <0.01 , *= p -value <0.05).

session ($F_{(1,10)}=25.56$, p -value <0.001 , $\eta^2_p=0.72$), as well as a main effect of the training modality ($F_{(1,10)}=24.825$, p -value <0.001 , $\eta^2_p=0.71$), while we did not find a significant interaction effect ($F_{(1,10)}=0.393$, p -value $=0.545$, $\eta^2_p=0.04$). Given our statistical design, we did not need further post-hoc

comparisons. These results confirmed that WF was overall lower in the post-training session (Figure 3.35A), suggesting that temporal perceptual learning can be conveyed using the *PsySuite* library *TID*. Moreover, WF was generally lower in the auditory modality, as proven by our initial statistical analysis and expected considering the existing literature.

To analyze both training effects, we calculated the difference between the WF measured in the pre- and post-training sessions for each participant, and then we compared the obtained values against each other. We decided to perform such analysis as we wanted to test whether eventual increments of temporal skills occurred intra-modally or whether participants changed their temporal sensitivities regardless of the training occurring. We thus performed a Two-way repeated ANOVA with within-subject factor Task (Auditory vs. Tactile) and between-subject factor Training (Auditory vs. Tactile) on Training Effects (i.e., the difference in WF between the post- and the pre-training session). Our analysis highlighted a significant main effect of the Training ($F_{(1,10)}=6.393$, $p\text{-value}=0.03$, $\eta^2=0.088$) and a significant interaction between factors ($F_{(1,10)}=24.747$, $p\text{-value}<0.001$, $\eta^2=0.342$), but no main effect of the Task ($F_{(1,10)}=0.945$, $p\text{-value}=0.354$, $\eta^2=0.037$). Post-hoc analysis (after Bonferroni correction for multiple comparisons, adjusting the p-value and confidence intervals for comparing a family of 6 estimates) highlighted a significant difference between the two tasks when participants performed the tactile training ($t_{(5)}=3.372$, $p\text{-value}=0.023$, 95% CI [-0.01 -0.18], Cohen's $d=1.28$) but, interestingly, not when participants performed the auditory training ($t_{(5)}=-1.698$, $p\text{-value}=0.65$, 95% CI [-0.132 0.037], Cohen's $d=0.8$).

At first glance, these results might suggest that the auditory training was not as effective as the tactile one, as no significant differences in post-auditory training were found between the two tasks. However, there are further hints suggesting that this is not the case. First, participants who trained with sounds performed significantly better in the auditory task than those who trained with phone vibrations ($t_{(10)}=-5.305$, $p\text{-value}=0.002$, 95% CI [-0.174 -0.041], Cohen's $d=1.83$). Second, if we consider both training effects individually, we found that when comparing the Training Effect against zero, both the auditory ($t_{(5)}=-4.947$, $p\text{-value}=0.004$, 95% CI [-0.087 -0.028], Cohen's $d=2.39$) and the tactile ($t_{(5)}=-2.68$, $p\text{-value}=0.04$, 95% CI [-0.087 -0.002], Cohen's $d=1.11$) training determined a statistically significant reduction of temporal thresholds between the pre- and post-training session in the trained task (Figure 3.35B). We thus advocate that, rather than being ineffective, the auditory training determined, to a lesser extent, a reduction of temporal thresholds also in the untrained, tactile task. This is further supported by the fact that, even if statistical significance was not reached, averaged temporal thresholds were slightly reduced in the tactile task ($M=-0.01$, $SD=0.05$) after auditory training, due to half of the participants experiencing temporal improvements (Figure 3.35C, note the high SEM in the tactile task for the group that trained with sounds).

Conclusions

Within *PsySuite*, we developed *TID*, a library designed to evaluate and enhance auditory and tactile temporal thresholds in the millisecond-to-second domain. Using *TID*, we first collected temporal thresholds delivering, in separate sessions, empty intervals delimited either by sounds or phone vibrations. Our results, obtained involving a different approach to data collection, support the App's reliability once again and confirm that psychophysical testing can be safely performed with just the use of a smartphone.

For the evaluation of temporal skills, data collected with *TID* were quantitatively similar to the ones already available in the existing literature, obtained through classic PC-based setups. Moreover, temporal thresholds measured in the auditory task were significantly lower than those measured in the tactile task, a result in line with previous research (Merchel & Altinsoy, 2020) and with the *Modality Appropriateness Hypothesis* (Welch & Warren, 1980).

Interestingly enough, using *TID* we managed not only to measure temporal thresholds in both sensory modalities involved in this study but also to enhance them by developing a short training that participants easily performed in their homes. After only four days of using *TID*, participants significantly reduced their temporal thresholds (i.e., they performed significantly better) in the trained modality. We also speculated that the effect of auditory training could potentially generalize to the untrained, tactile modality, even though this cross-sensory transfer was not present in our study. Our speculation is based on two major points: first, cross-sensory perceptual temporal learning occurs when involving auditory training, whose effect generalizes to the visual modality (McGovern et al., 2016); second, since auditory is the primary sense through which we perceive time (Burr et al., 2009; Chen & Yeh, 2009; Klink et al., 2011; Recanzone, 2003), and tactile is somehow better than vision but worse than auditory in encoding temporal information (Welch & Warren, 1980), it is plausible to assume that cross-sensory perceptual learning transfer might occur less frequently and in a less reliable way when compared to cross-sensory transfer between hearing and vision. Because of these considerations, the number of participants involved in this study is significantly low to investigate an effect that is possibly not as consistent as the one induced by training within the same modality, and our speculations are destined, for now, to remain as such. Nevertheless, being able to develop speculation on temporal perceptual learning processes, as well as on the cross-sensory transfer of learning effects, using the novel approach that we developed is noteworthy, and a result in its own fashion.

