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NEURODIVERSITY OF THE BODILY SELF: PERCEPTION, ACTION, AND COGNITION IN REAL AND VIRTUAL WORLDS

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Neurodiversity of the bodily self: perception, action, and cognition in real and virtual worlds

Overview of contents

Inclusive language: disclaimer

The social perception of a phenomenon, and the related policies and practices with which it is addressed, is structured by the language the community chooses to talk about it. In recent years, self-advocates from the autistic community spoke out against the medical model of autism, asked for identity-first language (i.e., “autistic person”) to define individuals on the autism spectrum, preferred the use of “Autism” instead of the diagnostic label of “Autism Spectrum Disorder”, and discussed neurodiversity, strengths and difficulties rather than impairments/deficits (Bottema-Beutel et al., 2021). This movement emphasises people's perception that autism is part of their identity (sometimes equated with gender and sexual orientation) and constitutes a disability when the person encounters a society that is not designed around his or her individuality. A complementary perspective is offered by the medical model of autism, which sees it as a neurodevelopmental disorder that increases people's likelihood of having difficulties in relating to others and exploring a wide range of interests (and ultimately, their well-being and quality of life), and therefore requires interventions and services. From the point of view of some researchers, educators and therapists, person-first language (i.e., “person with autism/ASD”) aspires to promote the idea that beyond (any) diagnosis there is a unique person whose human individuality should be recognised and respected (Vivanti, 2020).

Acknowledging the complexity of language choice and its cultural and practical implications, in this work I have personally chosen to embrace and value both perspectives, which can be considered complementary rather than conflicting. I refer to neurodiversity to make explicit reference to the fact that beyond any diagnosis and even within neurotypical developmental trajectories, each of us is a unique individual with strengths and difficulties. The use of terms such as “impairment”, “deficit”, “disorder” is to be interpreted as synonymous with “difficulties” and emphasises the need for support, intervention, or training of specific areas of the individual neuropsychological profile. Such terminology in no way negates the presence of strengths and competences (even above the average of the general population) in other areas. I have also chosen to refer to people with a diagnosis (e.g., ASD, ADHD, DCD) with a person-first language. This choice conveys the idea that each person's individuality is the undisputed priority, but that autism, like other neurodevelopmental conditions, is a risk factor for a person's wellbeing and quality of life, and as such can benefit from a medical approach that takes responsibility for proposing interventions aimed at reducing its negative effects and make its potential flourish. Identity-first language may also be used in the manuscript when referring to the autistic community that prefers this type of language.

Although the present work investigates intra-individual neuropsychological aspects of ASD, it does not neglect that disability is situated and emergent from social, cultural, educational, and political contexts that shape its contours. For this reason, the common definition and conception of autism is constantly being redefined and research on the subject must be intended as a process of acquiring new knowledge and awareness.

Abstract

The present doctoral thesis investigates some fundamental components of the bodily self, looking at the underlying mechanisms related to *perception, action,* and *cognition* and their typical and atypical development. The use of virtual reality and multimedia technologies for studying and stimulating the bodily self is discussed.

Focusing on *perception*, the first study explored self-location accuracy in real environments and Immersive Virtual Reality (IVR), whereby children and adults with or without autism had to locate themselves in space with different sensory information available (i.e., vision and proprioception were manipulated). Results indicate that IVR headsets reduce self-location accuracy in neurotypical children and adults, possibly due to the features of visual inputs. On the other hand, preliminary evidence from a pilot study suggests that those children with autism who show increased reliance on proprioception in real environments, benefit from vision to locate themselves in IVR. We can conclude that IVR has unique sensorimotor features that interact with individual differences in sensorimotor functioning, with meaningful impact on the possibility for people to perceive, move, act, and therefore learn in virtual environments.

Moving to *action*, the second study aimed at disentangling the role of Agency and Reward in driving action selection of individuals with autism or typical development, who were asked to freely select one of three candies and feed the animals appearing on a tablet. The candies were associated with different probabilities of delivering a neutral vs no effect (Agency task), or a positive vs neutral effect (Reward task). Choices and reaction times were measured to understand whether participants preferred and were faster at selecting options with higher probability of producing a neutral vs. no effect (Agency) or a positive vs. neutral effect (Reward). Children and adults with or without autism were involved. Participants' choices and RT were not affected by Agency, whereas a more frequent selection of the option with higher probability of a positive vs. neutral effect emerged across groups, thus suggesting motivation from Reward. Participants with autism selected less frequently the option with chance level of receiving a neutral or no effect. Since that option was the one with the greatest degree of uncertainty about the choice outcome, this choice pattern could be interpreted as a sign of reduced tolerance of uncertainty. Across tasks, conditions and age groups, participants with autism presented shorter RT, which is a marker of reduced action planning. Future research should deepen how tolerance of uncertainty and action planning impact the way individuals with autism make choices in everyday life situations, potentially contributing to restricted and repetitive behaviours.

By an emphasis on *cognition*, the third study delved into the use of kinematic measures to capture motor planning and control strategies beneath cognitive performance. Neurotypical adults, children with Attention Deficit and Hyperactivity Disorder (ADHD) or typical development performed an adapted Go/No-Go task that required either a prepotent response (*dominant* condition) or inhibition of the prepotent and selection of the

alternative one (*non-dominant* condition). Participants' response movement was monitored by a wearable accelerometer that was put to good use to obtain raw acceleration data, compute, and break down its velocity components. Reaction time, movement duration and percent time to peak velocity were analysed to disentangle the planning and control components beneath the two actions. Results show that neurotypical participants employed increased motor planning (i.e., percent time to peak velocity) to correctly inhibit a prepotent response and execute the instructed alternative. Although no group difference emerged on accuracy levels between children with and without ADHD, the kinematic analysis of correct responses revealed that, unlike neurotypical children, those with ADHD did not show increased motor planning (i.e., reaction time and percent time to peak velocity) in non-dominant compared to dominant trials. Reduced motor planning can be interpreted as a sign of impulsivity and contribute to everyday life difficulties. Future studies should investigate whether motor control could help children with ADHD compensate for planning difficulties. However, this strategy might make inhibition harder in naturalistic situations that involve complex actions. In sum, combining cognitive and kinematic measures has potential for assessment and intervention of subtle differences in executive processes such as inhibition, going deeper than is possible based on accuracy outcomes alone.

The general discussion presents the future of virtual reality in leveraging embodiment to shape perception, action, and cognition. While these technologies have unique potential for controlled, yet naturalistic experiences, being vastly employed in research and increasingly in clinical practice, its distinctive effects are still largely unknown.

Published papers

Chapter 1-2

Valori, I., McKenna-Plumley, P.E., Bayramova, R. & Farroni, T. (2021). Perception and motion in real and virtual environments: a narrative review of Autism Spectrum Disorders, *Frontiers in Psychology.*

Farroni, T., **Valori, I.**, & Carnevali, L. (2022). Multimedia Interventions for Neurodiversity: Leveraging Insights from Developmental Cognitive Neuroscience to Build an Innovative Practice. *Brain Sciences.*

Della Longa, L., **Valori, I.,** Farroni, T. (2022). Interpersonal affective touch in a virtual world: feeling the social presence of others to overcome loneliness, *Frontiers in Psychology.*

Chapter 3

Valori, I., McKenna-Plumley, P. E., Bayramova, R., Zandonella Callegher, C., Altoè, G., & Farroni, T. (2020). Proprioceptive accuracy in Immersive Virtual Reality: A developmental perspective. *PloS one.*

Valori, I., Bayramova, R., McKenna-Plumley, P.E., & Farroni, T. (2020). Sensorimotor Research Utilising Immersive Virtual Reality: A Pilot Study with Children and Adults with Autism Spectrum Disorders. *Brain Sciences.*

Bayramova, R., **Valori, I**., McKenna-Plumley, P.E., Zandonella Callegher, C. & Farroni, T. (2021). The role of Vision and Proprioception in Self-Motion Encoding: An Immersive Virtual Reality Study. *Attention, Perception, & Psychophysics.*

Chapter 4

Valori, I., Carnevali, L., Mantovani, G., & Farroni, T. (2022). Motivation from Agency and Reward in Typical Development and Autism: Narrative Review of Behavioral and Neural Evidence. *Brain Sciences.*

Valori, I., Carnevali, L. & Farroni, T. (*in preparation*). Agency and Reward in typical development and autism: a free-choice paradigm.

Chapter 5

Angeli*, A., **Valori*, I**., Farroni, T., Marfia, G. (2021). Reaching to inhibit a prepotent response: a wearable 3-axis accelerometer kinematic analysis. *PloS one.*

Valori, I., Della Longa, L., Angeli, A., Marfia, G., & Farroni, T. (2022). Reduced motor planning underlying inhibition of prepotent responses in children with ADHD. *Scientific Reports*.

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Part I

1 The development of the bodily self

What is it like to have a body? The bodily self is the ability to perceive our body as separate from other entities and provides the basis for self-perception (Montirosso & McGlone, 2020). Bodily self-consciousness (or embodiment) consists of at least three main components: *Ownership* (my body belongs to me), *Self-Location* (my body occupies a specific portion of space), and sense of *Agency* (I have control over the effects of my actions) (Longo et al., 2008). In a dance between perception, action, and cognition all these elements emerge from processes that specialise from prenatal life and are refined in the interaction between genetic predispositions and experiences within one's developmental environment. They all contribute to the perception that each person has of their own body and self, which is fundamental for interacting with the physical and social world and being active promoters of one's own learning. This chapter reviews the extant scientific evidence on the roots of the bodily self, to understand its developmental pathway and role in the child's wellbeing. I will also delve into a specific case of neurodiversity of the bodily-self experience, which is Autism Spectrum Disorder.

1.1 From the senses to the body

Body representations are shaped by “the ability to integrate multisensory (visual, proprioceptive and tactile) bodily information into coherent representations of one’s own body” (de Klerk et al., 2021, pag. 1). Our senses are the entry gates by which a given stimulation can be perceived and elaborated, starting from the numerous sensory inputs present in our environment at any given time. In particular, sensory information about the body comes from both the external world (*exteroception*) and the self (*interoception*). While exteroception describes sensory information like sight, hearing, and touch, interoception is the perception of the internal states of the body (Pollatos et al., 2018). The latter includes “temperature, pain, itch, tickle, muscular and visceral sensations, vasomotor flush, hunger, thirst” and other internal sensations (Craig, 2002, pag. 655). Therefore, bodily information comes from different, complementary sensory modalities, and has to be integrated so that we can have a coherent sense of our own body.

The multisensory integration that follows specialises with experience, which guides individuals’ developmental trajectories in a probabilistic epigenesis (i.e., bidirectional environment-genes influences on neuropsychological phenotypes) and shapes the brain through progressive specialization for elaborating certain types of stimuli (Gottlieb, 2007; Johnson, 2001). We rely on the various sensory modalities to different degrees at different points in the human developmental trajectory, with touch being the first functioning sense in utero, and vision becoming highly predominant soon after birth (Bremner, Lewkowicz, et al., 2012). Although children can benefit from cross-modal calibration from infancy, there is a long-lasting tuning of their ability to integrate exteroceptive and interoceptive information that contribute to bodily-self experiences (Gori et al., 2008). Multisensory information is combined to a different extent depending on which modality is the most precise and appropriate to the given context, goal, and task. To deal with the uncertainty of multimodal combination and integration (e.g., in case of discordant, ambiguous, or missing information), the mind has to base its reasoning on prior experience and decide which is the most plausible interpretation of several possibilities (Ernst & Bülthoff, 2004).

One important physical dimension of the concept of self is *proprioception*, which has a definition that is particularly complex and debated in the extant literature. Proprioception belongs to the somatosensory system (Nelson, 2001) and has traditionally been defined as the "awareness of the spatial and mechanical status of the musculoskeletal framework" which includes the senses of position, movement, and balance (Stillman, 2002, pag. 667). From this perspective, proprioception is the awareness of the position and movement of our body in space and results from the processing of information from muscle, joint, tendon, and skin receptors. It arises from static (position) and dynamic (movement) information and is crucial to the production of coordinated movements (Ergen & Ulkar, 2007). It is interesting to note that this "sense" of the position of one's body in space does not derive simply from somatosensory input, but rather from a process of multisensory integration. While humans rely on somatosensory information to achieve proprioception in blind conditions, vision can lead to proprioception when proprioceptively informative cues are provided. Indeed, specific visual cues can be proprioceptively informative to the extent that they aid proprioception. For example, research concerning mirror therapy for phantom limb pain indicates that visual representations of the body (e.g., the lost limb) can be manipulated to induce proprioceptive sensations and perception of movement, touch, and body ownership, even with a complete absence of somatosensory input (Ramachandran & Rogers-Ramachandran, 1996). In this respect, some visual cues can be more informative than other to calibrate proprioception. For instance, self-motion studies show that global visual landmarks such as the corners of a room appear to be useful for localising ourselves in space, while local visual cues such as surrounding objects are not (Wang & Spelke, 2000). Moreover, proprioceptive information is combined with information from the vestibular system, which detects movement of the head in space, to give us a sense of motion and allow us to make estimates about our movements (Cullen, 2012). As such, it plays a vital role in everyday experiences of body ownership, self-location and motion, sense of Agency.

As regards the development of proprioception, children up to two years of age tend to make significant proprioceptive errors (Bremner, Holmes, et al., 2012). While several studies have shown that proprioceptive competence is stably developed by eight years of age (Sigmundsson et al., 2000; von Hofsten & Rösblad, 1988), others support the finding of a longer developmental trajectory for proprioception, observing that 8- to 10-year-old children are less accurate than 16- to 18-year-old adolescents when making proprioceptively guided movements (Goble et al., 2005). Moreover, some studies find improvements in proprioceptive accuracy continuing up to 24 years of age (Hearn et al., 1989).

This proprioceptive development seems to be strictly dependent on visual calibration. In general, sensory organization is qualitatively different across development and across different tasks. In infancy and early childhood, vision appears dominant over somatosensory and vestibular information (Nardini & Cowie, 2012). Between five and seven years of age, visual influence on proprioception shows non-linear developmental differences (Bremner et al., 2013), although this has not yet been widely studied in a broader range of ages. The developmental trajectory of proprioception may be affected by the fact that across childhood, the sections of the body change in terms of size, shape, and relative location. Indeed, the early importance of vision over somatosensory information could be a result of the lack of reliability of somatosensory input, which is highly unstable during these childhood physical changes (Bremner, Lewkowicz, et al., 2012).

1.2 Body ownership and self-location

The experience of our body as belonging to us certainly derives from implicit mechanisms of multisensory integration of temporally congruent information, thus being roughly present from birth and then undergoing developmental refinement. Indeed, newborns prefer looking to a baby face being stroked in synchronous with their own face than a baby face being stroked asynchronously. This preference for synchrony with the other's body emerges only with straight faces, so that infants seem to have a preliminary predisposition to process social cues that reflect the configuration of the bodily self (Filippetti et al., 2013, 2015). During infancy, the preference for synchronous visuo-tactile stimulation constitutes the foundations of infants' ability to build a sense of self and connect their bodily perception to the external events (Filippetti et al., 2016). However, the early ability to discriminate and integrate contingent multisensory information does not imply that infants are conscious that their body belong to them (Filippetti & Tsakiris, 2018). Indeed, humans also explicitly feel body ownership, thus being able, for example, to recognise themselves in mirrors, pictures, and videos. At around 2 years of age, children start succeeding at the mark test of mirror self-recognition, in which a red marker is placed on the child's body, who is expected to notice its presence in the mirror as a sign of self-recognition. Children that fail this test at 18 months, compared to self-recognisers, prefer looking at images of themselves compared to other baby faces, with no difference in their preference for contingent multisensory cues (Filippetti & Tsakiris, 2018). We can therefore speculate that implicit and explicit body-ownership rely on different mechanisms and potentially undergo different developmental pathways.

One of the experimental paradigms that is widely employed to distinguish these two components of body ownership is the Rubber Hand Illusion (RHI) (Botvinick & Cohen, 1998). Watching a rubber hand being stroked, while one's own unseen hand is synchronously stroked, may cause the rubber hand to be explicitly attributed to one's own body and felt "like it's my hand". At implicit levels, the illusion leads to a proprioceptive drift toward the rubber hand. Indeed, when people are asked to point to their real hand position, they misperceive their hand as closer to the rubber hand. Bottom-up processes of visuo-tactile integration are necessary but not sufficient to elicit the illusion, which is also modulated by top-down body representation (e.g., the real and rubber hands must be in congruent postures) (Tsakiris & Haggard, 2005). As these mechanisms specialise with age, researchers have been using the RHI with children to investigate their developmental pathways.

A dissociation was found between explicit feelings of ownership and implicit proprioceptive drift toward the rubber hand in children from 4 to 9 years of age. Children and adults gave similar explicit judgements of body ownership, which has been interpreted as an early tuning of visuo-tactile integration that contributes to the explicit perception of body ownership. On the other hand, children show larger proprioceptive drift than adults, which could indicate a longer-lasting development of visuo-proprioceptive processes, that contribute to more implicit body awareness (Cowie et al., 2013). Visuo-proprioceptive integration and implicit body consciousness keep refining up to 10 to 13 years of age, when children show adult levels of proprioceptive drift in response to the RHI (Cowie et al., 2016). Additional findings confirmed that explicit feelings of body ownership are already sensitive to the RHI by age 4, corroborated the late development of optimal calibration of visual and proprioceptive signals, and therefore implicit body awareness. Indeed, the effect of the illusion on the hand localisation increases with age and is still refining by age 9 (Nava et al., 2017). Children from 6 to 8 years of age experienced the RHI toward either a child-sized or adult-sized rubber hand. Although synchronous versus asynchronous visuo-tactile stroking was more effective in inducing explicit body ownership, visuo-tactile synchrony did not make a difference in perceived hand location. Intriguingly, simply viewing a child-sized compared to an adult-sized hand, led to greater proprioceptive drift (Filippetti & Crucianelli, 2019).