3.3 Portable Psychophysics in Clinical Contexts

In paragraph 3.2, we brought evidence in support of *TID*'s feasibility when performing evaluations of temporal skills, measuring participants' temporal thresholds both in the auditory and in the tactile modality. Nonetheless, data collection with *TID* (and with *PsySuite* in general) involved only adult individuals with no sensory (e.g., deafness) nor learning (e.g., DD) disabilities. While evaluating the App's appropriateness in fostering a portable approach to psychophysical testing that necessarily required typical participants, we also wanted to test whether *TID* could be used in specific clinical contexts to highlight deteriorations in temporal processing successfully.

As discussed in Chapter 1 and supported by behavioral results presented in Chapter 2, temporal perception in both deaf (Amadeo et al., 2019; Bolognini et al., 2012; Kowalska & Szelag, 2006) and individuals with DD (Casini et al., 2018; Nicolson et al., 1995; Rocheron et al., 2002) appears to be severely impaired at a general level. We thus decided to use *TID* to evaluate temporal abilities in the preserved sensory modalities in deaf individuals and the auditory, visual, and tactile modalities in children with DD. We expect that if *TID* is indeed a powerful tool in assessing temporal perceptual skills – and if a remote approach to psychophysical testing is overall implementable – both groups should perform significantly worse than control participants when using the App.

3.3.1 Portable Psychophysics and Deafness

Participants

17 participants were tested using *TID*, nine deaf (Age: $M=49.75$ y, $SD=14.81$ y) and eight age-matched hearing (Age: $M=55$ y, $SD=14.35$ y). All deaf participants were signers and knew the Italian sign language (LIS) at the moment of testing. All participants had normal or correct-to-normal vision, and no participant in the control group had a history of neurological diseases. All participants were naïve to the purpose of the study and gave informed consent before participation. Testing procedures were developed following Helsinki's declaration and were approved by the local ethical committee (Comitato Etico ASL3, Genova). Data collection was directly performed at participants' homes or the Ente Nazionale Sordi (ENS) association in a room used explicitly for collection purposes.

Apparatus and Stimuli

The apparatus and stimuli involved were already described in paragraphs 3.1 and 3.2.

Experimental Procedure

Since we used *TID* to evaluate temporal thresholds in both deaf and hearing participants, the involved experimental procedure is identical to the one already described in paragraph 3.2. The only difference from the original design is that we did not use the auditory task instead of a visual 2AFC. In the visual task, intervals were delimited by blue circles with a diameter of 4 cm displayed on a white background. All other experimental parameters, such as *Test* and *Reference* interval durations, were kept constant.

Data Analysis

To analyze temporal processing in both deaf and hearing individuals, we implemented the same data analysis procedure described in paragraph 3.2, used to validate *TID*. We, therefore, fitted psychophysical functions into individual participants' data and considered the WF as an appropriate index of temporal sensitivity.

Quantification and Statistical Analysis

All statistical procedures were conducted using JASP v. 0.14 (Love et al., 2019). In the current work, we used classic parametric statistical tests (Two-way ANOVA and dependent t-test for two samples), as well as non-parametric statistical tests (Mann-Whitney U test) when required. Statistical significance was defined considering p-values lower than 0.05. No participant was excluded from the final analysis.

Results

To evaluate differences in temporal performance between groups, we ran a Two-way ANOVA with within-subject factor Sensory Modality (Visual vs. Tactile) and between-subject factor Group (Deaf vs. Hearing) on WFs. Our analysis highlighted a main effect of the factor Sensory Modality ($F_{(1,15)}=5.393$, $p\text{-value}=0.035$, $\eta^2=0.09$) and of the factor Group ($F_{(1,15)}=17.226$, $p\text{-value}<0.001$, $\eta^2=0.336$), while no significant interaction effect was found ($F_{(1,15)}=1.825$, $p\text{-value}=0.197$, $\eta^2=0.03$). Given our statistical design, these results hinted not only that participants displayed overall lower temporal thresholds in the tactile ($M=0.351$, $SD=0.288$) than in the visual ($M=0.572$, $SD=0.402$) modality but also that hearing participants ($M=0.243$, $SD=0.103$) performed significantly better than deaf participants ($M=0.623$, $SD=0.355$). We then decided to underline additional differences between groups across sensory modalities, performing a comparison between WFs observed in deaf and hearing participants considering in separate analyses the visual and the tactile task. We found that temporal thresholds in deaf participants were significantly higher when temporal information was visually presented ($t_{(15)}=3.833$, $p\text{-value}=0.002$, 95 % CI [-0.735 0.21], Cohen's $d=1.8$), as well as when stimuli were delimited by phone vibrations (difference evaluated using

Mann-Whitney U test, since Levene's test significance suggested a violation of the equal variance assumption: $U=59$, $p\text{-value}=0.027$, $r_{tb}=0.69$). These results utterly confirmed that deaf participants performed worse than hearing ones and that the impaired performance was successfully monitored by *TID* both in the visual and in the tactile task (Figure 3.36).

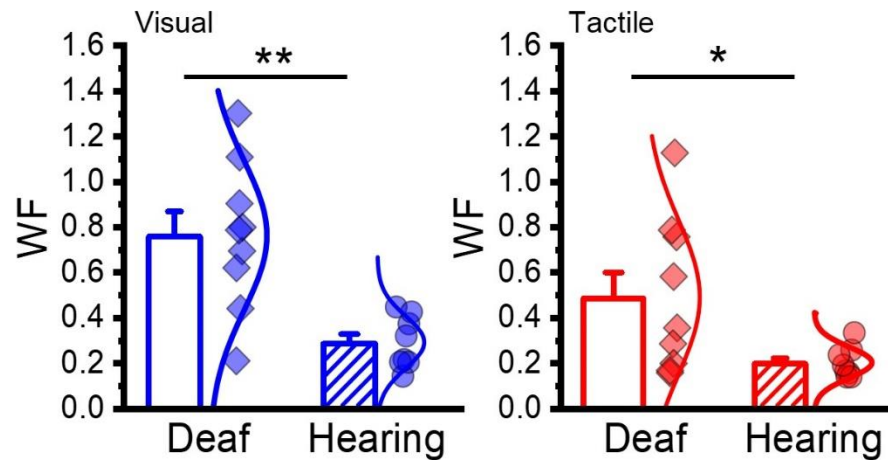


Figure 3.36 Temporal thresholds evaluated using *TID* in both deaf and hearing participants.