It should be noted that the classical versions of the RHI are induced by passive multisensory stimulation. In real life situations, individuals are most of the time agents that interact with the environment to actively use both external and internal cues during self-made actions. Therefore, the way we integrate multisensory information to maintain our sense of body ownership might be shaped by our own actions. In a recent study, children and adults actively stroke the visible rubber hand, while passively receiving the stroke on the real hand. In adults, active movement reduced both the explicit and implicit illusion of body ownership toward the rubber hand, thus suggesting that they heavily rely on somatosensory cues (i.e., the real hand position) to solve conflicting multisensory information. On the contrary, children's explicit ownership was similar in both active and passive RHI, while the implicit proprioceptive drift was achieved only through active movement (Nava et al., 2018). The authors proposed several interpretations of these findings and conclude that both perception and action contribute to bodily-self experiences, with developmental differences that should be further investigated.

The divergent results found between the explicit and implicit effects of the RHI might be due to the illusion tapping on two distinct components and neural underpinnings of body awareness (Matsumiya, 2019; A. Serino et al., 2013). The subjective feeling of ownership reflects body ownership ("is this my hand?") and is associated to remapping in the premotor cortex. On the other hand, the proprioceptive drift toward the rubber hand taps on the ability to locate themselves in space ("where is my hand?") and correlates to remapping in the posterior parietal cortex (Brozzoli et al., 2012). The interplay between body ownership and self-location in giving rise to a coherent body awareness is mediated by common neural substrates like the posterior cingulate cortex, that underpins spatial cognition (e.g., navigation and perspective taking) (Guterstam et al., 2015).

In sum, there is a dynamic and plastic contribution of multisensory integration, top-down representations, and action execution to the emergence of a coherent bodily self, which constitutes of explicit and implicit components of body ownership and self-location, which differently specialise across age.

1.3 Agency: implicit and explicit mechanisms

The construct of Agency in the literature indicates the perception of control over one's own actions and the external world and can be traced back to the ability to recognize oneself as the cause of an event (Moore, 2016). An important distinction must be introduced between the sense of Agency and the sense of ownership, which reflect different processes. The sense of ownership relates to the ability to recognize thoughts, emotions, movements, and body parts as one's own (e.g., "this is my hand"). The sense of Agency, on the other hand, emerges secondarily and reflects the ability to attribute responsibility for an event to oneself (e.g., "I was the one who pushed that button and caused that effect") (Braun et al., 2018). Although, different conceptualizations of the phenomenon have been proposed over time, the perspective that currently seems to be most widely accepted sees Agency as the result of functionally distinct neurocognitive processes.

1.3.1 Theoretical models

The first studies on Agency focused on the processes of learning and motor control and led to the conceptualisation of the *comparator model*. According to this framework, the motor system builds a prediction of the sensory consequences of a movement before its actual execution (forward model). This prediction will be compared with the sensory feedback generated after the completion of the action. In the case of a match between prediction and outcome, the individual will tend to consider themselves responsible of the action. In case the expected and actual sensory information do not match, the individual will be inclined to search for the external cause of the event (Haggard, 2017). Numerous studies supporting this model highlighted how the elements of spatial and temporal contiguity between action and effect are central features in the action attribution process. Indeed, the inclusion of a spatial or temporal alteration between the execution of a movement and the corresponding effect results in a decreased compatibility between expected and actual outcomes (Farrer et al., 2013; Nobusako, Osumi, et al., 2020). According to the comparator model, Agency is generated based on retrospective mechanisms, thus it emerges exclusively following the completion of an action (Haggard, 2017).

While the comparator model has delved into how retrospective processes work, several studies have focused on pre-action processes (Chambon et al., 2014). Among these, Wenke and colleagues (2010) used a subliminal priming paradigm to understand the role of action selection processes in the emergence of Agency. The authors observed that participants report greater perceptions of control over a given event when prime stimuli allow for more fluent and immediate action selection (Wenke et al., 2010). In everyday life, it could be that fluently selecting an action makes it more likely that our intentions will be realized, and the expected outcome achieved. According to this interpretation, habitual actions are accompanied by a strong sense of control. In more ambiguous situations, on the other hand, in which several possible actions compete, the system will be inclined to consider the retrospective component more carefully (Chambon et al., 2014).

However, we not infrequently consider ourselves authors of an event, even without being directly responsible for it. Whenever an event turns out to be in line with one's intentions, there is a strong tendency to interpret it as self-generated (Moore, 2016). For example, we use to push the crosswalk light buttons because we expect this to reduce the wait before the green light arrives. When the traffic light turns green, after variable and even prolonged time delays, we attribute this event to our action of pressing the button, although there is no evidence of our role in turning the light green. With good probability, this has nothing to do with our action, and we are fooling ourselves to make the wait bearable by making us feel like agents. It is precisely from this evidence that the inferential model of Agency is outlined. According to the *inferential model*, the experience of Agency depends on the relationship between intentions and events. Agency emerges when the former is prioritised (temporally preceding), exclusive (the only plausible explanation), and consistent (coherent) with respect to events (Moore, 2016). The theoretical approaches described attribute relevance to different information, which in one case is internal and implicit (sensory and motor) and in the other external and explicit (contextual and environmental information).

Recently, Synofzik and colleagues proposed a *multifactorial model*, which allows to overcome the dichotomy of the approaches considered so far (Synofzik et al., 2008). According to the authors, Agency would be influenced by both high- and low-level information (cognitive and sensorimotor, respectively). Feeling of Agency (FoA) comes from implicit self-representation and can be considered as the preconceptual component of the sense of Agency. The comparator model explains this component as emerging from the congruence between motor programs and proprioceptive and exteroceptive sensory information (Synofzik et al., 2008). Altering the spatial or temporal contiguity between action and affect significantly disrupts this level of Agency (Karsh et al., 2016). On the other hand, Judgement of Agency (JoA) consists of explicit recognition of oneself as the cause of an event. It is influenced by personal beliefs, contextual and social information (Synofzik et al., 2008), and insensitive to factors of spatial and temporal contiguity (Karsh et al., 2016). Different measures have been employed in literature to capture explicit and implicit Agency. Self-reported measures of explicit Agency come from the person's answer to the question "Did you do that?" (Haggard, 2017). On the other hand, intentional binding is the most widely used paradigm to measure implicit Agency. It consists in the tendency of participants to perceive the time interval between a voluntary action and a sensory stimulus as shorter than it actually is. More specifically, the onset of the voluntary action is reported later in time and awareness of the sensory feedback is temporally anticipated (Haggard et al., 2002). Notably, distinct neural mechanisms might underpin implicit and explicit components of Agency, giving rise to the interplay between frontal and prefrontal motor areas that initiate action and parietal areas that monitor sensory events (Haggard, 2017).

Agency can also be interpreted within the more general framework of the *Bayesian predictive brain* (Friston & Frith, 2015) (Figure 1.1). Every agent carries out an action on the base of prior knowledge about the context and expectations around action execution and its consequences (i.e., priors). Actual motor output and sensory effects are monitored during and after action execution to detect potential deviations from expectations (i.e., prediction errors). While Agency arises from minimal prediction errors, higher error rates make the agent revise their prior knowledge, thus promoting search for alternative explanations, and ultimately learning. This predictive cycle also takes on a central role in social exchanges, where partners' predictions interact and influence each other. Sharing the same predictive model of the interaction facilitates interpersonal coordination (Koban et al., 2019), defined as the temporal coordination of actions, emotions, thoughts, neural and physiological processes (Mayo & Gordon, 2020).

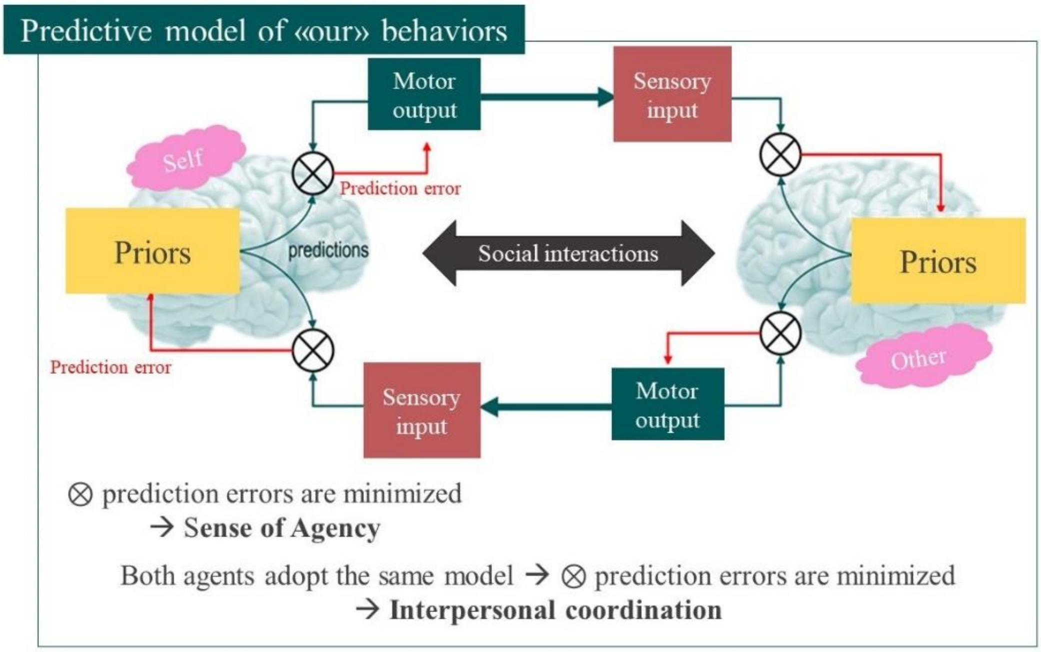


Figure 1.1. Predictive model of Agency and Interpersonal coordination (Adapted from Friston & Frith, 2015)

Recently, the *Control-Based Response Selection* (CBRS) framework proposed that action selection and execution are facilitated by producing effects that are perceived as self-caused (Karsh & Eitam, 2015). People more frequently and faster select response options associated with higher probability of producing an effect, compared to no effect. The authors refer to this phenomenon as a motivation from control, or implicit Agency, which impacts motor parameters of actions, relies on action-effect temporal contingency, and goes beyond individuals' explicit judgements of Agency (Karsh & Eitam, 2015). Intriguingly, the motor system seems insensitive to abstract representations of the valence of an effect (i.e., receiving a positive or neutral effect does not change motor parameters of action) (Karsh et al., 2020).

Agency research appears fragmented, both at the level of theoretical formulation and at the level of methods of studying the different components. Deepening its developmental trajectory would shed lights on the underlying mechanisms of this fundamental component of the Self.

1.3.2 Across development

Decades of research demonstrated that infants learn through embodied sensorimotor contingencies, thus using their bodies to produce effects in the external world (Sen & Gredebäck, 2021). Some researchers found behavioural and neural markers of action-effect binding at around 3 months of age. After disrupting the action-effect contingency of infants' movements, some of them showed EEG mismatch negativity and a reduction in their movement behaviour, which respectively underpin violation of expectation and behavioural extinction, potentially related to reduced Agency (Zaadnoordijk et al., 2020). Moreover, infants at around 9 months of age are aware of the association between actions and effects, thus responding faster to events that they previously had actively produced than to action-independent events (Verschoor et al., 2010). Other authors question the appropriateness of these methods for studying the sense of Agency in preverbal children and point out that the mere association between stimulus and response is not sufficient to constitute minimal sense of Agency, which should be distinguished from reinforced learning (Bednarski et al., 2022).

Additional studies have used the intentional binding paradigm to investigate implicit Agency in school-aged children, who showed reduced temporal binding than adults (Cavazzana et al., 2014, 2017). Other authors found adult-level of intentional binding in children from 6 years of age (Lorimer et al., 2020). Notably, the threshold for detecting temporal biases between action and consequence might change during development. From the age of 4 to 15, there is a progressive decrease in the minimum temporal delay necessary for the person to be aware of the action-effect alteration (Nobusako et al., 2018). Overall, the temporal interval within which multisensory stimuli are likely to be perceptually bound (namely, multisensory temporal binding window) gradually decreases up to adolescence (Hillock-Dunn & Wallace, 2012). The time window for intentional binding seems to be associated with manual dexterity and extended in children with Developmental Coordination Disorder (DCD) (Nobusako, Osumi, et al., 2020). Reduced implicit Agency seems associated with depressive tendency, thus contributing to children's well-being (Nobusako, Osumi, et al., 2020). Contradictory findings come from adolescence research. In a first study, adolescents showed reduced implicit Agency compared to children and adults (Aytemur & Levita, 2021). On a further EEG study, greater experience of implicit Agency was observed during mid-adolescence and was mediated by a neural over-suppression of action outcomes (sensory attenuation), and over-reliance on motor preparation (late readiness potential) (Aytemur et al., 2021). We can conclude that different sensitivity in detecting temporal biases could also lead to differences in implicit mechanisms of Agency and impact on broader dimensions of development.

As far as the explicit judgment of Agency as a function of action-outcome congruency, school-aged children and adults seem to be equally accurate (van Elk et al., 2015). However, top-down processes such as metacognition change across the lifespan and affect children's' explicit Agency up to later childhood. In particular, the outcome valence influences individuals' causal attributions. A self-attribution bias that over-attributes positive outcomes to oneself and negative outcomes to external factors is pervasive in the general population but greater in children than adults (van Elk et al., 2015). For instance, children from 8 to 10 years-old accurately judged a negative outcome as not self-caused but thought to be responsible for positive outcomes they did not actually cause (Metcalfe et al., 2010a). Overall, school-aged children are happier when allowed to make choices among options, rather than being given only one option, thus being motivated by explicit Agency (Castelli et al., 2017). However, in case of a negative outcome, children's emotions might worsen especially after self-made choices compared to having no choice (Castelli et al., 2017). Moreover, children's academic success is positively associated with their judgment of control, or explicit Agency (i.e., believing that they know how to influence success and failure outcomes in their academic life) (Martin, Burns, et al., 2017). The neural underpinnings of explicit Agency, and their age-specific changes, can contribute to understanding developmental differences. For instance, the frontal lobes (in particular, the dorsolateral prefrontal cortex) are fundamental in the experience of Agency (Chambon et al., 2014), and undergo a slow specialisation process up to adolescence (Johnson & de Haan, 2015).

Crucially, explicit Agency is built on high-level cognitive processes (e.g., expectations, beliefs, attitudes), which may be different in neurodevelopmental disorders. For instance, people with Attention Deficit and Hyperactivity Disorder (ADHD) show reduced self-attribution bias (Mezulis et al., 2004), and reduced Agency, with potential effects on their well-being (Martin, Cumming, et al., 2017). On the other hand, children with ADHD might be more sensitive to their action outcomes valence. An enhanced sensitivity to positive and negative outcomes has been found in children with ADHD, with underlying atypicalities in neural reward circuits (Luman et al., 2010; Marx et al., 2021; van Meel et al., 2005). Still little is known about the distinct contribution of Agency and Reward in children's choices and actions. Further investigation is needed for a better understanding of these mechanisms across the lifespan, in typical and atypical development, to shed light on the foundations of volition, active learning and ultimately self-determination. Atypical sense of Agency in neurodevelopmental disorders can have huge impacts on the way children make choices, with broader effects on learning processes. Obviously, the study of the intra-individual and neuropsychological bases of children's Agency does not neglect that it is situated and emergent from social, cultural, educational, and political contexts that shape its contours (Oswell, 2013).

1.4 Neurodiverse bodily self in Autism

The sense of self is rooted in a perception-action-cognition interplay that can be different in Autism Spectrum Disorder (ASD) (Aspell et al., 2022). This neurodevelopmental condition is diagnosed from the very first years of children's life based on persistent and pervasive deficits in social communication and social interaction, as well as restricted and repetitive patterns of behaviours, interests, or activities. The latter category of symptoms consists of repetitive motor movements, use of objects, or speech; insistence on sameness, routines, or rituals in verbal or non-verbal behaviours; restricted, repetitive patterns of behaviours or intensely focused interests and preoccupations, and hyper/hypo-reactivity to sensation (American Psychiatric Association, 2013). Although much research has focused on studying how people with ASD perceive and interact with the outside world, little is known about how they perceive themselves. The study of the way their sense of self develops is giving rise to a thriving debate about what the underlying sensorimotor mechanisms and the cascading effects are on individuals' cognitive and social development.

1.4.1 Sensory and motor atypia

Sensory atypicalities are early risk factors which confer cascading effects on child development, potentially marking the onset of neurodevelopmental difficulties and conditions (Hill et al., 2012). In particular, ASD is characterized by atypical sensory processing that may have subsequent effects on the later development of higher-order cognitive and social abilities (Baum et al., 2015). Children with ASD present heterogeneous sensory profiles, such as hyper- or hyposensitivity, unique patterns of response to sensory stimuli, sensory seeking (Baranek et al., 2006; Uljarević et al., 2017), and reduced discrimination between novel and repetitive stimuli investigated by habituation paradigms (Vivanti et al., 2018). People with ASD present unique processing of unimodal stimuli, such as higher temporal binding of visual cues from two years of age (Freschl et al., 2020), reduced sound tolerance (Williams et al., 2021), atypical brain responses to both affective and non-affective touch (Kaiser et al., 2016), olfactory dysfunctions (Crow et al., 2020), and peculiar taste reactivity (Avery et al., 2018). Together with atypicalities in the individual sensory channels, children with ASD show broad differences at the multisensory level (Baum et al., 2015; Hill et al., 2012). Researchers have reported reduced multisensory facilitation and higher reliance on unimodal processing (Collignon et al., 2013), and an extended (hence less precise and specialized) multisensory temporal binding window (Foss-Feig et al., 2010), reduced integration of audio-visual cues at younger ages, which is associated with autistic characteristics (Feldman et al., 2018). The heterogeneity in sensory responsiveness within the Autism spectrum (Schoen et al., 2014) might have different cascading effects on other areas of cognitive and social functioning (Raymaekers et al., 2004; Schultz, 2005). For example, lower interoceptive sensitivity and awareness seem associated with alexithymia and then reduced empathy in ASD (Mul et al., 2018). Therefore, self-perception also affects the perception of others and the individual's ability to engage with others.