Symbols indicate individual participants' data, while bars reported averaged values across groups. Using *TID*, we managed to highlight significant temporal impairments in deaf individuals in both the visual and the tactile modality, as their WFs were significantly higher than the ones observed in the hearing group. Error bars indicate $\pm$ SEM (*= $p\text{-value}<0.05$, **= $p\text{-value}<0.01$).

Conclusions

Using *TID*, we managed to highlight a generalized reduction of temporal sensitivity in deaf participants compared to hearing ones. Overall, deaf individuals performed worse than control in discriminating between two intervals, both when using the visual and the tactile sensory modality. Interestingly, measured participants' temporal thresholds were lower in the tactile than in the visual task, a trend that is in line with evidence suggesting that touch is dominant over vision when encoding temporal information. Furthermore, the better performance observed for both groups in the tactile task can be conceptualized within the *Modality Appropriateness Hypothesis* (Welch & Warren, 1980). The sensory hierarchy for which vision is the worse modality to convey temporal information appears indeed to still be valid, even in cases in which temporal perception is overall impaired, such as in congenital and early deafness.

Taken together, these results further support *TID*'s ability to precisely evaluate temporal sensitivities, even when measuring temporal abilities in populations in which temporal processing is significantly impaired. Notably, *PsySuite*'s ability to highlight different perceptual behaviors advocate for its implementation not only in basic, but also in applied research, as well as – potentially – in different clinical contexts.

3.3.2 Portable Psychophysics and Developmental Dyslexia

Participants

12 children with DD ($M=11.25$ y, $SD=2.14$ y, 5F) and 12 normal-reading, age-matched peers ($M=11.33$ y, $SD=1.37$ y, 4F) took part in the study. All participants had normal or correct-to-normal vision, and no participant had a history of neurological disease. All participants were naïve to the purpose of the study, and the legal representatives of the children gave informed consent before any child participated in the experimental procedure. Children with DD were tested in a local rehabilitative center for learning disabilities, while normal-reading children were tested at Genova's Istituto Italiano di Tecnologia. Testing procedures were developed following Helsinki's declaration and were approved by the local ethical committee (Comitato Etico ASL3, Genova).

Apparatus and Stimuli

The apparatus and stimuli involved were already described in paragraphs 3.1 and 3.2.

Experimental Procedure

As we used *TID* to evaluate temporal thresholds in both children with DD and normal-reading peers, the involved experimental procedure is identical to the one already described in paragraph 3.2. Differently from what was reported for deaf participants, children with DD and normal reading-peers were tested using all three (auditory, visual, and tactile) 2AFC tasks.

Data Analysis

Data analysis procedures were identical to the ones followed when using *TID* to evaluate temporal processing in deaf individuals, already described in paragraph 3.2.

Quantification and Statistical Analysis

All statistical procedures were conducted using JASP v. 0.14 (Love et al., 2019). In the current work, we used classic parametric statistical tests (Two-way ANOVA and Independent t-test for two samples) since all samples met normality and homogeneity assumptions (evaluated using Shapiro Wilk and Levene's test, respectively). Statistical significance was defined considering p-values lower than 0.05. No participant was excluded from the final analysis.

Results

To investigate whether reduced temporal sensitivities between children with DD and normal-reading peers could be tracked using *TID*, we first ran a Two-way ANOVA with within-subject factor Condition (Visual vs. Tactile vs. Auditory) and between-subject factor Group (Dyslexic vs. Control) on WFs. Our analysis highlighted a main effect of the Group ($F_{(1,22)}=13.323$, $p\text{-value}=0.001$, $\eta=0.177$), as well as a main effect of the Condition ($F_{(2,22)}=6.348$, $p\text{-value}=0.004$, $\eta=0.109$). However, no significant interaction effect was found ($F_{(2,22)}=2.479$, $p\text{-value}=0.095$, $\eta=0.043$), although a trend emerged due to performance in the tactile task being similar between groups. Post-hoc analysis on the factor Condition (after Bonferroni correction for multiple comparisons, adjusting the $p\text{-value}$ and confidence intervals for comparing a family of 3 estimates) suggested that lower temporal sensitivities were found in the auditory task compared to the visual ($t_{(23)}=-2.849$, $p\text{-value}=0.02$, 95% CI [-0.288 -0.019]) and tactile ($t_{(23)}=-3.278$, $p\text{-value}=0.006$, 95% CI [-0.311 - 0.043]) ones. No differences between performance in the visual and the tactile task were observed ($t_{(23)}=-0.428$, $p\text{-value}=1$, 95% CI [-0.157 0.111]). Given our statistical design, we did not need further analyses on the factor Group, as highlighting its main effect already determined that children with DD performed overall worse than normal-reading peers.