Perception and movement are closely interconnected. Motor learning occurs thanks to internal models of action: the association between self-generated motor commands (efferent systems) and sensory feedback from the body and the external world (afferent systems), so that it is possible to predict what would happen as the consequence of an action (Haswell et al., 2009). When learning a new movement, there is evidence that children with ASD are less influenced by visual feedback (Haswell et al., 2009) and that they perform better than neurotypical children when the motor learning is driven by proprioceptive input (Marko et al., 2015). For instance, the authors asked typically developing children and children with ASD to reach a target by holding a robotic arm. In some random trials, the robotic arm was perturbed and unexpectedly influenced the children's reaching movement. In the following trial, a learning-from-error effect would lead to an altered movement, which was planned to compensate for the perturbation. The perturbation could be presented to children either through visual feedback (displacement of the cursor representing the robotic arm on the screen) or proprioceptive feedback (a force imposed on the robotic arm). Compared to typically developing children, children with ASD show higher levels of learning from proprioceptive feedback and a lower levels of learning from visual feedback (Marko et al., 2015). In acquiring motor sequences, adults with ASD show deficits in the use of vision, which is the sense that neurotypical adults rely on, but preserved proprioception-driven learning (Sharer et al., 2016). Neurotypical adults have been found to experience a postural illusion (which manifests as a forward lean) when exposed to an intermittent vibratory stimulation of the posterior side of the neck, as long as vision was occluded. On the other hand, those with ASD experienced the illusion even when vision was available, demonstrating limited contribution of vision in modulating proprioception (Molloy et al., 2003).

This bias in favour of proprioceptive feedback as opposed to visual feedback from the external world might predict impairments in motor control, social skills, and imitation ability (Izawa et al., 2012). For instance, over reliance on proprioception seems associated to reduce ability to recognise others' emotions (Chevalier et al., 2017). While further research supported this over-reliance on proprioception (Hirai et al., 2021), some research has contrastingly related motor impairments in ASD to an over-reliance on vision and proprioceptive deficits (Molloy et al., 2003; Weimer et al., 2001). Some other studies highlighted a specific difficulty in visuo-proprioceptive integration (Glazebrook et al., 2009). Meanwhile, neuroimaging research has shown associations between ASD severity and asynchronous functional connectivity between visual and motor networks in children at rest (Nebel et al., 2016), reduced functional connectivity between visual areas and somatosensory motor networks, and increased connectivity between the cerebellum and sensorimotor areas in both children and adults at rest (Oldehinkel et al., 2019).

From an embodied cognition perspective, the child's development is rooted on what their body can do, so that motor and sensory development give rise to a perception-action cycle that allows the individual to learn and explore both the self and the external world (Kiefer & Trumpp, 2012). Physical and motor development set out age-specific constraints and sensitive periods for the possibility of learning certain skills. By exploring and acting as an agent within the world, children develop mechanisms that enable optimal integration between sensory input and motor output. Motor development is not a trivial acquisition of milestones, but a complex self-organization challenge to integrate the mechanical part of the body with perceptions, thoughts, emotions, and their physiological underpinnings (Thelen, 1989). From infancy, babies at high risk for later diagnosis of ASD manifest delayed and qualitatively different motor development. This is a pervasive and consistent phenomenon, as highlighted by a recent meta-analysis (West, 2019). Later in life, children with ASD show a variety of motor difficulties in the domains of praxis and fine and gross motor skills (Kaur et al., 2018). Toddlers with ASD also seem to present asymmetrical gait (Esposito et al., 2011), and impaired postural stability has been found up to adolescence and adulthood in one-leg standing (Travers et al., 2013). The postural deficit seems to be quite established in literature, according to a systematic review and meta-analysis of 19 studies (Lim et al., 2017).

Perceptual experiences and actions arise from both incoming sensory information and prior knowledge about one's internal and external world. Let us start by conceptualising perception as inference: at the visual level, for example, optical illusions derive not from mere retinal inputs, but from the cortical integration of these with a priori representations of visual entities. This allows perceptual ambiguities and uncertainties to be resolved by the brain, which constructs a coherent view of reality. The use of prior information in perception and motion has been recently investigated as an account for ASD, which might entail atypical processes underlying the derivation of the most probable interpretations of the environment. Some authors proposed that autistic perception results from attenuated priors or 'hypo-priors', with more 'accurate' perception (i.e., less filtered sensory inputs), less susceptibility to illusions, but also less ability to disambiguate noisy information and sensory uncertainty (Pellicano & Burr, 2012). In this different perceptual functioning, sensory inputs are weighted more than prior or contextual knowledge in building up perception (C. J. Palmer et al., 2017). This Bayesian account of ASD (Figure 1.2) "allows for the possibility that similar atypicalities of perception may arise for different reasons in different individuals" (Brock, 2012, pag. 3), thus embracing the profound heterogeneity of a multifaceted condition.

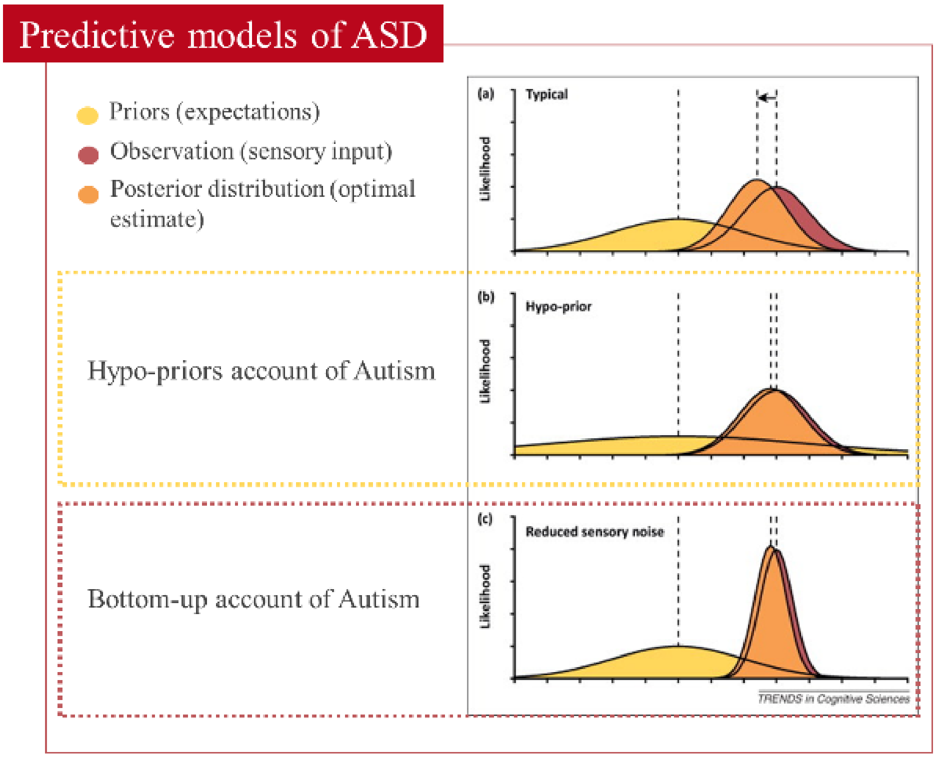


Figure 1.2. Predictive account of atypical sensory processing in ASD, adapted from Brock, 2012

Some researchers have attempted to experimentally test the validity of this theoretical framework. Autistic perception has been indeed found to be more ‘accurate’: while neurotypical toddlers show limited multisensory integration, which develops up to adolescence and results in a sort of mandatory integration of either congruent or incongruent cues, individuals with ASD present a more selective multisensory integration only for congruent stimuli (Bedford et al., 2016). As previously mentioned, the ‘hypo-priors’ account would lead us to predict that people with ASD are less susceptible to perceptual illusions, that arises from the mind trying to solve perceptual ambiguities using prior knowledge to calibrate actual sensory information. However, recent findings suggest that non-clinical autistic traits in the general population are not associated with reduced sensitivity to illusions. Regardless of autistic traits, adults perceive small objects as feeling heavier than larger ones of an equal mass (Buckingham et al., 2016), and rated heavy-looking materials (e.g., granite) as lighter than lighter-looking (e.g., polystyrene) items of the same mass (Arthur et al., 2019). Beyond self-reported experience of illusions, motor parameters of anticipation, planning and control could shed further light on the implicit sensorimotor effects of prior expectations in people with autistic traits or ASD. No clear kinematic differences have been found among neurotypical adults with autistic traits (Arthur et al., 2019; Buckingham et al., 2016) nor autistic adults (Arthur et al., 2021). However, when playing a racquetball game in virtual reality, autistic adults showed similar kinematic and gaze behaviours in more or less uncertain conditions (Arthur et al., 2021). The authors suggested that autistic adults overestimate the volatility of the environment, thus being more incline to expect the unexpected.

Despite the theoretical appeal of the predictive account for ASD, there is still a lack of empirical evidence of its validity, and applicative indications on how this theory could guide clinical practice to impact on the real lives of people with ASD.

In sum, given the unbreakable link between sensorimotor processes and higher-order operations, interventions for ASD targeting sensorimotor functioning might have positive impacts on child development. Although it has been suggested that multisensory function may be malleable with training, there is a relative lack of evidence that training improves this functioning in people with ASD (Cascio et al., 2016). The existing body of research does not support the use of therapies that provide additional possibilities to obtain visual, tactile, auditory, vestibular, or proprioceptive sensory stimulation (for a review, see Lang et al., 2012). They primarily include sensory integration, music therapy, massage, acupuncture, and weighted blankets. Part of the problem is that the potential of targeting sensory functioning with therapy is suggested by developmental studies on the association between sensory mechanisms and other areas of child development. However, the few and heterogeneous intervention models that operationalised methods for conducting sensory-based interventions failed to provide evidence of effectiveness (for a meta-analysis, see Sandbank et al., 2020). This suggests that too little is still known about how to promote change at the level of sensorimotor processes in ASD.

1.4.2 Different experience of body ownership and location

Neurotypical children and those with ASD are equally good at distinguishing between self and others' body and face-parts, thus being facilitated by processing self-related bodily stimuli (Gessaroli et al., 2013). However, the integration of different sensory stimuli behind bodily-self components is known to be different in ASD. Several authors used bodily illusions to investigate the contribution of multisensory stimulation to shape body ownership and location in participants with ASD. Neurotypical people experience illusory ownership and location towards fake or others' body parts that are stimulated in synch with their own ones. On the other hand, individuals with ASD experience delayed or reduced effects of visuo-tactile stimulation during the RHI, with less subjective feeling of ownership and self-location drift towards the rubber body (Cascio et al., 2012; Greenfield et al., 2015; Paton et al., 2012; Ropar et al., 2018). Similar evidence has been found in adults with non-clinical autistic traits (C. J. Palmer et al., 2013). This could be due to a reduced sensitivity to temporal contingencies, that contributes to reduced integration of interoceptive and exteroceptive stimuli, as manifested by reduced cardio-visual temporal acuity in ASD (Noel et al., 2018). Notably, diverse bodily self-consciousness in ASD may also be linked to difficulties in social interactions. Reduced susceptibility to body illusions has been found to be associated with higher presence of autistic traits and reduced empathy scores (Mul et al., 2019).

Several studies on spatial cognition explored the contribution of vision and proprioception to individuals' ability to move, navigate and orient in space. In both unisensory and multisensory conditions, people with

ASD rely more on proprioception than vision (Haswell et al., 2009; Marko et al., 2015) from childhood (Izawa et al., 2012) to adulthood (Morris et al., 2015). Additionally, children with ASD are more accurate at tracking their heartbeats over long time intervals, suggesting increased sustained attention to internal cues, which is negatively correlated with susceptibility to the RHI (Schauder et al., 2015). Indeed, when the RHI is administered through unimodal somatosensory (i.e., tacto-tactile) vs multimodal visuo-tactile stimuli, children with ASD seem to experience greater illusion of self-location (i.e., proprioceptive drift) towards the rubber hand (Galigani et al., 2021). This body of evidence proposes that body ownership and location in ASD are less calibrated by external cues, and overly dependent on internal somatosensory information. A sharper bodily self could also contribute to less malleable self-other boundaries, thus contributing to social difficulties and neurocognitive isolation (Noel et al., 2017).

While there are multisensory differences in the way people with ASD build their body awareness, it entails a certain degree of plasticity. Indeed, although body illusions have a reduced or delayed effect over time, also individuals with ASD are sensitive to them. Some researchers used visuo-tactile stimulation on participants' hand and elicited the so-called numbness illusion also in autistic adults. To achieve this illusion, the participant places the palm of their left hand on the palm of the right hand of another person, as if to high-five. Then, the participant uses their right thumb to stroke their own left index finger, and their right index finger to synchronously stroke the other person's index finger. When doing this, people often report a feeling of 'numbness' (Dieguez et al., 2009). In the self-administered condition, while neurotypical participants needed synchronous stimulation to feel the illusion, the autistic group seemed equally driven by both synchronous and asynchronous stimulation (Guerra et al., 2017). This makes us reflect on the interdependence between body ownership and Agency. When we do something, the perception of the action-effect time window is reduced (Haggard et al., 2002), thus facilitating multisensory and sensorimotor processing. It might be that the extended multisensory temporal binding window found in ASD contribute to an atypical perception-action dynamic, potentially affecting not only body ownership but also Agency.

1.4.3 Barriers to Agency

One of the first studies in which Agency was investigated in ASD showed that high-functioning autistic and neurotypical adults were equally able to judge whether a visual effect was self-caused or not (David et al., 2008). Participants were asked to move a joystick and its cursor representation on a screen. The authors manipulated the degree of correspondence between participants' actual movement and the visual feedback (i.e., the cursor movement). Half of the trials delivered synchronous visual feedback of participants' real movement. The other half of trials showed pre-recorded cursor movements from a randomly selected previous trial performed by the same participant. When analysing explicit measures of Agency, collected through the question "Did you perform the action on the monitor?", no significant differences emerged between the two groups (David et al., 2008). Using implicit measurements of Agency, other researchers found differences in the autistic adult population. Participants were asked to press the spacebar whenever they want. Sensory feedback was presented after a variable temporal delay (i.e., 250, 450, or 650 ms), and participants were required to estimate the delay. Despite being overall accurate in time perception, autistic adults showed reduced intentional binding compared to controls (Sperduti et al., 2014a).

These findings might suggest a potential dissociation between explicit and implicit components of Agency. Alternatively, the different results obtained by these two studies might be attributable to the presence of altered prospective components and intact retrospective components in ASD (Zalla & Sperduti, 2015). In the first study, visual feedback distortion occurred in 50% of cases, thus making the experimental situation highly uncertain and Agency primarily relying on retrospective mechanisms (David et al., 2008). In other words, much importance is given to the comparison between expected stimulation and actual visual feedback. In the second study, on the other hand, the action was always followed by the same effect, making the outcome highly predictable (Sperduti et al., 2014a). In this circumstance, prospective information assumed great relevance since the achievement of the expected outcome was predictable with a higher degree of reliability. According to a possible interpretation, the prospective component of Agency could be affected by ASD and associated with difficulties in accessing prior information for action (Zalla & Sperduti, 2015). The hypothesis put forward by Zalla and Sperduti collides with the predictive account of the sensorimotor features of ASD.

To the best of our knowledge, there are no previous studies investigating Agency in children with ASD, thus preventing us from understanding the developmental trajectory leading to any atypicalities we can find in adult populations. We can take a hint from studies on other clinical populations, that beyond diagnosis have atypicalities in common with ASD. For instance, Developmental Coordination Disorder (DCD) entails early emerging, persistent difficulties in the acquisition and execution of coordinated movements (American Psychiatric Association, 2013). Motor coordination difficulties seem to be negatively associated with socio-affective abilities, thus being a potential bridge between DCD and ASD (Piek & Dyck, 2004). The sensory processes underlying explicit Agency have been found to be different in children with DCD compared to neurotypical ones. Children were asked to make an action that would cause an effect after a random temporal delay, and then to judge whether the effect was self-caused. The time window for Agency was extended in children with DCD, negatively associated with manual dexterity and positively related to depressive symptoms (Nobusako, Osumi, et al., 2020). As multisensory temporal binding windows are enlarged in ASD (Foss-Feig et al., 2010), that could also impact the emergence of Agency. Looking at the cognitive mechanisms of Agency, some interesting insights come from Attention Deficit Hyperactivity Disorder (ADHD) research. The cognitive mechanisms underlying the inattentiveness and impulsive symptoms that characterise ADHD might also affect Agency. For example, a self-attribution bias that over-attributes positive outcomes to oneself and negative outcomes to external factors is pervasive in the general population but greater in children than adults and reduced in ADHD (Mezulis et al., 2004). However, no difference in self-attribution bias was found in ASD (Kestemont et al., 2016).

Trying to summarise the limited evidence on the sense of Agency in ASD and drawing on findings on other neurodevelopmental conditions that share differences and similarities with Autism, we can hypothesise that the latter involves differences in low-level sensorimotor mechanisms, which are particularly fundamental to the implicit sense of Agency. It would be extremely important for future research to study these aspects, and to assess their developmental trajectories, potential implications for the social-cognitive functioning of people with ASD, and possibly consider how to take Agency into account during interventions. Multi-Sensory Environments (also called sensory or Snoezelen® rooms) have been used to give children tools to control and modify their environment. In such environments, the child having the control is a key element that mediates increased attention and reduced repetitive and stereotyped behaviours (Unwin et al., 2021). These findings suggest that providing control over sensory changes to children may create better conditions for learning. The principle of "following the child's lead" is also at the core of naturalistic developmental behavioural interventions, which promote active learning by leveraging the child's initiative and preferred activities (Vivanti & Zhong, 2020).