Since we wanted to specifically pinpoint differences in performance between groups across different sensory modalities, we individually compared temporal sensitivities by performing Independent two samples t-tests on WF for each sensory modality. We found that WFs in children with DD were significantly higher than in normal-reading peers both for the auditory ($t_{(22)}=-3.713$, $p\text{-value}=0.001$, 95% CI [-0.511 - 0.145], Cohen's $d=1.52$) and visual ($t_{(22)}=-3.033$, $p\text{-value}=0.006$, 95% CI [-0.302 -0.057], Cohen's $d=1.24$)

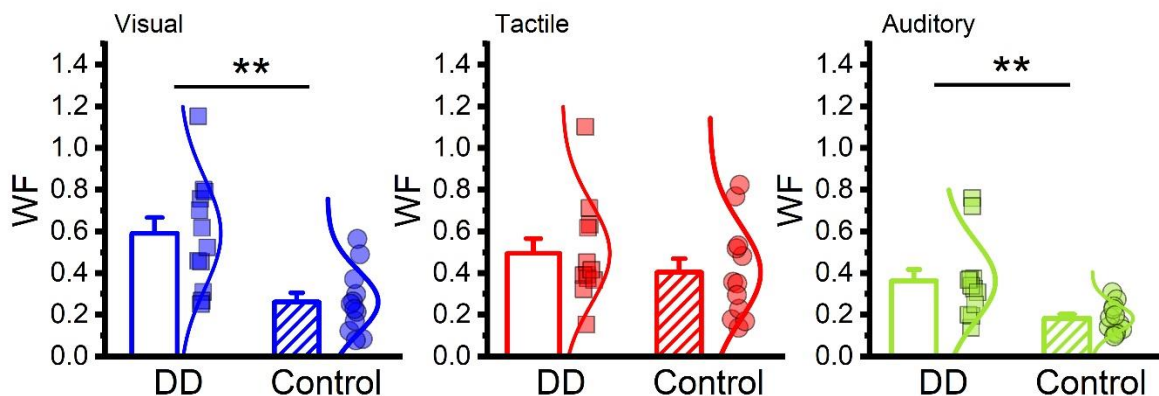


Figure 3.37 Temporal thresholds evaluated with *TID* in both DD and normal-reading children.

Symbols indicate individual participants' data, while bars reported averaged values across groups. Using *TID*, we managed to highlight significant temporal impairments in participants with DD in both the auditory and the visual modalities. Error bars indicate $\pm$ SEM (**= $p\text{-value}<0.01$).

task. However, differences in temporal sensitivities did not emerge in the tactile ($t_{(22)}=-0.94$, $p\text{-value}=0.358$, 95% CI [-0.29 0.109], Cohen's $d=0.38$) task (Figure 3.37).

Conclusions

Given *TID*'s ability to deliver stimuli across the auditory, visual, and tactile modalities, we successfully investigated performance in both children with and without DD in a series of 2AFC, pure temporal tasks. With the simple use of a smartphone, we managed to describe an overall reduced temporal sensitivity in children with DD compared to normal-reading peers. Specifically, children with DD showed a significant reduction of temporal thresholds in both the auditory and the visual modalities while behaving as normal-reading peers in the tactile task.

At first glance, such a result appears oddly interpretable. Indeed, in paragraph 3.3.1 temporal thresholds were found to be lower in the tactile than in the visual modality, and the results obtained in this study not only are in opposition to that but also to the *Modality Appropriateness Hypothesis*. We argue that the higher WF values observed in the tactile task for normal-reading children might have been determined by them not firmly holding the smartphone in their hands, thereby inconsistently perceiving the vibrations produced by the device. Even though we cannot provide further evidence to support our interpretation, we believe that requesting young participants to hold the smartphone firmly is a necessary precaution to consider. While we did ask young participants to perform the task only when phone vibrations were clearly perceived, it is not easy to ensure that testing procedures are precisely followed when involving the tactile modality. This is due to the fact that the experimenter cannot monitor the task's execution, while for other modalities the procedure's correctness is easier to assess (e.g., in the visual modality, the experimenter can evaluate whether the gaze of the participant is focused on the screen or not).

Chapter Four

General Conclusions

The aim of this work has been twofold. In the first part, I investigated temporal processing in populations showing significant impairment in auditory perception during the early stages of life, namely early/congenital deaf individuals and children with developmental dyslexia (DD). I used classical behavioral paradigms to evaluate impairments in visual temporal processing, involving tasks specifically designed to assess the encoding of temporal information within magnocellular streams. Since this cell mainly encodes temporal information (due to their specific preference toward rapid changes and transient events), I designed two experimental protocols that exploited this encoding peculiarity. In the second part, I designed and validated *PsySuite*, an Android App specifically designed to set psychophysics to a portable level and foster a remote approach to data collection. Using *PsySuite*, I managed to evaluate and enhance temporal abilities in typical adults, as well as to highlight significant temporal impairments in deaf and individuals with DD, replicating the results already found with classic PC-based setups. Thus, this thesis focused on intertwining the core elements of basic research within an easy-to-use and affordable device, such as a smartphone. Even though my initial goal was to tackle recruiting difficulties that emerged due to the COVID-19 outbreak, a portable approach to psychophysics is an overall valuable tool whose utility will not run out with the pandemic's end. Considering its affordance, cheapness, and practicality, I am confident that *PsySuite* will maintain its usefulness in the future, providing a reliable solution to all accessibility issues related to both basic, applied, and clinical research.

4.1 Temporal Processing as a Marker for Cross-sensory Calibration Disruption

In their original work, Neville and Stevens pointed out that perceptual visual deficits exhibited by deaf and individuals with DD show some exciting and overlooked similarities (Stevens & Neville, 2006). In fact, the authors hypothesized that, due to the brain's maladaptive and adaptive plastic reorganization, the most plastic elements of perceptual processing (i.e., the aspects most likely influenced by early experience) should be impaired in developmental disabilities and enhanced after sensory deprivation. By virtue of this reorganization, sensitivity to visual motion is reduced in DD (Hansen et al., 2001; Talcott et al., 2000;

Witton et al., 1998) and increased in deaf people (Bavelier et al., 2000; Neville & Lawson, 1987). Nonetheless, the two pieces of literature about motion processing in deafness and DD have been developed in parallel, with only a few sporadic intersections.