2 Immersive Virtual Reality: potential for understanding the bodily self

2.1 Definitions and research applications

As the mind is a simulation system that filters reality with the precise goal of coming up with a coherent interpretation of the world, we have considerable chances of hacking the process and making people perceive, feel, and believe something unreal. Virtual Reality (VR) systems create simulations of reality, generally by providing computer-generated visual information but also sometimes integrating auditory, haptic, or other sensory information. One main distinction must be drawn between two different kinds of VR technologies: non-immersive VR and immersive VR. *Immersion* is the objective ability of VR to exclude the external world and provide artificial stimulations that make the user perceive the virtual environment as real, and results in the subjective sense of *presence* (of "being there") that can be evoked in the user (T. D. Parsons, Gaggioli, et al., 2017). The degree of immersion primarily depends on the type of VR device. Systems that use the Cave Automatic Virtual Environment (CAVE) or head-mounted displays (HMDs) are classified as Immersive VR (IVR). 3D systems and desktop-delivered stimuli are usually classified as non-immersive VR. In IVR, stimuli have such high sensory fidelity that they block out the external world, free movement, object manipulation, and social interaction are possible, thus offering lifelike experiences that fully engage the user (Biocca & Delaney, 1995). Immersion is also determined by the number of sensory and motor systems that are involved in the virtual environment (the more different senses are implicated, the more VR is immersive), by the quality of sensory stimulation and by the VR system's responsiveness to user actions (Bohil et al., 2011). Even though a totally life-like experience is still an ideal goal for VR developers, technological advances and improvements are enhancing immersion and presence. On the subjective side of "being there", the sense of presence is mediated by how many possibilities the user (the actor) has for action and interaction in the virtual environment. Presence results not only in a self-reported sense of presence, but also in physiological, emotional, and behavioural responses, as if the virtual world exists physically (Slater, 2018).

IVR can be used to manipulate individual sources of sensory information, be they visual, vestibular, or proprioceptive, which are physiologically bound together. This makes it possible to study the contribution of these individual sensory inputs and of multisensory integration to self-perception, motor control, spatial and social cognition (Sanchez-Vives & Slater, 2005). It is worth keeping in mind that perception and action in IVR can be different from real-life experiences, and therefore entail specific potential and limitations that are still largely unknown. Although vision is the channel most stimulated by HMDs, fewer and conflicting cues to depth, the absent or simplified haptic feedback, make researchers wonder whether IVR could actually limit the involvement of the dorsal visual system, which is devoted to processing visual information that allows us not only to recognise and discriminate stimuli, but also to interact with and use them to perform purposeful actions (D. J. Harris et al., 2019). The issue of compromised visual processing or higher load on the visual networks than in real visual environments to achieve aspects of visual cognition like depth perception is currently an active area of empirical testing and applied research (Fulvio et al., 2020). Moreover, the simultaneous experience of both virtual environment (e.g., through vision and hearing) and real environment (e.g., through somatosensation) often leads to new or confounded perceptual experiences (Gromala et al., 2009). For example, users can see themselves standing in the empty space between two mountains but, instead of falling, perceive the floor under their feet.

Even with a virtual body representation (e.g., visual perception of an avatar) or without the possibility to see one's own body, IVR can alter a user's body schema (Murray & Sixsmith, 1999). Users are found to decrease their speed and take smaller steps (Mohler, Campos, et al., 2007) and experience greater difficulties orienting themselves in IVR (Riecke & Wiener, 2007). To orient and move in space in different environments and tasks, people can switch between reference frames related to the body (e.g., proprioception) or to the external world (e.g., vision). It has been suggested that IVR provides unexpected incongruent stimuli and induces a sensory conflict between vision and proprioception which differently affects users (e.g., sometimes causing motion sickness) depending on their dominant reliance on one of these two reference frames (Prothero & Parker, 2003). The possibility to make active movements during the interaction with IVR improves proprioception, even without proprioceptively informative visual landmarks (Bakker et al., 1999; Lathrop & Kaiser, 2002). However, despite the importance of the body senses, the physical feedback (derived, for example, from actively walking during the virtual immersion) is not sufficient to eliminate errors in self-motion and spatial orientation while wearing an HMD (Kearns et al., 2002). Evidence from functional magnetic resonance imaging (fMRI) also shows that brain activity related to spatial processing (assessed through participants' judgements of whether 3D objects were centred, shifted to the left or to the right) is different in IVR as compared to known brain activations in reality (Beck et al., 2010). Although visual processing and motor accuracy can be temporarily disrupted when learning motor skills in IVR to then move in reality, real-world and IVR motor training can produce comparable improvements in motor accuracy (D. J. Harris et al., 2020).

Notably, "virtual worlds are constructed by the senses and only really exist in the mind of users. VR is a medium for the extension of body and mind" (Biocca & Delaney, 1995, pag. 58). Indeed, the body and mind can be extended through IVR, which is vastly used to induce bodily illusions. The most common are the rubber-hand illusion (RHI) (Yuan & Steed, 2010), the full-body illusion that makes users feel that they are embodied in a virtual avatar body (Maselli & Slater, 2013), and is sometimes referred to as body-swap illusion when it involves two users changing perspective and embodying each other's bodies (Petkova & Ehrsson, 2008). Notably, such experiences can change feelings, behaviours, and attitudes towards the sensory and social characteristics represented by the virtual body (Bergström et al., 2016; Maister et al., 2015; S. Serino et al., 2016). However, a recent electroencephalography (EEG) study on the RHI pointed out that the illusion might induce different oscillatory underpinnings when achieved through real stimuli or IVR. The authors suggest that the integration of spatially congruent visuo-tactile information requires additional cognitive control in IVR compared to real settings, as if there were some sort of unresolved mismatch between the two modalities (Kanayama et al., 2021).

In sum, recent evidence points out that IVR differs from real environments for both low-level sensory processes and higher-order cognitive aspects. Even in perceptually "perfect" virtual environments, individuals' prior knowledge of acting in a virtual rather than real world influences their expectations of action consequences, thus affecting behaviours (Giesel et al., 2020).

2.2 Developmental differences in users' experience

There is a lack of research regarding how IVR features interact with individual differences in sensorimotor functioning, which is particularly influenced by age and developmental trajectories. A recent experimental study with children (8–12 years old) and adolescents (15–18 years old) provides evidence about children's use of vision during self-motion in IVR (Adams et al., 2018). The authors intentionally created a mismatch between visual feedback (visual flow) and proprioceptive feedback (active motion) during different motor tasks. They measured children's ability to *recalibrate* (to adapt their motor actions to the provided abnormal visual input) and *re-adapt* to the normal characteristics of the real environment. As with adults in previous studies (Bodenheimer et al., 2017; Mohler, Thompson, et al., 2007), children and adolescents showed the ability to recalibrate in a few minutes. However, children re-adapted to reality significantly more slowly than adolescents, demonstrating more pronounced post-exposure effects. These findings indicate that the motor performance of children, more so than adolescents, could be driven by vision and modified by IVR. As different age groups may be differently affected by IVR, it is necessary to shed light on how age might affect one's interaction with this technology.

Another recent study used IVR to decouple visual information from self-motion and investigate whether adults and 10- and 11-year-old children can optimally integrate visual and proprioceptive cues (Petrini et al., 2016). An HMD was used to make participants learn a two-legged path either in darkness ("only proprioception"), in a virtual room ("vision + proprioception") or staying stationary while viewing a pre-recorded video of walking the path in the virtual room ("only vision"). Participants then reproduced this path in darkness. In contrast to what was expected, the authors found that adults failed to optimally integrate visual and proprioceptive cues to improve path reproduction. However, children did integrate these cues to improve their performance. The authors suggest that this may be because children cannot help but rely on visual cues in spatial tasks even when the nature of the task does not require it. We previously discussed findings demonstrating that HMDs disrupt proprioception, which adults and children rely on in different ways. It may be the case that IVR imparts different effects on adults' and children's performance. We could speculate that, if IVR causes some sort of conflict between vision and proprioception, adults' lack of multisensory integration in these environments could be due to their more accurate reliance on proprioception or increased multisensory integration.

IVR has been also used to test children's sensitivity to the full body illusion (namely, perceiving a virtual body as one's own), as induced by visuo-tactile stimulation on both the real and virtual bodies. Even the youngest school-aged children reported ownership toward a virtual body, but this effect increased with age. Moreover, synchrony of multisensory stimulation to achieve the full body illusion had greater importance with older children and adults (Cowie et al., 2017; Keenaghan et al., 2020). Compared to adults, children exposed to the full body illusion reported greater judgments of Agency, which was less affected by the dampening effects of visuomotor asynchrony or reduced human likeness of the virtual body (Weijs et al., 2021). However, movement synchrony between the user's real and virtual hand seems fundamental for ownership, self-location, and Agency in children from 4 to 14 years of age (Dewe et al., 2021). As hands are particularly important to manipulate objects and perform goal-directed actions, we can speculate that hand-centred visuomotor integration specialises earlier compared to other body parts. Age differences might be not limited to childhood but also relevant for aging. While young women have been found to change the estimation of their own body size after an IVR full body illusion, older women's body perception was less malleable (S. Serino et al., 2018).

Speaking of safety issues, young children seem to experience less discomfort than adults during and after play sessions within HMDs, without noteworthy effects on visuomotor functions or postural stability, and rare cases of motion sickness (Tychsen & Foeller, 2020). Even if no adverse effects of exposure to HMDs was found on stereoacuity or postural balance, children showed riskier behaviours than adults when trying everyday life activities in IVR (Pala et al., 2021). Children could also be more at risk of building false memories through virtual experiences (Segovia & Bailenson, 2009), and overall perceive the experience as more realistic or intense. To date, very few studies have addressed these concerns and too little is known about the mechanisms underlying IVR experience across development. HMDs are increasingly used for entertainment, educational and even clinical purposes with children (Bailey & Bailenson, 2017), and not much is known about the short- and long-term effects this exposure may have. Research is increasingly needed to provide guidelines on the recommended duration of these experiences and the precautionary measures to be taken to safeguard the youngest users (Kaimara et al., 2022).

2.3 Embracing neurodiversity

Multimedia technologies allow us to create environments that overcome the perceptual and physical barriers of reality to explore people's experience of different realities. This can also allow us to create environments designed for people who perceive and interact with themselves and the outside world differently, as in the case of neurodevelopmental conditions. Encouraging experiences come from projects such as the European-funded

Multisensory Environment Design for an Interface between Autistic and Typical Expressiveness (MEDIATE, Pares et al., 2005), the Magic Room: A Smart Space for Children with Neurodevelopmental Disorders (Garzotto et al., 2019), and the Lands of Fog (Crowell et al., 2020). These teams realized mixed realities and multimedia interactive environments that foster children's sense of Agency, provide sensorimotor stimulation, and can be used by children with limited verbal, cognitive, and/or social skills. Multimedia technologies in autism research have been employed as a medium to train several skills, such as cognitive abilities, motor, play and academic skills, adaptive behaviours, joint attention, socio-communicative proficiency (Heng et al., 2021). Overall, a few studies have employed IVR rather than computers and screens and most studies have small samples, no control group, and primarily focus on social, daily-life, and safety skills (Lorenzo et al., 2019). Some suggested that HMDs rather than monitors enhance spatial presence and are preferred by children with ASD (Malihi et al., 2020b). However, this sense of presence might be modulated by individual factors such as IQ and anxiety (Malihi et al., 2020a). Fully immersive technologies have further potential for people on the autism spectrum, as a tool to experience novel situations, learn in safe spaces through motivating and fun activities (Grynszpan et al., 2014; Heng et al., 2021; Valentine et al., 2020).

Beyond the increasing use of IVR, there has been little progress in studying the way people with different profiles perceive, interact, and learn within these environments. We are still far from developing IVR applications that go beyond the fascination of technology and rather spring from a deep understanding of the specific neuropsychological processes to be nurtured in individuals. Insights from developmental cognitive neuroscience should be leveraged to design and implement IVR activities for people with neurodevelopmental conditions (Farroni, Valori, et al., 2022). The following paragraphs propose some guidelines to go in that direction.

2.3.1 Keep the senses in mind, promote action and motion

Compared to traditional monitors, IVR and HMDs have unique features that fully immerse the user in simulations of reality, increasing the sense of presence in the interaction space, allowing to provide and manipulate visual, auditory, tactile, vestibular, and proprioceptive information (for a review, see Valori et al., 2021). The contribution of each individual sensory channel and multisensory integration to perception and movement can be assessed and stimulated based on the individual needs and profile of the person. Recent studies suggested that headsets can stimulate multiple sensory systems in people with sensory processing disorders (Rossi et al., 2019), promote multisensory integration in cases of vestibular disorders (Lubetzky et al., 2020), and provide three-dimensional auditory stimuli in a play context, thereby reducing perceived anxiety toward target auditory stimuli in adolescents with ASD (Johnston et al., 2020). Children and adolescents with ASD seem to benefit from binaural spatialized audio when exploring virtual environments with HMDs (Johnston et al., 2019). On the other hand, 12- to 15-year-old adolescents with ASD, compared to a neurotypical control group, showed less vestibular reactivity to a visual stimulation aimed at inducing body instability through high frequency oscillations of a virtual tunnel presented inside an HMD. This difference between experimental and control groups was not detected in older participants (16–33 years) (Greffou et al., 2012).

Some evidence suggests that adults with ASD compared to controls are less susceptible to the full body illusion in IVR, not demonstrating the embodiment in a VB (Mul et al., 2019). The lack of embodiment has been found to be associated with autistic traits and reduced peripersonal space, which is the space immediately around our body in which actions are possible (for a review on peripersonal space, see Holmes & Spence, 2004). Indeed, given the importance of visuo-proprioceptive congruency to induce a sense of Agency in IVR (Zopf et al., 2018), atypical visuo-proprioceptive integration in ASD (Oldehinkel et al., 2019) might underlie the limited sensitivity to the virtual body illusion. The authors suggest that an atypical body awareness might be related to multisensory integration difficulties, with potential adverse effects on social abilities (Mul et al., 2019). For instance, higher reliance on body-based interoceptive signals impairs sensitivity to body illusions due to a limited use of external information, which is fundamental to interact with people and objects around us (Schauder et al., 2015).

Some IVR and ASD features let us wonder whether this technology may be particularly suitable for people with ASD. While virtual environments have been suggested to reduce the engagement of the dorsal visual stream (vision for action) in favour of the ventral one (vision for recognition) (D. J. Harris et al., 2019), people with ASD seem to increasingly rely on the ventral system (Grinter et al., 2010). We might ask whether people with ASD could be facilitated by the visual characteristics of IVR, which involves the visual system that is a strength of the person with autism. Furthermore, technical aspects such as the display lag in tracking head position in space (Allison et al., 2001) might allow HMDs to enlarge the temporal window between stimuli, thus facilitating multisensory integration for people with ASD, who manifest an enlarged multisensory temporal binding window (TBW). Indeed, while the width of the TBW can be narrowed through temporal discrimination training (Zhou et al., 2018), an alternative to this “remediation approach” would be embracing individual differences and provide people with environments suited to their individual TBW. From this perspective, we could speculate that an enlarged inter-stimuli delay might reduce the “multisensory crowding” associated with enlarged TBWs, resulting in sensory (and learning) facilitation.

IVR is one of the most promising technologies to enable users to move and navigate in space with one's whole body while immersed in digital environments, with potential to stimulate body awareness, promote gross and fine-motor rehabilitation, and enhance eye-motor coordination in diverse contexts (Bortone et al., 2018; Gagliardi et al., 2018; Lee et al., 2019; Rutkowski et al., 2021). While IVR mainly relies on visual stimulation, other multimedia technologies can be used to exploit different sensory modalities and train motor skills. For instance, virtual realities built upon motion platforms and acoustic tools might increase self-motion perception of visually impaired people (Zanchi et al., 2021), with broader implications for the use of sound to empower bodily perceptions. On this account, virtual realities may be particularly facilitating learning environments for children and adults with specific sensorimotor profiles.

2.3.2 Together is better

The balance between processing and perceiving what is happening *inside* or *outside* the self is at the heart of social cognition, that enables individuals to distinguish between the self and the others, and then interact and connect (Palmer & Tsakiris, 2018). While feeling close to other people promotes well-being, feeling disconnected has been shown to compromise mental and physical health - in both neurotypical and clinical groups - strengthening a feeling of isolation and loneliness (Kwan et al., 2020). Fascinating evidence suggests that sharing experiences with others, rather than being alone, increases the sensory intensity with which we perceive stimuli. Good or bad chocolate would respectively taste better or worse if we have it with someone else (Boothby et al., 2014), and visual scenes would be perceived as more pleasant and realistic when watched together with another person (Boothby et al., 2017). The most intriguing thing is that this effect does not depend on explicit, verbal sharing of how people evaluate the experience, but on mere co-presence. Furthermore, developmental research strongly suggests that sensory information conveyed during social interactions facilitates learning from the earliest stages of a child's life. Social cues such as gaze (Farroni et al., 2007), happy facial expressions (Farroni et al., 2007), voice prosody (Spinelli et al., 2017), and affective touch (Della Longa et al., 2017) are powerful drivers of learning, especially for children.

Promoting social engagement is particularly important for people with ASD, who frequently suffer from communication and social difficulties. Early interventions usually have the primary objective of promoting social engagement, shared attention, play and communication skills. In order to establish the connection with the child with ASD and keep his or her social motivation high, the attitude of the adult (whether therapist, parent or teacher) is crucial. They can emphasise positive expressions, through highly emotional tone of voice and gestures, facilitate eye contact and enrich the encounters with sensory and social routines such as tickling and 'peek-a-boo' (Vivanti & Zhong, 2020). Evidence-based interventions for ASD emphasize the importance of implementing interventions in small peer groups, which are particularly suited to the promotion of socio-communicative skills (Vivanti et al., 2017). Targeting social skills is therefore a primary objective of interventions, but also a means of pursuing each child's sensorimotor, cognitive, and learning goals.

These general principles must be taken into account when using technologies, lest they reduce opportunities for social exchanges and risk becoming a source of isolation for the person. Over the past decades, IVR has been widely used for enhancing communication and social skills in safe and controllable, yet ecological contexts. Children with ASD exposed to such interventions have shown improvements in nonverbal communication, initiative, and social cognition (Chen et al., 2015). In addition, technologies can offer to pairs or small groups of children, innovative activities that are designed to create a cooperative environment in which they learn not only from the adult but especially from their playmate. Collaborative virtual environments (CVEs) can be used with children with ASD to enable several users to remotely interact with the environment at the same time. Each person is represented by their unique avatar, acting, moving, and navigating the environment independently, thus communicating directly when they are close enough to another user's avatar (S. Parsons & Cobb, 2011). Beyond the use of IVR for remote peer interaction (i.e., individuals are working together on a shared task or activity, but are physically apart), in person interaction enables multiple users to work on the same virtual activity, while also sharing the real space. The latter option enriches the audio-visual interaction of bodily signals such as interpersonal touch, which may promote a sense of presence and social connection, thus improving the affective information conveyed during virtual communication (Della Longa et al., 2022).