Similarly, both pieces of literature revolving around temporal impairments in deafness and DD progressed separately one from the other until these days. At first glance, a comparison between motion and temporal processing in deafness and DD display a distinct, notable difference: while visual motion processing is impaired in DD and enhanced in deafness, temporal processing is impaired in both deafness and DD. This difference notwithstanding, I still decided to bridge the two pieces of literature, considering that subsets of visual processing can be selectively enhanced or impaired by early experience (Stevens & Neville, 2006) and that describing generalized magnocellular properties without underlying this distinction might be a faulty oversimplification. Following this scheme, if visual motion processing is enhanced in deaf individuals, exploiting motion information could restore veridical temporal representations of the environment due to the strong interconnection between motion and time. Notably, deaf people have already been proven to infer temporal metrics through redundant sensory information (Amadeo et al., 2019). Conversely, individuals with DD should show a different temporal encoding pattern when tested using a task specifically involving changes at the magnocellular processing level, such as experimental protocols designed to elicit saccadic spatiotemporal compressions (Binda et al., 2009; Morrone et al., 2005; Ross et al., 1997). With these considerations in mind, I thereby developed two studies specifically targeting magnocellular temporal processing in deafness and DD.

The first study, discussed in paragraph 2.1, evaluated temporal processing abilities in deaf and hearing participants using a visual temporal oddball-like task. When only temporal cues were available during the task, deaf participants showed a broad impairment in temporal processing as they could not reliably discriminate the duration of the stimuli displayed during the procedure. However, when spatiotemporal information was added, performance in the deaf group was significantly enhanced to the point that it almost reached the hearing participants' level. These results suggest that to restore optimal temporal processing, deaf participants could exploit spatiotemporal information resulting from the integration of visual spatial and temporal cues – as motion is considered a change in space across time. Both displacement and temporal cues are likely equally combined within the visual modality in hearing adults (Champion & Freeman, 2010; Wardle & Alais, 2013). Moreover, further research suggests that there might be a one-to-one influence between spatial cues, temporal cues, and their corresponding spatiotemporal output. This is supported by the fact that one stimulus' spatiotemporal features can influence its perceived duration (Kanai et al., 2006; Kaneko & Murakami, 2009; Linares & Gorea, 2015; Matthews, 2011) and spatial position (Ramachandran & Anstis, 1990; Valois & Valois, 1991).

Additionally, congenital and early deafness does not negatively impact spatial (Amadeo et al., 2019; Bolognini et al., 2012) nor spatiotemporal (Bosworth & Dobkins, 1999; Brozinski & Bavelier, 2004; Hauthal et al., 2013) perception, suggesting that precise prospective timing may be unnecessary in the process of correctly perceiving spatiotemporal patterns. The results already available in the existing literature further support our initial speculation, which was developed based on a potential enhancement of magnocellular processing in deaf individuals due to adaptive plasticity processes. Considering that visual spatiotemporal patterns, as well as rapid-changing, transient information, are mainly encoded by the magnocellular pathway and that temporal (but not spatial nor spatiotemporal) processing is impaired in early and congenital deafness, I suggested that deaf individuals use the uncompromised perceptual information, when available, to complete the task successfully. Thereby, I concluded that deaf participants used compensatory mechanisms to estimate visual time events and that such perceptual compensation is based on magnocellular properties.

In the second study, presented in paragraph 2.2, I evaluated spatial and temporal saccadic compressions in both children with and without DD. During saccadic movements, spatial mislocalizations and compressions of perceived duration occur when stimuli are briefly flashed around the saccadic onset. Changes in visual perception during saccadic movements have been linked to the receptive fields' predictive anticipatory remapping (Duhamel et al., 1992; Nakamura & Colby, 2002; Umeno & Goldberg, 1997; Walker et al., 1995) and a general suppression of the magnocellular pathway (Ross et al., 1996), which determines distortions of spatial and temporal internal metrics. When performing a saccadic movement, normal-reading children successfully compressed spatial and temporal visual information when stimuli were displayed around the start of the saccades. Conversely, saccadic movements failed to elicit any temporal compression in children with DD, while only partially compressing spatial information of a factor that was significantly lower than the one observed in normal-reading peers. The absence of spatial and temporal compressions might indicate that the magnocellular stream is not entirely suppressed in DD during saccadic movements, suggesting that much weaker modulations at the spatial and temporal internal metric occur in the *perisaccadic* timeframe. Our results pinpointed that visual temporal information, and spatial information to a lesser extent, are processed in significantly different ways between children with DD and normal-reading peers when performing a saccadic movement. This differential temporal processing is most surely a prerogative of magnocellular neurons, which preferentially encode temporal cues due to their response properties (Leonova et al., 2003; Levitt et al., 2001; Livingstone & Hubel, 1988), pointing out that magnocellular temporal processing might be heavily compromised in DD. Interestingly, both saccadic compression indices could be combined as covariates to correctly classify children based on the clinical diagnosis more than 90% of the time.

Both experiments discussed in Chapter 2 showed that visual magnocellular encoding exhibits different properties in deaf and children with DD compared to the corresponding typical populations. These results are in line with the original idea of Neville and Stevens (Stevens & Neville, 2006), which suggested that adaptive and maladaptive plastic changes occur in the brain after sensory deprivation and concurrently with developmental disabilities, respectively. Indeed, results discussed in Chapter 2 described both functional (in deaf participants) and dysfunctional (in participants with DD) patterns of behavioral responses involving temporal perception, on the broader level, and magnocellular processing, at the neurophysiological level. Unlike the original idea from which I took inspiration, I do not believe these plastic changes necessarily and solely occur within cortical areas. Even though cortical reorganization after sensory deprivation (Kral et al., 2002; Margolis et al., 2012; Neville & Bavelier, 2002; Rauschecker, 1999) or within developmental disabilities (De Smedt et al., 2019; Eden et al., 2004; Molko et al., 2003; Raschle et al., 2011) has been extensively documented, results discussed in the current work suggest that similar neural modifications driven by early experience might also involve subcortical substrates.