Compared to reality, IVR may offer unique possibilities to make the exposure gradual and adaptable to the individual, while at the same time easily collecting data on the person's behaviour (choices made, type of exploration, up to including eye-tracking and kinematic aspects). This possibility is promising for both research and intervention, enabling the implementation of activities that respond in a predefined, controlled, and adaptive way to the user's behaviour. However, we are far from understanding the similarities and differences between real and virtual social exchanges. While interpersonal comfort distance of neurotypical people changes across real and virtual environments, individuals with ASD seem to feel confident at similar distances from real or virtual partners (Simões et al., 2020). We still need to understand how different individuals interact with each other or with social stimuli in different environments, to better define the potential and limitations of technology.

In sum, individuals can make virtual experiences within realistic environments that can be programmed to manipulate sensory and social inputs at an optimal level for each individual. The role of caregivers, educators, and therapists in offering guidance and scaffolding to the child remain essential, as they must facilitate the experience through modelling, encouragement, suggestions, and reinforcement of target behaviours (Figure 2.1). Technology should never be an end in itself, nor induce isolation from reality, but rather a means for exploration and learning. The general guideline is that "technology may be most useful when it is integrated into previously developed and validated approaches as a means to expand the populations for whom the intervention is accessible, rather than as an intervention in its own right" (Sandbank et al., 2020, pag. 18).

Figure 2.1. (From left to right) therapists guiding children through (**a**) emotion recognition activity, (**b**) immersive virtual exposure to daily life situations (e.g., taking the bus), (**c**) adaptation of a Walking Corsi test for visuo-spatial working memory.

2.3.3 A stairway to cognition: executive functions

From a neuroconstructivist perspective (Karmiloff-Smith, 2009), working on low-level sensorimotor mechanisms has cascading effects on the stimulation of higher-level cognitive abilities and is the prerequisite for impacting mechanisms such as memory, attention, and Executive Functions (EFs), which can be affected by ASD and associated with behavioural and socio-communicative difficulties (Demetriou et al., 2018). More specifically, EFs, defined as the set of skills that allows to regulate and control other cognitive functions and behaviour to achieve a goal and adapt to new and complex situations, have been recently shown to mediate the association between sensory processing and behaviour in ASD (Fernandez-Prieto et al., 2021). Being capable of self-regulation and flexibility indeed helps people deal with everyday situations, with repercussions on learning and adaptive behaviour (Dellapiazza et al., 2018; Diamond, 2014). Moreover, executive processes are closely linked to socio-affective ones (Farroni, Della Longa, et al., 2022), thus benefiting from being trained in social situations.

Along with working on the sensorimotor and social domains to foster cognitive functions, directly strengthening attentive and executive processes appears crucial. Indeed, one of the main challenges for children with both typical and atypical development is “to learn how to learn”, which entails EFs that are trainable and can be improved with practice (Diamond, 2013a). To this end, research questions and targeted interventions should go beyond the diagnostic label and be based on a functional description that identifies an individual's strengths and needs for strengthening on the sub-components of each cognitive function to be stimulated. The interactive specialization theory (Johnson, 2001, 2011) predicts that by working on a certain function, we will have a well-rounded change in both targeted and additional brain areas and neuropsychological functions that are interconnected.

Multimedia environments offer the unique advantage of being easy to customise with contents adapted to each user, to observe the child facing various cognitive tasks, and train the relative cognitive abilities. Leveraging embodied cognition, we can repurpose classic cognitive tasks in multisensory, motor, fun and motivating versions. Although virtual adaptations of well-known neuropsychological tasks are frequently used to capture neuropsychological constructs, there are contradictory findings about the correlation between cognitive performances in real and VR modalities (T. D. Parsons, Carlew, et al., 2017). For instance, IVR can be used to assess and train topographical memory with adapted versions of the Walking Corsi test, which seems to induce comparable performances in both real and virtual environments (Nori et al., 2015). On the other side, an IVR gamified adaptation of the Wisconsin Card Sorting Test (tapping on cognitive flexibility), which allowed participants to not only match cards but rather navigate the environment and open doors (Pugnetti et al., 1998) resulted in a poor correlation between performances in real and IVR modalities. That means that interactive modalities and technology features might affect the targeted neuropsychological functions. It might also be the case that IVR creates more ecologic and naturalistic experiences, being particularly promising but potentially leading to different results compared to traditional tests.

Expanding on this, some researchers suggested that the unique potential of IVR is to go beyond construct-based tests of cognitive mechanisms, which may fail to predict functional behaviours in everyday-life situations, and rather implement function-based assessments and interventions, whereby EF can be evaluated within ecologic and generalisable contexts that represent real-life tasks (T. D. Parsons, Carlew, et al., 2017). There is evidence to suggest that learning in a variety of social scenarios and environmental contexts promotes the generalization of skills trained in VR to everyday life situations (Bradley & Newbutt, 2018). For instance, adolescents with ASD who experienced IVR training on shopping skills showed, in a real supermarket, to be more capable than the control group in finding items, and greater confidence in the activity (Adjorlu et al., 2017). In this respect, IVR has also been used to support vocational training for adults with ASD, and train skills such as loading a truck, cleaning, managing money, and organizing shelves (Bozgeyikli et al., 2017). This approach would challenge executive processes in contexts similar to everyday activities that rely on those capabilities.

Importantly, learning should never be separated from fun. Indeed, optimal experiences are those leveraging enjoyment, which arises from going beyond what an individual has been programmed to do and achieving something unexpected. Enjoyment characterises tasks where there is no concern for the self, goals are clear, there is a reasonable chance of completion and immediate feedback. Moreover, people need to put forth a deep but effortless commitment and feel in control over their actions (Csikszentmihalyi, 2014). In this respect, the main benefits of virtual environments for individuals with ASD are that they are controllable and offer safe spaces for learning new skills in individualised situations (S. Parsons & Cobb, 2011). Notably, they can be implemented to scale the level of predictability or uncertainty, thus pursuing a balance between safe harbour for the intolerance of uncertainty that often characterizes ASD (Boulter et al., 2014), and the challenge of curiosity and flexibility that comes from being able to actively seek for new stimuli (Kidd & Hayden, 2015).

3 Self-location in real and virtual environments (Study 1)

3.1 Research goals and hypotheses

The aim of the present study is to investigate the extent to which the reliability of visual information contributes to self-location across typical development and in ASD. We also aim to explore whether HMD-delivered IVR, compared to equivalent real environments, affects visuo-proprioceptive integration and self-location. Given that findings in the area of multisensory interaction with IVR across development are still conflicting and unexplained with respect to the use of HMDs, the current study seeks to clarify how using an HMD affects children's and adults' self-location, and how these effects could be related to the reliability of the provided visual and proprioceptive information. To compare performances in reality and IVR, all sensory conditions being equal, would clarify the role of both sensory manipulation and IVR. Research has broadly considered the computer side of IVR features affecting human-computer interaction, but there is a lack of research investigating how individual characteristics of users interact with IVR. How might different users, with different multisensory profiles, interact with IVR? The present study explores this question, examining how IVR differs from reality in affecting self-location in adults and children with typical development or ASD. Based on the extant literature described in the introductory section of this work, we hypothesized that children's self-location accuracy would be globally lower than that of adults, but that children would be less impaired than adults by the disruption of proprioception. We further hypothesized that IVR would disrupt proprioception and impact self-location accuracy more in adults than children. Moreover, we expected individuals with ASD to be less accurate in self-location, and to rely more on proprioception, thus being less facilitated by visual information in a real environment. Given the lack of previous evidence, we explored their performance in IVR, to get preliminary insights on potential HMDs-specific effects for people with ASD.

3.2 Materials and methods

We designed and built a testing room in which different sensory stimulations could be provided and the availability of visual and proprioceptive information could be manipulated while completely excluding unwanted external stimuli (Figure 3.1). In the centre of the room, a customized swivel chair on a round platform was fixed to the floor. A 360° protractor under the seat was visible to experimenters via a dedicated camera which allowed the measurement of the degree of each rotation (Figure 3.2A). One 50 cm white LED strip (12V DC, 24 Watt per meter) allowed sufficient illumination for a clear and realistic visual experience of the room. One UV lamp (E27 26W) was used to obscure other visual stimuli such that the white clouds on the walls were the only visual cues available. With the UV light on, participants were asked to wear a black poncho which covered their bodies, making them not visible (Figure 3.2C). One infrared LED spotlight (BIG BARGAIN BW103) enabled clear video recordings of the inside of the room even when it was completely in darkness.

This light system was anchored to the ceiling, over participants' heads, and was covered by a black panel which prevented participants from directly seeing the lights.

Figure 3.1. Experimental room. The room measured 2 x 2 meters and was soundproof, with black interior walls and equal numbers of white clouds randomly fixed on each wall. The external walls were painted with a child-friendly landscape which was designed to encourage children to enter

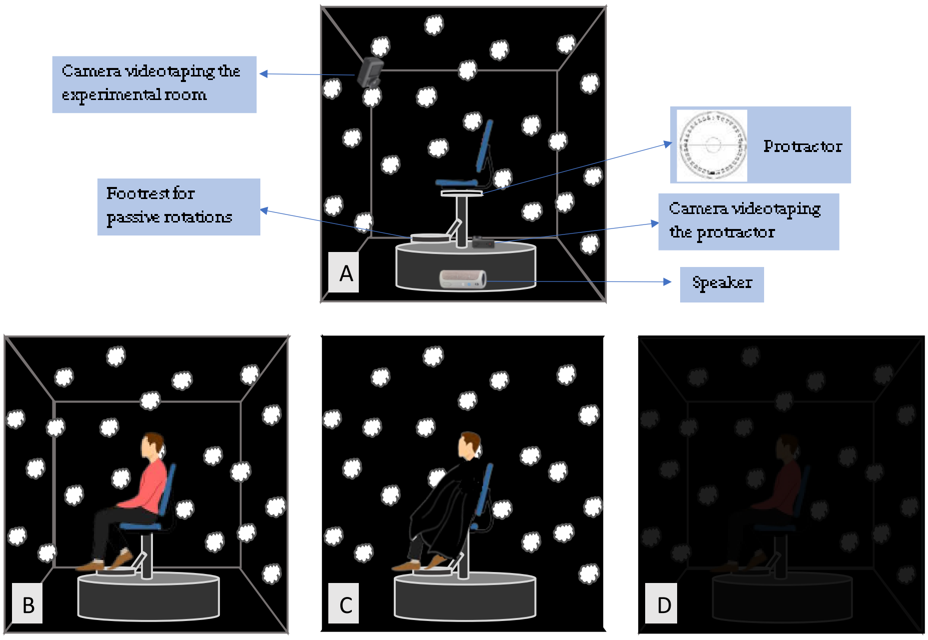


Figure 3.2. A) Experimental room, interior. The swivel chair is in the centre of the room with a protractor and a camera videotaping the protractor located under it. B) R_VP: the swivel chair in the visuo-proprioceptive real environment; C) R_V: a participant wearing the black poncho in the 'vision only' real environment. UV light on; D) R_P: a participant in complete darkness in the 'proprioception only' condition.

A Nikon KeyMission 360 camera was used to create 360° images of the room and to build the IVR. We provided the IVR simulation through the HMD Oculus Gear VR 2016, 101° FOV, 345 g weight, interfaced with a Samsung Galaxy S7 (ANDROID 8.0.0 operating system). The room was monitored via one USB 2.0

DirectShow webcam, and one USB 2.0 DirectShow webcam with integrated infrared LED. To monitor the video recordings and IVR simulations, we used a SATELLITE Z30-B, Win- dows 10, 64bit, Intel Core i5-5200U CPU @ 2.20 Ghz, 8.0 GB RAM, Intel HD Graphics 5500. The communication between people inside and outside the room was enabled via a system of a USB speaker, microphone, headphones, and one USB soundcard. The VR server application developed for this experiment is an Android application with VR environments, developed in Unity. A remote interface, also developed in Unity for Windows or Android OS, allowed experimenters to control the VR server application. Software for audio-video recording and real-time communication was developed in TouchDesigner.

3.2.1 Procedure and task

Adult participants were welcomed into the lab and asked to sign a consent form. Parents of children were asked to sign the form on their child's behalf. The study was approved by the Ethics Committee of Psychology Research, University of Padua. At least two experimenters conducted the experiment. On commencing the experiment, participants were asked to sit on the swivel chair which was fixed in the middle of the recording area inside the room. Experimenter 1 would close the door and stay inside near the participant for the duration of the experiment. Experimenter 2 managed the experiment from outside the room: they switched the lights on and off, changed the visual stimuli which were presented through the HMD, and gave verbal instructions to Experimenter 1 and to the participants. Although the room was soundproof, Experimenter 2 could communicate with the people inside through a microphone and speaker system. During the experimental task, Experimenter 1 managed the passive rotation and remained silent behind the participant, providing no visual or auditory cues.

We adopted a self-turn paradigm in which the experimenter rotates the chair a certain degree (passive rotation) from a *start position* to an *end position*. After each passive rotation, participants were asked to rotate back to the start position (active rotation). The position at which the participant stopped their active rotation is recorded as the *return position*. During the passive rotation, participants sat still and kept their feet on a footrest which rotated with the chair. To perform the active rotations, participants could use their feet on the still platform under the chair to move themselves. Within a given experimental condition, during both the encoding *(passive rotation)* and the recall *(active rotation)* phase, all sensory information was consistent. During the recall phase, proprioception derived from the active movement was involved in performing the *active rotation* and recalling the *start position*. We did not manipulate vestibular information, which was consistent across all experimental conditions. On the other hand, we manipulated vision across the three experimental conditions as described in the following section.

The accuracy of self-location performances was calculated in terms of error as the absolute difference between the start position (from which the experimenter started the passive rotation) and the return position (in which the participant stopped the active rotation). In this way, greater values indicated a less accurate performance, where a value of 0 would indicate that the participant actively rotated back to the exact start position, and a value of 100 would indicate that the participant actively rotated back to a position that was 100 degrees away from the start position. Accuracy was manually measured during an offline coding of the video recording. The video showed two matched recordings of both the entire room (with the participant and Experimenter 1 in frame) and the protractor positioned under the seat of the swivel chair. A vertical green line was superimposed on the protractor image to facilitate detection of the specific degree of each rotation.

3.2.2 Experimental conditions

We had a 3 (young-children; older-children; adults) x 2 (Reality; IVR) x 3 (Proprioception; Vision; Vision + Proprioception) design, with an additional continuous independent variable of rotation amplitude. In a within-subjects design, all participants were exposed to all conditions in a randomized order. Within the environment variable, there were reality conditions in a real environment (the interactive room) and IVR conditions with participants wearing the HMD that showed 360° pictures of perceptually equivalent versions of the reality conditions. Within the perception variable, there were three conditions. One blind condition removed all visual information such that only proprioceptive information could be used (P). One visual condition limited the access to proprioceptively informative visual landmarks (hiding the participants' body and the room corners) in order to disrupt proprioception, while providing a proprioceptively uninformative visual texture (a pattern of small bright clouds on the walls) (V). Indeed, previous research has found that after being disorientated by a passive rotation in a real environment, people could still detect the position of global landmarks (the room's corners), while making huge errors locating surrounding objects (Wang & Spelke, 2000). Our intention was to disrupt proprioception through altering the visual information available, without making changes to the proprioceptive information arising from participants' bodies during the passive and active movements, which are consistent within participants. The last condition allowed the participant to access reliable visual and proprioceptive information (VP).

We aimed to check whether the equivalent visual information would lead to equivalent self-location accuracy when comparing reality and IVR conditions. In fact, the degree to which visual cues aid self-location seems to be environment-specific. For instance, in HMD-delivered IVR, users' self-motion could not benefit so much from global landmarks (Meilinger et al., 2015). Although it was not a main aim of the experiment, we aimed to control whether the rotation direction and amplitude would affect performance. For this purpose, the passive rotation of each condition was made in both directions (clockwise-"R", counterclockwise-"L"), and with two angle amplitudes (90 and 180 degrees). As the passive rotation was manually performed by the experimenter, perfect accuracy in reaching 90 and 180 degrees was not possible. Given the variability in the actual passive rotations, we considered amplitude as a continuous variable. In this way, we controlled for this potential source of noise. The order of conditions was randomized. Participants performed two trials per Environment X Perception condition, resulting in 12 observations per participant.

The experimental conditions are as follows:

1. **R_P** (Reality; only proprioception: no visual information available).
2. **R_V** (Reality; only vision: proprioceptively uninformative visual texture of small bright clouds on the walls. No first-person view of the body or room corners in order to disrupt proprioception by manipulating vision).
3. **R_VP** (Reality; proprioceptively informative visual cues available, including first-person view of the body and room corners. The visual texture of clouds on the walls is available).
4. **IVR_P** (HMD on; only proprioception: no visual information available).
5. **IVR_V** (HMD on; only vision: proprioceptively uninformative visual texture of small bright clouds on the walls. No first-person view of the body or room corners in order to disrupt proprioception by manipulating vision).
6. **IVR_VP** (HMD on; proprioceptively informative visual cues available, including visible room corners, although the first-person view of the body is not visible. The visual texture of clouds on the walls is available).

3.3 The importance of vision in typical development (Experiment A)

Abstract. The present experiment explored how vision and proprioception contribute to self-location when neurotypical children and adults move in either reality or IVR. Individuals from 4 to 43 years old completed a self-turning task which asked them to actively return to a previous location with different sensory modalities available in both environments. An exploratory perspective and Bayesian model comparison analysis was used to interpret data using probabilistic statements rather than simplified reject/not-reject decisions. Results showed that 4–8-year-old children can generally be expected to make more self-location errors than older children and adults. Across age groups, self-location is more accurate when vision is available, and is disrupted in the visual environment provided by the IVR headset. We can conclude that self-location mostly specializes during the first eight years of life and that it relies largely on vision. Moreover, our findings indicate that IVR headsets can reduce people's ability to locate themselves in space. This raises questions about its use, opening the door to study its potential to facilitate experiences outside the here and now of one's own body. Applications in therapies that need to distract people from somatosensory perception are discussed.

3.3.1 Participants

In order to capture a range of developmental stages, we included primary and secondary school-aged children and adults. We collected data from young children aged from 4 to 8 years old, and older children aged from 9 to 15 years old. With regard to the adult group, we included participants within the age range of 18 to 45 years. We excluded older participants based on literature reporting deterioration of proprioceptive accuracy from middle age (Hurley et al., 1998; Wingert et al., 2014). For this study, we collected data from 55 participants. In line with our a priori exclusion criteria, we excluded six participants who reported that they had received a diagnosis for any kind of neuropsychological, sensory, or learning disorder from the final analysis. The final sample included 49 participants, distributed across age groups as reported in Table 3.1.

Table 3.1. Participants according to age groups.

Age group		**Years**		**Range**		**Sex**	
	N	**Mean**	**SD**	**Min**	**Max**	**Male**	**Female**
Young Children	13	7.1	1.3	4	8	9	4
Older Children	13	11.3	2.1	9	15	5	8
Adults	23	32.4	6.7	20	43	12	11

3.3.2 Statistical approach for exploratory investigations: Bayesian model comparison

Given the lack of evidence concerning the complex interaction between developmental stages, visuo-proprioceptive integration, and IVR, exploratory studies are needed and can benefit from assuming a model comparison approach. Model comparison allows for the selection of the most plausible model given data and a set of candidate models (McElreath, 2020). Firstly, the different research hypotheses are formalized as statistical models. Subsequently, the obtained models are compared in terms of statistical evidence (i.e., support by the obtained data), using information criteria (Wagenmakers & Farrell, 2004). Information criteria enables the evaluation of models considering the trade-off between parsimony and goodness-of-fit (Vandekerckhove et al., 2015): as the complexity of the model increases (i.e. more parameters), the fit to the data increases as well, but generalizability (i.e. ability to predict new data) decreases. The researchers' aim is to find the right balance between fit and generalizability in order to describe, with a statistical model, the important features of the studied phenomenon, but not the random noise of the observed data.

A Bayesian approach is a valid alternative to the traditional frequentist approach (Gelman et al., 1995; Kruschke & Liddell, 2018), allowing researchers to accurately estimate complex models that otherwise would fail to converge (i.e., unreliable results) in a traditional frequentist approach (Bolker et al., 2009; Fong et al., 2010). Bayesian inference has some unique elements that make the meaning and interpretation of the results different from the classical frequentist approach (Etz & Vandekerckhove, 2018). In particular, in the Bayesian approach, parameters are estimated using probability distributions (i.e., a range of possible values) and not a single point estimate (i.e., a single value). Bayesian inference has three main components (van de Schoot et al., 2014): (1) *Priors*, the probability distributions of possible parameter values considering the information available before conducting the experiment; (2) *Likelihood*, the information given by the observed data about the probability distributions of possible parameter values; (3) *Posteriors*, the resulting probability distributions of possible parameter values, obtained by combining Priors and Likelihood through Bayes' Theorem. As a result, a Bayesian approach assesses the variability (i.e., uncertainty) of parameter estimates and provides associated inferences via 95% Bayesian Credible Intervals (BCIs), the range of most credible parameter values given the prior distribution and the observed data. Thus, a Bayesian approach allows researchers to describe the phenomenon of interest through probabilistic statements, rather than a series of simplified reject/not-reject dichotomous decisions typically used in the null hypothesis significance testing approach (McElreath, 2020).

In order to explore how Age, Perception conditions, and Environment conditions interact to affect self-location accuracy, a model comparison approach was used. Firstly, each research hypothesis was formalized as a statistical model. Subsequently, the obtained models were compared in terms of statistical evidence (i.e., support by the data) using information criteria (Wagenmakers & Farrell, 2004).

Given the complex structure of the data, Bayesian generalized mixed-effects models were used (Gelman et al., 1995; Pinheiro & Bates, 2000). Specifically, data were characterized by: (1) a continuous non-normally distributed dependent variable (i.e., rotation error); (2) a between-subject factor (i.e., Age); (3) within- subject factors (i.e., Perception condition and Environment condition); (4) a quantitative independent variable (i.e., rotation Amplitude). Mixed-effects models allow us to consider the repeated measures design of the experiment (i.e., observations nested within participants). Thus, participants were treated as random effects, with random intercepts that account for interpersonal variability, while the other variables are considered as fixed effects. Generalized mixed-effects models were used considering the Gamma distribution, with logarithmic link function, as the probability distribution of the dependent variable. Generalized mixed-effects models allow us to model non-normally distributed data using appropriate probability distributions that reflect the characteristics of the data (Fox, 2015). Selecting an appropriate probability distribution provides better fit to the data and more reliable results (Lo & Andrews, 2015). Gamma distribution is advised in the case of positively skewed, non-negative data, when the variances are expected to be proportional to the square of the means (Ng & Cribbie, 2017). These conditions are respected by our dependent variable: we only have positive values, with a positive skewed distribution, and we expect a greater variability of the possible results as the model predicted mean increases (i.e., a greater dispersion of participants' scores when greater mean values are predicted by the model).

Analyses were conducted with the R software version 3.5.1 (R Core Team, 2020). Models were estimated using the R package *'brms'* (Bürkner, 2017) which is based on STAN programming language. All our models used default prior specification of the R package *'brms'*. These priors are considered non-informative since they leave the posterior distributions to be mostly influenced by the observed data rather than by prior information. Each model was estimated using 6 independent chains of 8,000 iterations with a "warm-up" period of 2,000 iterations, resulting in 36,000 usable samples.

The Watanabe-Akaike information criterion (WAIC; Gelman et al., 2014; Vehtari et al., 2017) was used as information criteria to select the most plausible model among the tested models, given the data. WAIC is the corresponding Bayesian version of the commonly used Akaike information criterion (AIC; Akaike, 1998). WAIC weights were computed to present the probability of each model of making the best predictions on new data, conditional on the set of models considered (McElreath, 2020). This allows for the comparison of models with a continuous informative measure of evidence. Finally, the most plausible model was interpreted considering the estimated posterior parameter distributions. Main effects and interaction effects were evaluated using planned comparison and graphical representations of the predicted values by model.

3.3.3 Results

Intercoder agreement

Two independent evaluators coded the videos and entered the start and return positions in the dataset. Values which were divergent for more than two degrees were a priori considered disagreement values. That was the case for 82 out of 578 observations (14.2%). A third coder examined the video recordings of the disagreement values to make the final decision. In case of a disagreement value, the third coder's value was used instead of the value that differed most from the third coder's value. We obtained a dataset with two codings for each piece of data. We evaluated the intercoder agreement by conducting an intra-class correlation (ICC), which is one of the most commonly used statistics for assessing inter-rater reliability (IRR) for ratio variables (Hallgren, 2012). On the double values indicating the start, end, and return positions of each rotation, the ICC index has been calculated. The analysis estimates an ICC = .99. This nearly perfect inter-coder agreement derives from the small mean difference between the two coders' values (MeancoderA−coderB < .16), within the huge range of possible values (0/360). We carried out the data analysis on the final dataset with the average of the two values.

Descriptive statistics

Out of the 49 participants, 43 participants completed the task in all 12 trials, 4 participants completed 11 trials, 1 participant completed 10 trials, and 1 participant completed 8 trials. This failure to complete all trials with some participants was due to technical problems which occurred with the experimental apparatus. Thus, the final data consist of 578 observations nested in 49 participants.

We considered Amplitude of the passive rotations as a continuous variable whose distribution is shown in Figure 3.3. To obtain interpretable results in the analyses, the Amplitude variable was standardized (i.e., Z scores were obtained).

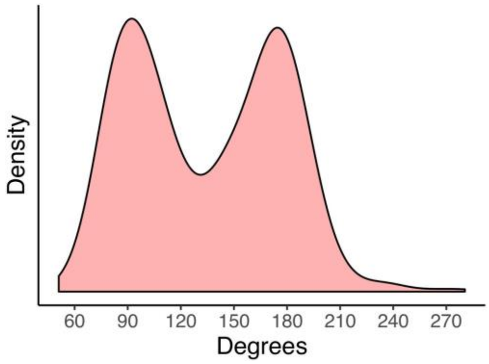


Figure 3.3. Estimated distribution of the actual amplitude in the passive rotation. ($n_{participants} = 49$; $n_{observations} = 578$).

The mean self-turn error in the present sample was 17.1 degrees (SD = 8.0). The frequency of the observed values is reported in Figure 3.4. Considering how we computed the self-turn error, only positive values are possible and from visual inspection, the dependent variable has an evident positive skewed distribution.

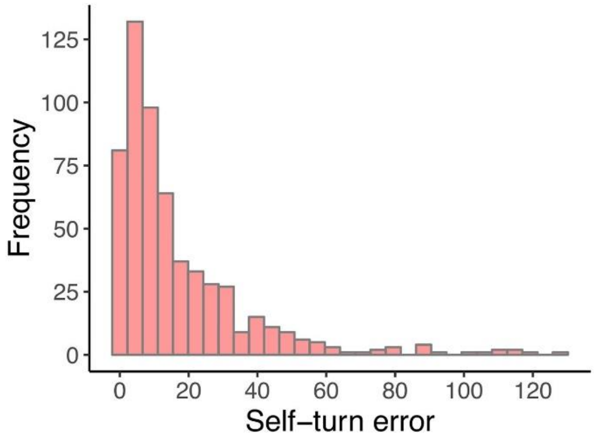
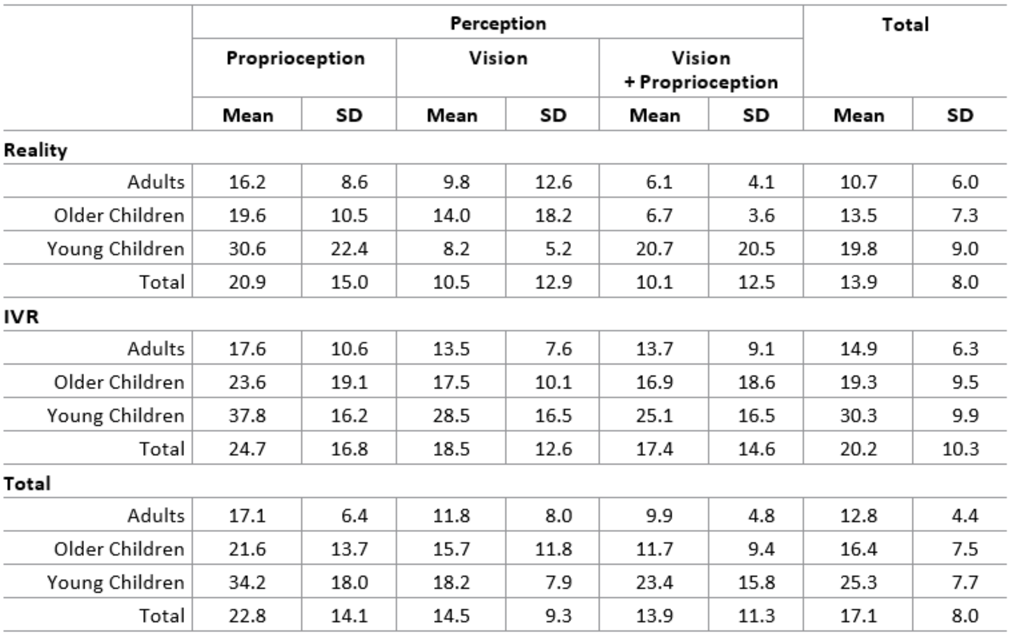


Figure 3.4. Frequencies of the observed self-turn errors. ($n_{participants} = 49$; $n_{observations} = 578$).

The means and standard deviations of the self-turn error for the three age groups in the six different experimental conditions are reported in Table 3.2 and the distributions of the observed data are presented in Figure 3.5. For the sake of interpretability, descriptive statistics were computed according to Age, Environment, and Perception, without taking into account the variable Amplitude (i.e., all observations in the same condition were considered independently of the Amplitude values), which will be considered later on in the analysis. Considering the observed values according to Age, adults (M = 12.8, SD = 4.4) made less self-turn errors than older children (M = 16.4, SD = 7.5) and young children (M = 25.3, SD = 7.7). Looking at the Environment conditions, participants made less errors and were thusly more accurate in the reality condition (M = 13.9, SD = 8.0) than in the IVR condition (M = 20.2, SD = 10.3). Finally, considering the different levels of the variable Perception, participants made less self-turn errors when they could rely on both vision and proprioception (M = 13.9, SD = 11.3) than when they could use only vision (M = 14.5, SD = 9.3) or proprioception (M = 22.8, SD = 14.1).

Table 3.2. Descriptive statistics. Means and standard deviations of self-turn error according to age and the experimental conditions. Note: $n_{participants} = 49$; $n_{observations} = 578$.



	Perception						**Total**	
	Proprioception		**Vision**		**Vision + Proprioception**			
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Reality								
Adults	16.2	8.6	9.8	12.6	6.1	4.1	10.7	6.0
Older Children	19.6	10.5	14.0	18.2	6.7	3.6	13.5	7.3
Young Children	30.6	22.4	8.2	5.2	20.7	20.5	19.8	9.0
Total	20.9	15.0	10.5	12.9	10.1	12.5	13.9	8.0
IVR								
Adults	17.6	10.6	13.5	7.6	13.7	9.1	14.9	6.3
Older Children	23.6	19.1	17.5	10.1	16.9	18.6	19.3	9.5
Young Children	37.8	16.2	28.5	16.5	25.1	16.5	30.3	9.9
Total	24.7	16.8	18.5	12.6	17.4	14.6	20.2	10.3
Total								
Adults	17.1	6.4	11.8	8.0	9.9	4.8	12.8	4.4
Older Children	21.6	13.7	15.7	11.8	11.7	9.4	16.4	7.5
Young Children	34.2	18.0	18.2	7.9	23.4	15.8	25.3	7.7
Total	22.8	14.1	14.5	9.3	13.9	11.3	17.1	8.0

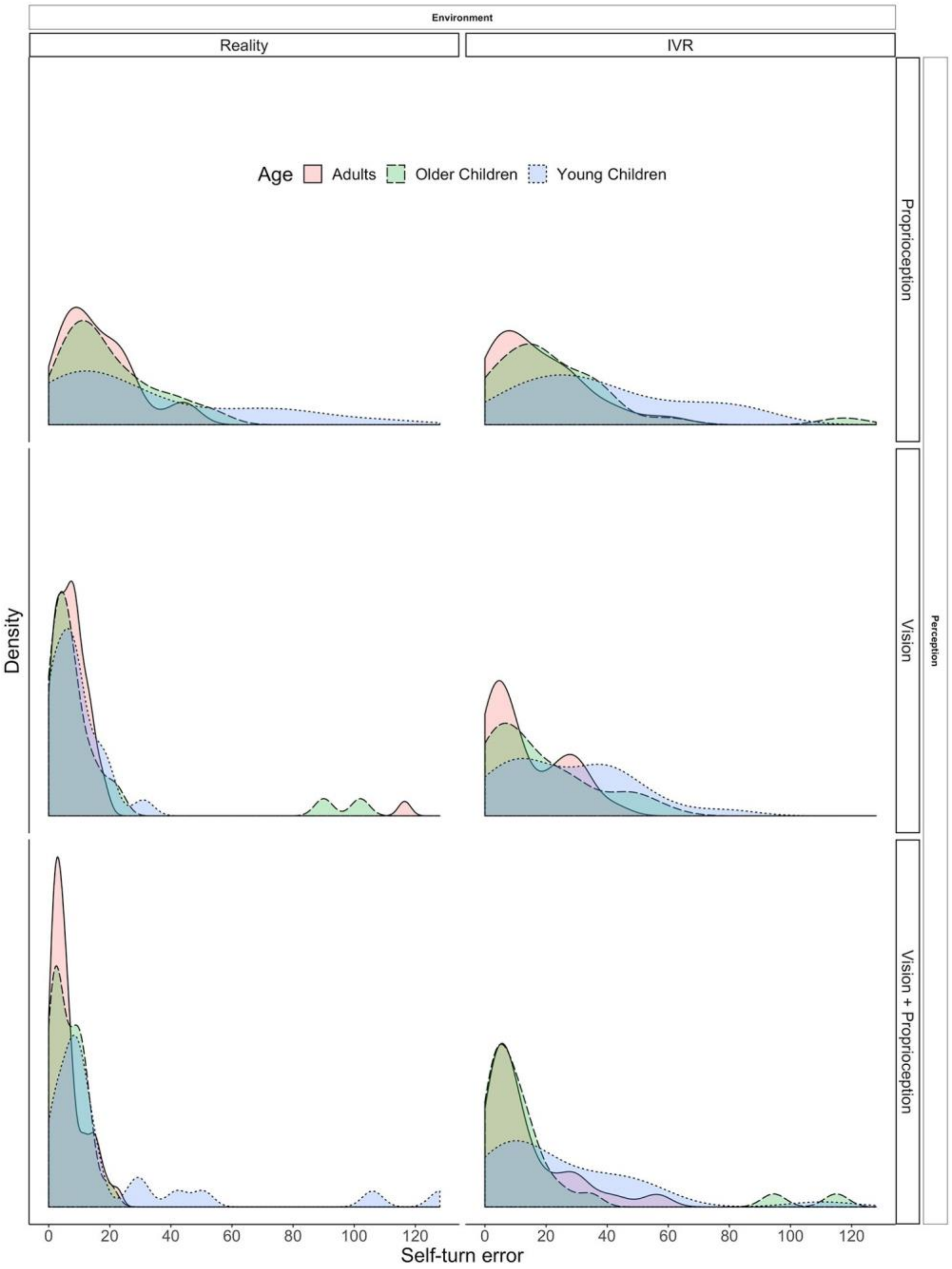


Figure 3.5. Estimated distributions of the observed self-turn errors in the different conditions according to age ($n_{participants} = 49$; $n_{observations} = 578$).