Many evidence collected in the last 40 years suggests that many factors heavily determine the development of magnocellular cells. From genetics (Galaburda et al., 2006; Paracchini et al., 2006) to immunological (Hugdahl et al., 1990; Vincent et al., 2002) and nutritional (Horrocks & Farooqui, 2004; Wall et al., 2010) influences, inefficient development of magnocellular properties in the sensory domains has been extensively investigated and conceptualized. Nevertheless, none of these factors alone successfully managed to describe the disruption of the magnocellular development, nor did it bridge the literature between different populations that share similar impairments, such as temporal processing in deafness and DD. Since magnocellular cells are especially prone to reflect plastic changes due to early abnormal sensory experience (Guimarães et al., 1990; Sur et al., 1988), one specific factor that has often been neglected, and that I highlighted within the current thesis, is related to the availability of precise and accurate sensory information during early, critical stages of life.

I therefore aimed at conceptualizing such inefficient temporal processing within the cross-sensory calibration theory framework. Including such theoretical implication does not preclude that plastic changes at the magnocellular level can still occur and influence temporal perception; rather, these two interpretations can be considered complementary instead of mutually exclusive. As discussed in paragraph 1.2.1, cross-sensory calibration processes arise during development to refine perceptual judgments across sensory modalities (Gori, 2015; Gori et al., 2008, 2012). At the early stages of life, the most reliable sense for a given perceptual feature refines the others in perceiving that very perceptual feature. For example, touch calibrates size perception, while vision calibrates orientation discrimination (Gori et al., 2008). This cross-sensory relationship is also maintained on a more broad level since sensory calibration can also be domain-

specific. As another example, the absence of vision during development negatively affects Euclidean auditory relationships, suggesting that vision is fundamental to developing coherent and functional spatial maps of the environment (Gori et al., 2014). As there is a plain temporal dominance of hearing over other senses (Burr et al., 2009; Gori et al., 2012), it is no surprise that its absence leads to inefficient temporal representations (Amadeo et al., 2019; Bolognini et al., 2012; Kowalska & Szelag, 2006; Zhang et al., 2020).

As reported in paragraph 1.2.3, DD is often associated with auditory processing impairments (Banai & Ahissar, 2004; Boets et al., 2007; Dawes et al., 2009; Halliday & Bishop, 2006; Hill et al., 2005; McAnally & Stein, 1996; McArthur et al., 2008; Menell et al., 1999; Ramus et al., 2003; Witton et al., 2002). Therefore, it is plausible to assume that noisy auditory processing leads to an overall inefficient temporal calibration and a generalized deficit in perceptual temporal processing in children with DD. By such means, abnormal hearing experience is one of the joining links between deafness and early and congenital DD, even though in one case hearing is completely missing and in the other auditory information is significantly impaired. Interestingly enough, this difference might be the one determining the adaptive and maladaptive nature of neural changes induced by these two conditions, as it has already been shown that access to deteriorated sensory information has hampering consequences on how we perceive and interact with the environment (Gori et al., 2017; Lesica, 2018; Tomomitsu et al., 2013).

Considering once again the novel theoretical approach developed by Stevens and Neville (Stevens & Neville, 2006) discussed at the beginning of this paragraph, it is undeniable that both adaptive and maladaptive plasticity mechanisms occur in deaf and DD groups' brains individuals, respectively. I further expanded this conceptualization, suggesting that plastic changes might also occur at a relatively low level of information processing, such as the magnocellular pathway, and that the nature of reorganization processes might be selectively determined by either the absence or the compromising of hearing processing. A generalized temporal deficit emerges when auditory processing is not functional during the early stages of life, as precise acoustic information dominates other sensory information within temporal estimations (Burr et al., 2009; Gori et al., 2012) and could be fundamental for proper development of a perceptual sense of time. Nevertheless, deaf and dyslexic individuals cope at the neural level with such deficits in specular ways due to the peculiarities of their corresponding sensory deficits. Congenital and early deaf individuals do not have experience of auditory information and magnocellular cells, which are especially prone to be influenced by perceptual experience (Guimarães et al., 1990; Tasker et al., 2002), thus undergo adaptive plastic changes allowing the use of temporal compensatory strategies, as demonstrated in the study discussed in paragraph 2.1. However, when auditory information is accessible but uninformative, or worse, noisy and misleading, magnocellular pathways improperly tune themselves using such information and develop maladaptive connections leading to abnormal temporal perception, as highlighted in the study

discussed in paragraph 2.2. Considering that magnocellular cells are diffused across the neural system, as this type of cells can be found not only in the visual but also in the auditory, tactile, and motor systems (Stein, 2019), the interpretation that I am proposing could account for temporal deficits involving potentially all sensory modalities.

In conclusion, bridging the pieces of literature on temporal processing impairments in deafness and DD might be a daunting task, even though its effectiveness has been, at least partially, already highlighted (Stevens & Neville, 2006). A direct comparison between phenomenological representations of temporal perception in different clinical conditions should be beneficial for various reasons. First, it will help expand our knowledge on how temporal information is encoded and decoded within the brain. Second, it will bring physiological, other than behavioral, insights on the neural substrates involved in temporal processing, the brain structures plastically modified by the absence or the impairment of auditory processing, and the neural components that might need enhancement to foster specific compensation strategies.

4.2 Portable Psychophysics: Prospective and Future Implications

In recent years, collecting sufficient and reliable data to support experimental hypotheses has been far from effortless. Considering the 2020 COVID-19 pandemic and the fact that testing hypotheses might require comparing performances between typical participants and populations of reference, which are challenging to recruit, research can sometimes significantly slow down. Regardless of recruiting issues that emerged during the pandemic, moving data collection procedures from laboratories to a more user-friendly, ecological setting has always been an exciting possibility. I spent the second half of my research project designing, developing, and validating *PsySuite*, an Android APP focused on promoting a remote, handy, and safe approach to psychophysical data collection. Indeed, *PsySuite* was created to allow participants to perform classic psychophysical experiments in a secure and ecological environment without necessarily reaching research facilities or universities. By simply connecting the smartphone to a WI-FI™ network, results are then directly sent to the experimenter, which can start analyzing the data right after the participant completes the task. Considering that, by 2021, the share of EU households with internet access had risen to 92% and that broadband internet access was used by 90% of the households in the EU in the same year, sending experiments' results using this procedure is highly efficient in most cases.

To validate *PsySuite*, I evaluated its technical performance by hardware validation, user acceptance, and the possibility of replicating veridical psychophysical data through behavioral validation. Hardware validation was pursued to ensure that both stimulus durations and minimum temporal differences achievable between stimulations matched the input values chosen by the experimenter. For completion purposes, *PsySuite*'s stability was investigated using two different midrange smartphone models: a Xiaomi Mi A2,

produced in 2018, and a Samsung A40, firstly released in 2019. Conversely, behavioral validation was conducted to test whether the double-flash illusion (DFI) was equally eligible using *PsySuite* and a classic PC-based setup. The DFI was chosen because it requires extremely short and precise presentation timing to be successfully elicited, significantly stressing the smartphone's hardware components.

To sum up the results of the hardware validation, through the analysis of delivered uni- and multi-modal signals, I assessed the App's feasibility in delivering accurate and precise stimulations within the visual, auditory, and tactile sensory modalities. The first important consideration is that the App managed to deliver both auditory and visual stimulations with satisfactory accuracy and precision in any possible combination, regardless of the smartphone model involved. However, tactile stimulations lacked similar faithfulness, being seriously unreliable when using the Samsung A40 model and reaching acceptable accuracy and precision only when using the Xiaomi smartphone. The second important consideration is that the software components significantly determined stimuli durations, which is especially true for the visual stimuli (whose minimum duration was tied to the display's refresh rate). Auditory stimuli were delivered with extreme accuracy and precision in all considered cases. At the same time, the lack of control emerged when producing tactile stimulations with the Samsung A40, and the slightly lower precision observed when using the Xiaomi is unequivocally determined by the smartphone's capacity to turn on and off the engine vibrators with extremely reliable timing. As hardware components are likely to become better and better in the following years, *PsySuite*'s reliability is nonetheless destined to increase due to future technical improvements available within the smartphones market.

For what concerns the behavioral validation, the comparison between the DFI elicited using *PsySuite* and the more classic PC-based setup highlighted that comparable results can be collected using both experimental settings. Behavioral validation was needed to corroborate that participants could still validly perform psychophysical tasks even when using a smartphone, a tool not initially designed for data collection. Many possible confounds can negatively impact performance when using *PsySuite* in an unsupervised environment (e.g., at participants' homes), some of them being even extremely hard to define. I decided to foster this comparison to ensure that data collected with this novel approach resembles similar scientific validity of data collected within the more controlled laboratory environment. For example, the participants' commitment could have varied due to their familiarity with the surroundings, or using a smartphone instead of a PC might have altered the engagement in doing the task. Since not only the DFI was induced using *PsySuite*, but also the illusion's magnitude was comparable to the one elicited using a classic PC-based setup held in a research facility, the App proved itself to be once more a reliable tool to perform psychophysical testing. These findings utterly support *PsySuite*'s feasibility in promoting a remote approach to data collection and suggest that behavioral measurements obtained with the App are a reliable

approximation of human performance, even though they were collected with such an unorthodox and novel approach.

With the development and the optimization of *PsySuite*, I am attempting to port data collection procedures outside research facilities while maintaining the setup's specifics. One of the issues that often arise when performing remote data collection with already available tools, i.e., using online platforms, is that it is hard to balance the PC's specifics used to perform the experiment between participants. This is especially problematic when using stimuli that must be temporally accurate and whose duration must be stable across multiple trials, as less performing hardware components might lead to a misrepresentation of the stimuli during the procedure. With *PsySuite*, the chance of this occurrence has been virtually reduced to zero, as the smartphone used to validate the App, the Xiaomi Mi A2, has proven to be a solid device through which to develop psychophysical testing. On the one hand, research units can directly buy the Xiaomi Mi A2, which is an overall cheap solution being a midrange model. On the other hand, validating *PsySuite* on the Xiaomi Mi A2 set a benchmark for the minimum system requirements needed to successfully produce accurate and precise stimulations. Thereby, researchers willing to use *PsySuite* could involve smartphones they already own, proving that their hardware specifics are at least equal to the one provided by the Xiaomi Mi A2.

Given the recent pandemic outbreak, the benefits of a remote and safe data collection approach are more than evident. Nonetheless, the novel approach to psychophysical testing that I am proposing is favorable for more than the ability to tackle social distancing limitations that have slowed down research since March 2020. First, *PsySuite*'s dissemination will significantly boost large-scale data collections while maintaining the constancy of setups between participants, which is hardly controllable with online platforms. Second, *PsySuite*'s portability will be a great addition when designing psychophysical data collection in specific populations with mobility issues, such as hospitalized patients and paraplegic individuals, if the facility is not adequately equipped to name a few. Third, such portability will also facilitate the implementation of time-consuming experimental design, such as perceptual learning protocols, which require several days of training to be effective. In fact, using *PsySuite*, participants can perform training sessions at their homes, increasing the users' comfort and reducing economic expenses if the institution pays participants to come to the facility. Lastly, with *PsySuite*, it will be possible to develop specific user-centered testing procedures, such as successfully reducing the test anxiety that sometimes distress (especially, but not uniquely) the youngest participants who perform experiments in an unknown environment. Allowing psychophysical procedures to be performed in a familiar setting (e.g., their homes or a rehabilitation center attended long-time) will indeed be perceived as a less stressful experience, therefore supporting data collection on participants that otherwise would have probably not completed the task.