Model comparison and interpretation

Seven different Bayesian generalized mixed-effects models were performed to analyse the data. In each model the dependent variable was the error in the self-turn task. WAIC values and relative WAIC weights of all models are published in the S3 Table of Supplementary materials (Valori et al., 2020). WAIC results indicated that m.2 was the most plausible model for the observed data. It evaluated the 2-way interaction effect between

Perception and Environment conditions and had the lower WAIC value (WAIC = 4345.3) and a probability of being the best of .67.

In order to interpret the effects of model m.2, 95% Bayesian Credible Intervals (BCI) of the parameters posterior distribution were evaluated (see S4 and S5 Tables of Supplementary materials (see S4 and S5 Tables of Supplementary materials, Valori et al., 2020). Ninety-five percent BCI represent the range of the 95% most credible parameters values given the prior distribution and the observed data. Thus, an effect is considered plausible if the value zero is not included in the 95% BCI, whereas if the value zero is included in the 95% BCI, it is interpreted as not plausible.

Self-turn error was moderated by Amplitude, by Age, and by the interaction between Perception and Environment conditions. On the contrary, the direction of rotations seems to have no effect on the participants' performance (*β* = .10; 95% BCI = -.04; .23).

To evaluate the model fit (i.e., the model's ability to explain the data) we used a Bayesian definition of R-squared to estimate the proportion of variance explained. The estimated value of Bayesian R-squared for the model m.2 is.26 (95% BCI = .19; .34), that is the model explains 26% of the variability of the data.

Rotation amplitude. Self-turn error was moderated by Amplitude (*β* = .22; 95% BCI = .14; .29), for which increasing rotation amplitude is associated with a worse performance (Figure 3.6).

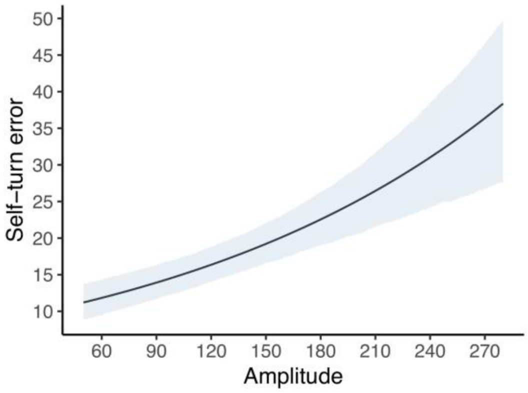


Figure 3.6. Predicted mean of self-turn error according to amplitude ($n_{participants}$ = 49; $n_{observations}$ = 578). The line represents the mean value, the shaded area the 95% BCI values.

Group age. To evaluate the role of Age, the distributions of predicted mean values for the three groups were considered (Figure 3.7). The predicted mean error for adults was 12.8 degrees (95% BCI = 10.6; 15.1), for older children was 15.5 degrees (95% BCI = 12.1; 19.2) and for young children was 24.8 degrees (95% BCI = 19.3; 30.8). Bayesian pairwise comparisons (i.e., predicted score differences between groups) showed that over- all, young children are expected to make more self-turn errors than adults (95% BCI = 6.3; 18.2) and also more than older children (95% BCI = 2.8; 16.0). However, we cannot state that older children are expected to make more self-turn errors because the 95% BCI of the difference includes the value zero (95% BCI = -1.4; 6.9).

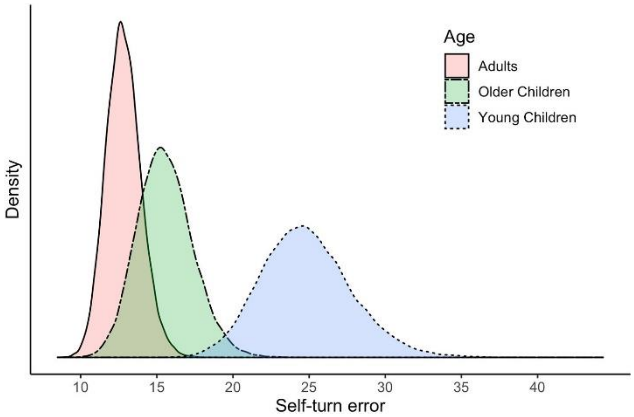


Figure 3.7. Distributions of the predicted means of self-turn error according to age. ($n_{participants}$ = 49; $n_{observations}$ = 578).

Perception and environment. To interpret the interaction between the Perception and Environment conditions, the distributions of predicted mean values for all six conditions were considered (Figure 3.8). BCI values are reported in S5 Table (see Supplementary materials, Valori et al., 2020). In the Reality conditions, the predicted mean error for proprioception was 22.4 degrees (95% BCI = 18.0; 27.2), for vision was 11.3 degrees (95% BCI = 9.0; 13.9) and for vision + proprioception was 9.8 degrees (95% BCI = 7.8; 12.0). In the IVR conditions, the predicted mean error for proprioception was 24.3 degrees (95% BCI = 19.3; 29.2), for vision was 18.0 degrees (95% BCI = 14.4; 21.8) and for vision + proprioception was 17.8 degrees (95% BCI = 14.2; 21.7). Bayesian pairwise comparisons (i.e., predicted error differences between conditions) showed that in both Reality and IVR, participants are expected to make more self-turn errors when they rely only on proprioception than when they can use only vision (Reality: 95% BCI = 6.5; 15.8; IVR: 95% BCI = 0.9; 11.7) or vision + proprioception (Reality: 95% BCI = 8.0; 17.2; IVR: 95% BCI = .08; 11.7). In addition, in both environments there is no difference between the use of vision and vision + proprioception (Reality: 95% BCI = -1.4; 4.4; IVR: 95% BCI = -4.3; 4.9). Moreover, comparing IVR to Reality conditions, results show that while wearing the HMD the self-turn errors increase when participants rely only on vision (95% BCI = 2.8; 10.6) or on vision + proprioception (95% BCI = 4.3; 11.9). On the other hand, participants are not expected to make more errors than in Reality when they rely only on proprioception (95% BCI = -4.3; 7.5).

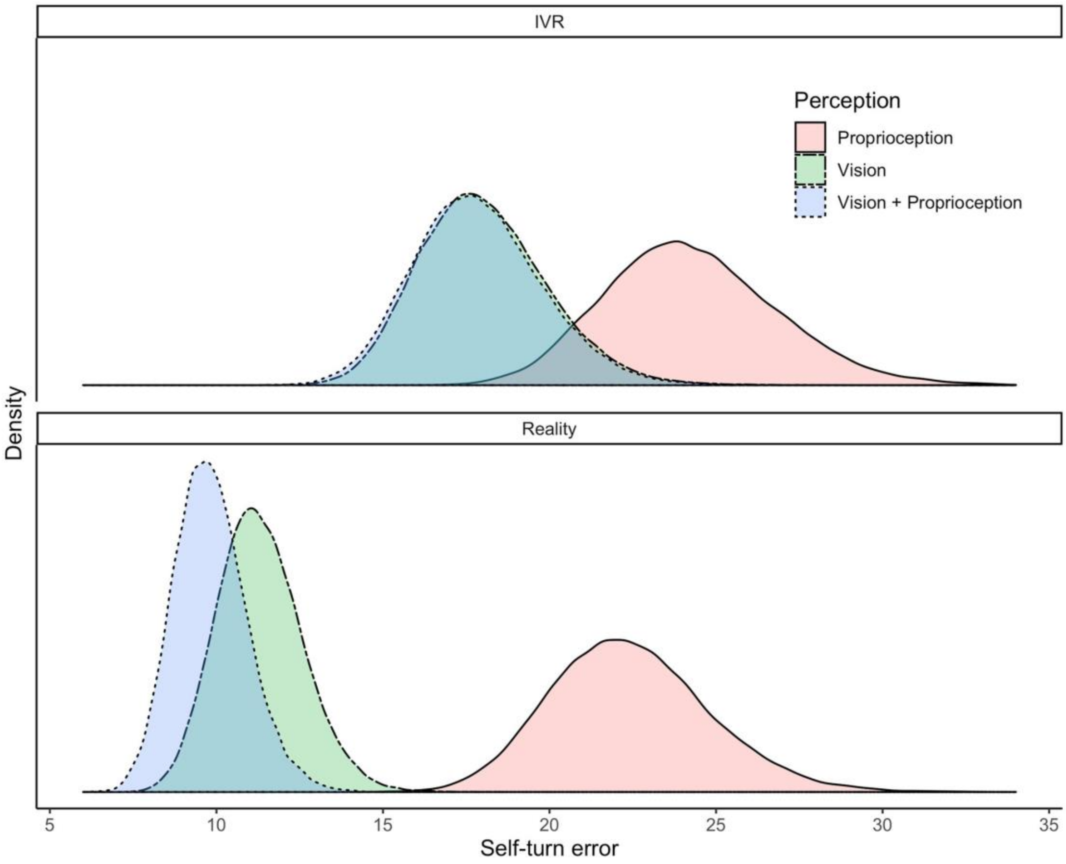


Figure 3.8. Distributions of the predicted means of self-turn error according to the different conditions ($n_{participants} = 49$; $n_{observations} = 578$).

Effect size. To quantify the differences between the various age groups and conditions, we expressed the effects as the ratio between the two scores of the comparison of interest. Thus, for example, young children are expected to make 88% more errors than adults and 58% more errors than older children. Considering the Reality environment conditions, when using only proprioception participants are expected to make 92% more errors than when they rely only on vision and 118% more errors than when using vision + proprioception. Considering the IVR conditions, when using only proprioception participants are expected to make 34% more errors than when they rely only on vision and 35% more errors than when using vision + proprioception. Moreover, comparing IVR to the Reality condition, in IVR participants are expected to make 56% more errors when using only vision and 75% more when using vision + proprioception.

3.3.4 Discussion

This experiment explored the extent to which visual information aids self-location accuracy across the lifespan, and specifically in three developmental groups: 4–- 8-year-old children, 9–15-year-old children, and adults. Moreover, the experiment assessed whether HMD-delivered IVR affects accuracy. As expected, we found a main developmental trend in the improvement of self-location across conditions. We found differences between the young child group (4–8 years old) and the older child and adult groups (9–15 and 20–43 years old), with this youngest group showing lower self-location accuracy than the two older groups. This indicates that self-location development predominantly takes place in the first eight years of life. In line with our hypotheses, we also found an interaction effect between Perception and Environment. Our findings indicate that accuracy was markedly impaired when participants could rely only on proprioceptive input, regardless of the environment. In the conditions which forced participants to rely solely on proprioception by removing all visual information, all groups were less accurate than in conditions where visual information was provided, regardless of the proprioceptive salience of this visual information. This finding is consistent with the assertion that visual and vestibular information combine with proprioceptive information to allow accurate self-motion (Cullen, 2012). Moreover, it indicates that typically developing child and adult populations rely specifically on vision to calibrate proprioception in order to accurately locate themselves in space. Regarding the role of different visual landmarks, no differences were found between vision + proprioception and vision only conditions, that is, conditions in which participants could view all aspects of the real or virtual room versus conditions in which participants only saw a visual texture of randomly placed clouds but were unable to see proprioceptively informative visual cues such as the corners of the room or their body.

Moreover, IVR, compared to Reality, disrupted self-location only when visual input was provided (vision + proprioception and vision only conditions). There were no differences between IVR and Reality in only proprioception (blind) conditions. This allows us to exclude the possibility that wearing the HMD alone, and the corresponding weight and head restriction, might have disrupted self-location. We did find that performance worsened in IVR conditions where visual information was available relative to corresponding reality conditions. The way in which the HMD delivers visual information has a complex (and essentially unknown) effect on self-motion perception and the kinematics of movement (Powell & Stevens, 2013). Factors such as display type, field of view, visual content (peripheral cues, high-low visual contrast, etc.), temporal lag between the user's action and the HMD's reaction, and so on could be the means by which IVR disrupts self-location through vision. This is an important finding, given that few IVR experiments have considered that performance may be affected simply due to the use of HMD-delivered IVR. Many previous IVR experiments seem to implicitly assume that performance in IVR constitutes an appropriate corollary for real-world performance, but our findings indicate that this may not be the case. Despite this HMD effect, our results provide evidence that IVR may be a useful means of studying multisensory integration and accuracy. Indeed, the same general Perception trend in self-location accuracy (proprioception only, vision only, vision + proprioception) was found both in IVR and Reality environments.

In contrast to our expectations, we failed to find any Age x Perception interaction effect. We expected that adults would be more affected by disrupted proprioception than children, but this was not the case. Various aspects of the experimental design should be taken into account to discuss this result. Firstly, our manipulation of the multisensory input in different conditions could have been insufficient to uncover the expected differences. We found the expected general trend of reduced accuracy in vision conditions relative to vision + proprioception conditions. However, this difference failed to reach a meaningful magnitude. As previous studies highlight, relative dominance of visual and proprioceptive input and visuo-proprioceptive integration are task-dependent (Adams et al., 2018; Bremner, Lewkowicz, et al., 2012). For example, proprioception has been reported to be more precise in the radial (near-far) direction and vision in the azimuthal (left-right) direction (Snijders et al., 2007; van Beers et al., 1999, 2002). It could be suggested that our azimuthal task was too dependent on vision to allow the detection of differences that were due to the disruption of proprioception. In fact, our "only vision" conditions were designed to disrupt proprioception by removing proprioceptively informative visual cues (the room corners and participant's body), while still providing proprioceptively uninformative visual landmarks (surrounding texture of clouds). It could be the case that proprioceptively uninformative visual landmarks are sufficient to allow accurate performance in our task. In addition, we based our research on similar studies that used a standing self-turn paradigm (Jürgens & Becker, 2006; Wang & Spelke, 2000). We utilized a seated self-turn paradigm so that we could use the chair position as a precise and consistent measurement point of reference, independently from the participants' individual postures which may vary. However, this seated task could be less challenging than a standing one, resulting in a ceiling effect, particularly for older children and adult groups. Moreover, we failed to find any Age x Environment interaction, which prevents us from providing evidence on age-dependent user-IVR interactions. Increased knowledge in this area could have meaningful implications for fields such as IVR education, rehabilitation, and therapy, shedding light on when and how IVR interventions could be effective at different developmental stages. Future research could focus specifically on children younger than eight years old to explore the early development of visuo-proprioceptive integration, as well as potentialities and threats related to IVR use.

We also found a main effect of rotation Amplitude, with accuracy consistently decreasing as rotation amplitude increased. It is possible that this effect is specifically due to working memory constraints (Waddington & Adams, 1999; Weerakkody et al., 2008). In our task, accuracy largely depends on participants' ability to actively maintain the start position in memory, and it may be the case that differences in working memory capacity across age groups and conditions could have affected results. As the study of the effect of rotation amplitude was not a primary goal of this work, we did not explore interaction effects between Amplitude and other variables (i.e., Age, Perception, or Environment). Remarkably, working memory limitations have been found up to pre-adolescence (Pickering, 2001) and age-related lower visuo-spatial working memory capacity can be associated with lower accuracy in body position-matching tasks (Goble et al., 2012). A more in-depth look is also necessary to investigate potential implications of both the proprioceptive and visual sensory register and its influence on performance, as individual sensory registers have been shown to affect working memory in multisensory environments (for a review, see Quak et al., 2015). In a following study, we have further investigated the memory effect of the rotation amplitude (namely, the amount of information to be encoded and reproduced) of our self-turn paradigm, with findings suggesting that the encoding of own body location is facilitated when vision and proprioception are optimally integrated (Bayramova et al., 2021).

This study opened intriguing perspectives for future research, despite having some limitations. Firstly, the experimenter manually rotated the participant, so although experimenters were trained to keep a similar speed and method of rotating, the rotation velocity was not perfectly consistent across trials and participants, potentially influencing participants' performance as in previous research (Jürgens & Becker, 2006). Another limitation concerned the manipulation of visual conditions distinguishing between "only vision" and "vision + proprioception". As we found no meaningful differences between these two Perception conditions, the "only vision" condition could have been insufficient to isolate vision and disrupt proprioception as we aimed to. It would be interesting to see how similar but more effective manipulations of visual information aimed at disrupting proprioception would affect performance. Moreover, the age groups could be too broad to clearly show early developmental trends and changes. Lastly, our self-location task (i.e., rotating on a chair) does not reflect the most common everyday situations in which the localisation of one's body in space is called into play (e.g., walking, running). Further research has to be conducted using a variety of naturalistic and ecologic tasks to acquire more generalisable results.

Data Availability: All data files and SM are available from the OSF public repository at the following URL (https://osf.io/b3qd4/).

3.4 Increased reliance on proprioception in ASD (Experiment B)

Abstract. When learning and interacting with the world, people with Autism Spectrum Disorder (ASD) show reduced use of vision and enhanced reliance on body-based information. As this atypical profile is associated with motor and social difficulties, interventions could aim to reduce the potentially isolating reliance on the body and foster the use of visual information. To this end, head-mounted displays (HMDs) have unique features that enable the design of Immersive Virtual Realities (IVR) for manipulating and training sensorimotor processing. The present study assessed feasibility and offers some early insights from a new paradigm for exploring how children and adults with ASD interact with Reality and IVR when vision and proprioception are manipulated. Seven participants (5 adults, 2 children) performed a self-location task in two environments (Reality and IVR) for each of three sensory conditions (Only Proprioception, Only Vision, Vision + Proprioception) in a purpose-designed testing room and an HMD-simulated environment. The study indicated good feasibility of the paradigm. Preliminary data visualisation suggested the importance of considering inter-individual variability. The participants in this study who performed worse with Only Vision and better with Only Proprioception seemed to benefit from the use of IVR. Those who performed better with Only Vision and worse with Only Proprioception seemed to benefit from Reality. Therefore, we invite researchers and clinicians to consider that IVR may facilitate or impair individuals depending on their sensorimotor profiles.