All the advantages promoted by this new portable psychophysics are an excellent addition to basic and applied research and clinical contexts. Indeed, with *PsySuite*, I fostered an increase in temporal abilities in typical adults and evaluated temporal thresholds in children with DD and congenital and early deaf adults. Using *TID*, a library specifically designed to test and enhance temporal abilities, I implemented a temporal perceptual learning protocol in typical adults, boosting auditory and tactile temporal sensitivities by using a smartphone and a four-days training performed at home. Then, using the same *PsySuite* library, I highlighted significant temporal deficits in children with DD and congenital and early deaf, even though data collection was performed outside the research facility and without a canonical PC-based setup. These results combined suggest that measuring and enhancing temporal skills do not necessarily require overly expensive devices, nor that participants reach research facilities, but can be safely executed – virtually anywhere – by the simple use of a smartphone.

Coming to the end of my research project, I am confident that *PsySuite* is an overall powerful tool through which obtain psychophysical measures while, at the same time, promoting a remote, portable, and safe approach to data collection. Notably, I also demonstrated that *PsySuite*'s implementation could be highly successful in basic and clinical research, and considering its ease of distribution, accessibility, and general cost-effectiveness, I believe that it will be a valuable addition in both scenarios. Nonetheless, I mainly focused on evaluating temporal processing mechanisms and, thus, decided to validate this novel, portable approach to psychophysical research with tasks revolving mainly around sensory timing. Since any psychophysical task can be implemented within the App and set to a portable level, the possibilities are virtually infinite as long as hardware limitations are considered. And I am still eager to explore them as much as possible.

4.3 What Now?

In the first part of the thesis, I discussed a novel theoretical framework through which I conceptualized temporal processing in deaf and dyslexics, two apparently different populations that – in reality – share some interesting analogies in terms of temporal impairments. As stated in paragraph 1.2, the joining link between these two populations is a substantial unreliability of auditory information during early stage of life, potentially at basis of the disruption of cross-sensory calibration processes, that leads to severe temporal impairments. I also tried to further speculate on which neural substrate could be mainly influenced by the absence of crucial hearing information, designing experimental paradigms aimed at investigating magnocellular temporal encoding in both deaf and dyslexic.

After the COVID-19 pandemic and the design and validation of *PsySuite*, I used the App to test temporal abilities in a variety of populations: children and adults with typical development, as well as children with

DD and deaf adults. However, I focused solely on the evaluation of a generalized temporal deficit, rather than further investigating the potential alteration of magnocellular processing in deaf and dyslexics. There are few reasons behind this choice: on the one hand, *PsySuite*'s conceptualization, as well as both its hardware and behavioral validation, were extensively conducted and significantly time-consuming; on the other hand, I first decided to try to replicate general findings already available in the literature, with the intention to understand whether *PsySuite* could have been successfully implemented in various clinical environments. Therefore, I opted for evaluating an overall reduction of temporal abilities using the portable version of a classical psychophysical task, rather than directly jump towards the pursuit of a more specific hypothesis, such as the magnocellular one. This choice was made also to evaluate the user's acceptancy towards the App, that could have varied depending on the population.

Nevertheless, my goal is set to the further evaluation of how magnocellular processing can be shaped by the disruption of cross-sensory calibration processes, and potentially to a better understanding of how we can enhance temporal perception in deafness and DD. Intuitively, one would expect that a general temporal training (e.g., as the one discussed in paragraph 3.2) should suffice to reach our scope. However, this might not be the case as, for example, deaf individuals seem to experience a significant reduction of temporal sensitivity when evaluating the duration of static visual stimuli (paragraph 2.1, Experiment 1), while showing overall better temporal performance when spatiotemporal information is available (paragraph 2.1, Experiment 2). Since it is impossible to train perceptual systems when the sensory information used to convey the training is hardly interpretable (Liu et al., 2008), a possibility is that enhancing temporal processing in deaf individuals requires dynamically transient stimulations. Conversely, given that individuals with DD display significant magnocellular deficits (Stein, 2019; Stein & Walsh, 1997; Stevens & Neville, 2006), one would expect that a similar perceptual learning protocol, while producing some minor benefits, might be less effective in restoring veridical internal temporal representations.

Thereby, the next step that I am willing to take involves the development of a visual temporal task that includes spatiotemporal (i.e., magnocellular) information, to test once again time perception in deaf and dyslexic (e.g., designing a portable version of the visual temporal oddball-like task used in paragraph 2.1). Differently from what already done in paragraph 3.3.1 and 3.3.2, I am planning to target magnocellular pathways to better underlying their role over the deterioration of temporal processing in these populations. In doing so, the aim of my future works will be focused around two major points: first, I want to set the theoretical basis for the development of a specific temporal perceptual learning protocol, tailored around the specificity of both deaf and dyslexics' abilities to sense temporal cues; second, I want to implement such training on large scale, using *PsySuite* as the primary channel through which foster this intervention. As already demonstrated in paragraph 3.2 enhancing temporal thresholds in typical adults using an

unorthodox tool such as a smartphone is a feasible solution. Considering that *PsySuite* allows extensive testing without the needing of participants to come to research facilities (where most of the time just one setup at a time is available), if these perceptual learning protocols are effective their impact on large scale will be even greater.

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