3.4.1 Participants

For this exploratory study, we recruited 4 male children (8−13 years old; M = 8.7; SD = 1.2) and 5 male adults (23−39 years old; M = 28.8; SD = 8.3) with a diagnosis of ASD (see Table 3.3 for demographic information). Data collection took place from May to July 2019, as part of a collaborative project between a clinical centre in northern Italy, which provides occupational activities to adults with ASD, and a public music school, which offered facilities for the research project. Adults were offered voluntary participation in the study by their occupational therapists. Children and their families were recruited through flyers at the music school. Participants' ASD diagnosis was confirmed by certificates provided by psychologists working at the clinical centre and children's parents (in this case, certificates were issued by the local child neuropsychiatry hospital). The experiment was explained to all parties and informed consent was obtained from adult participants, children's parents, and psychologists. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of psychology research, University of Padova.

Table 3.3. Participants' demographic information.

Participant	**Age**	**Diagnosis**
C1	8	ASD, ADHD[1], ODD[2], Dysgraphia
C2	8	ASD, Mild ID[3]
C3	10	ASD, Mild ID
C4	13	ASD, Moderate ID
A1	36	ASD, Severe ID
A2	26	ASD, Mild ID
A3	20	ASD, Mild ID
A4	23	ASD, Mild ID
A5	39	ASD, Severe ID

[1] ADHD (Attention Deficit Hyperactivity Disorder); [2] ODD (Oppositional Defiant Disorder); [3] ID (Intellectual Disability).

3.4.2 Descriptive and graphical analyses

Given the novelty of the research questions and paradigm, as well as the small size and profound heterogeneity of the sample we were able to recruit, the data were described through descriptive statistics and graphical representations, and results were interpreted from an exploratory perspective. As some statisticians have recently pointed out, "rather than focusing our study reports on uncertain conclusions, we should thus focus on describing accurately how the study was conducted, what problems occurred, what data were obtained" (Amrhein et al., 2019, pag. 262). Therefore, no inferential claims, but preliminary and cautious considerations will be presented. All the analyses and graphical visualisations were conducted using the software R (R Core Team, 2020, version 3.6.1).

Start, end, and return position data were manually coded by two independent raters of the video recordings. Inter-rater reliability was assessed via intra-class correlation (ICC). The intra-class correlation index (ICC) estimates an ICC = 1, with a 95% confidence interval being 1 < ICC < 1. This nearly perfect inter-coder agreement derives from the small mean difference between the two coders' values within the huge range of possible values (0–360). The mean difference between coder A and coder B is minimal ($M_{A\text{-}B} = 0.5$).

3.4.3 Results

The first aim of this pilot is to evaluate the feasibility of the experimental procedure with children and adults, even where severe conditions are present. One of the children ("C3", 10 years old) enjoyed the swivel chair and played with it, rotating himself without complying with any verbal instruction provided. Another child ("C4", 13 years old) disliked the testing room and refused to enter it to become familiar with the environment. Data from those participants could not be collected, and the descriptive analyses therefore include 7 participants.

The seven participants included here demonstrated that they understood the instructions and task after a short training period. All participants readily wore the HMD. Among them, the two children required several breaks and verbal praise for remaining focused on the task. One of them ("C1") was initially scared by the closing of the room door and by conditions performed in darkness, although he did decide to continue with the experiment. The other ("C2") found the task boring and needed to be continuously motivated. One adult ("A4") performed only the R_P condition and then exited the room, quitting the experiment. Due to technical issues, another adult ("A1") performed the R_VP condition twice and did not perform the IVR_VP condition. The final dataset consisted of 24 observations from children and 50 observations from adults.

The mean self-turn error in the children's sample was 28.4 degrees (SD = 32.3), while in the adults' sample, it was 34.3 degrees (SD = 35.6). The distributions of the observed values have positive skewness, as visualised in Figure 3.9 and 3.10.

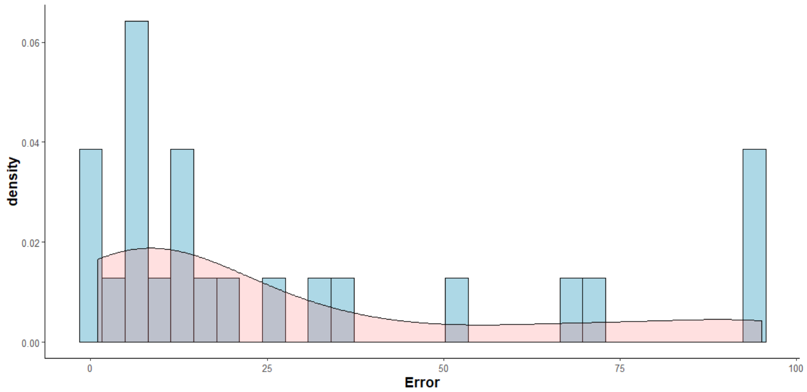


Figure 3.9. Distributions of the observed self-turn error. Children ($n_{participants} = 2$; $n_{observations} = 24$).

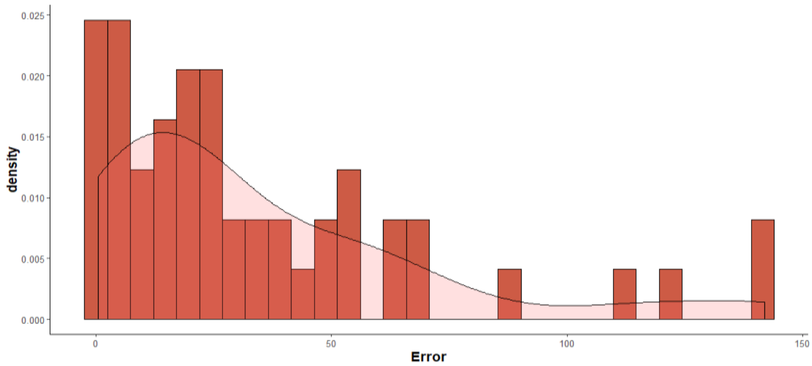


Figure 3.10. Distributions of the observed self-turn error. Adults ($n_{participants}$ = 5; $n_{observations}$ = 50).

Exploring the main effect of experimental conditions, it is informative to look at individual observations, where we can appreciate that there is heterogeneity of performance (Figure 3.11).

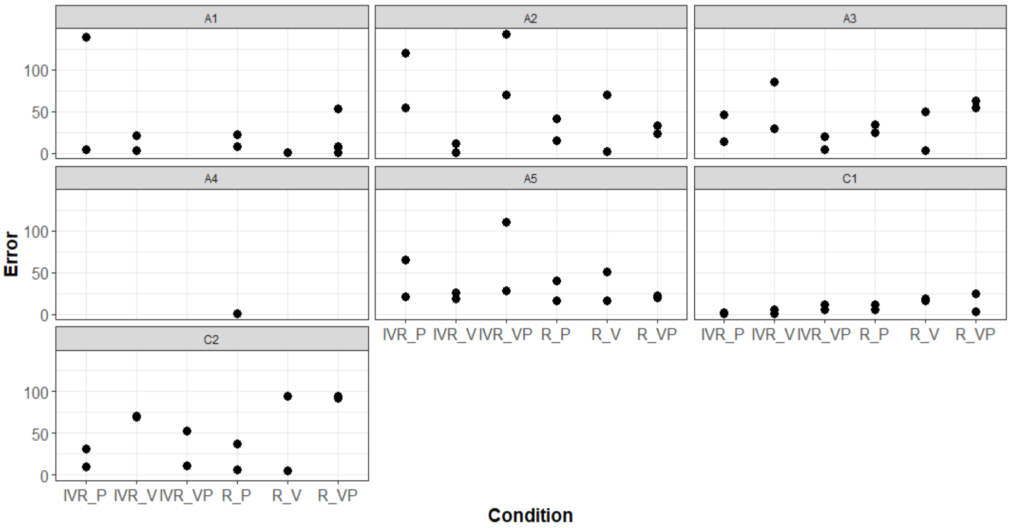


Figure 3.11. Self-turn error of single observations collected by each participant among conditions ($n_{participants}$ = 7; $n_{observations}$ = 74).

Means and standard deviations of self-turn error according to age group and the experimental condition are reported in Table 3.4.

Table 3.4. Means and (standard deviations) of self-turn error according to age group and the experimental condition ($n_{participants} = 7$; $n_{observations} = 74$).

Age Group	**Condition**					
	R_P	**R_V**	**R_VP**	**IVR_P**	**IVR_V**	**IVR_VP**
Children	15.1 (14.8)	33.6 (40.7)	53.9 (47)	10.8 (14.1)	36.6 (38.9)	20.4 (22)
Adults	20.2 (14.9)	24.3 (28.2)	28.4 (21.9)	58.1 (49.2)	24.4 (26.9)	62.5 (55)

Looking at the marginal role of perception and environment factors, we notice that those participants who perform worse in Only-Vision conditions and better in Only-Proprioception conditions seem to benefit from IVR ("A3"; "C1"; "C2"). Those who perform better with Only-Vision and worse with Only-Proprioception seem to be facilitated in Reality ("A1"; "A2"; "A5") (Figure 3.12 and 3.13).

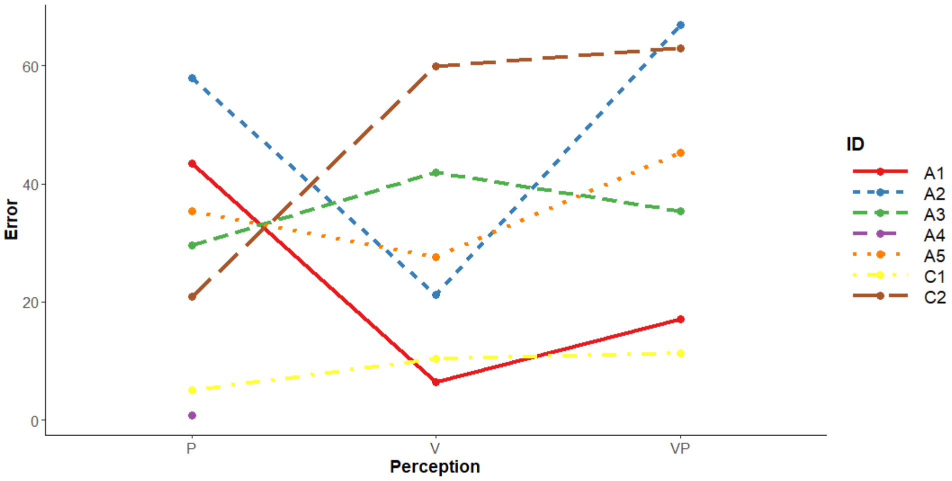


Figure 3.12. Mean error made by each participant according to perception (marginalised over the other variables).

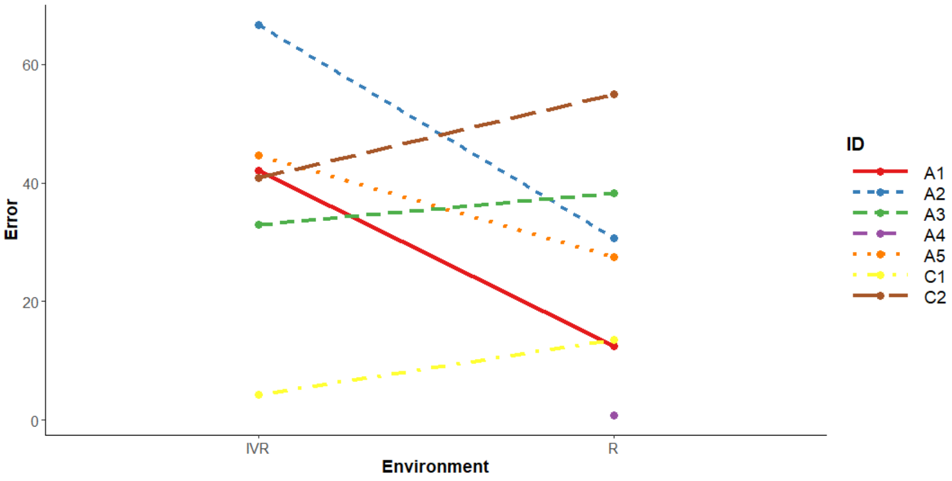


Figure 3.13. Mean error made by each participant according to environment (marginalised over the other variables).

Trials were equally distributed among the two possible directions (N = 37 trials in clockwise and counterclockwise directions), which do not appear to affect the self-turn error ($M_{clockwise}$ = 32.5; $SD_{clockwise}$ = 34.3; $M_{counterclockwise}$ 32.3; $SD_{counterclockwise}$ = 35.1). The amplitude of passive rotations ranges from 67.5 to 205 degrees (M = 137.2; SD = 38.5). Although the effects of amplitude are not of main interest for this study, consistently with previous findings from Experiment A (Valori et al., 2020), this variable is positively correlated with self-turn error. This association seems to be qualitatively different among conditions and age groups (Figure 3.14 and 3.15). Increasing amplitude appeared to reduce children's accuracy to the greatest extent in Only-Vision conditions performed in both Reality and IVR, while it reduced adults' accuracy to the greatest extent in the Vision + Proprioception condition performed in IVR. Further investigation could specifically address this topic.

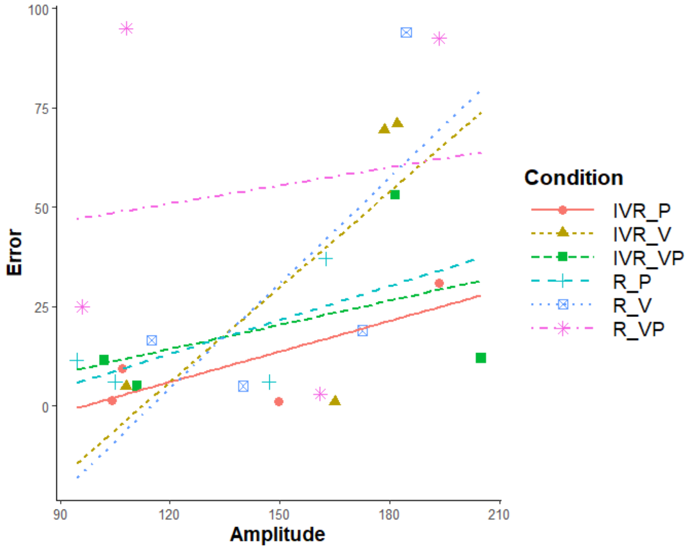


Figure 3.14. Regression lines of self-turn error according to rotation amplitude in each condition. Children ($n_{participants}$ = 2; $n_{observations}$ = 24).

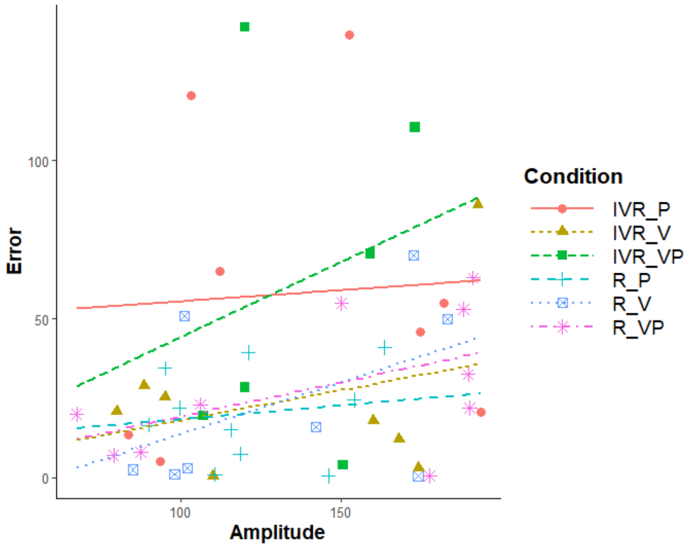


Figure 3.15. Regression lines of self-turn error according to rotation amplitude in each condition. Adults ($n_{participants}$ = 5; $n_{observations}$ = 50).

3.4.4 Discussion

This second study offered important initial insights regarding IVR research into the use of vision and proprioception in adults and children with ASD. With respect to feasibility, although some participants were not keen to wear the HMD or comply with the task instructions, also participants with greater behavioural and communicative difficulties accepted the use of HMD. However, participants' performance tended to fluctuate across within-condition trials and as such, average scores could make it difficult to detect an individual's best performance. A detailed evaluation of within-participant outlying performances could be run to detect the best performance the individual can show, rather than an average. Individual factors such as emotional state, motivation, skills of behavioural management, and fluctuations in attention might have contributed to intra- and inter-individual variability. Future research could adapt the experiment to build a more engaging, game-like activity and include frequent rewards for participation to create a more attractive testing environment for participants.

As we only presented preliminary data from a small sample, we make no inferential claims here. However, we did find this data informative for modest and cautious considerations. First, this methodology could show individual differences in the sensory conditions that facilitate self-location. Moreover, we could distinguish between the individuals that may benefit more or be more impaired by using HMDs. Within the present sample, those who were facilitated by moving when proprioception was available, and no vision was present also benefited from IVR. We do not intend to generalise this result to the whole population of individuals with ASD, but we strongly suggest that researchers and clinicians keep in mind that this technology can either facilitate or impair individuals depending on their profiles. For example, some individuals with ASD show an over-reliance on proprioception and hypo-reliance on vision (Haswell et al., 2009; Izawa et al., 2012; Morris et al., 2015). This perceptual strategy might not only lead to impaired motor skills in ASD, but also seems to be related to core features of social and communicative difficulties. Learning in IVR could be particularly effective for individuals who, in real-life, have reduced reliance on exteroception and greater reliance on bodily sensations. The visuo-proprioceptive features of IVR can help them focus on external information, thus aiming at promoting learning from the external world. We can speculate that the limited use of external stimuli to calibrate internal body-based information might lead to motor difficulties and stereotypies. Restricted repetitive behaviours and interests can reduce the individuals' learning opportunities and interfere with development (Cunningham & Schreibman, 2008).

Currently, too little is known about these mechanisms in ASD. As of June 2022, when searching for "Vision" AND "Proprioception" AND "Autism", Scopus provides only 29 documents. Following the first experimental study published in 1983 (Masterton & Biederman, 1983), there was a gap until 2005 for the next theoretical one (Vakalopoulos, 2005). Further experimental research is needed to shed light on this domain-general sensorimotor mechanism that potentially has huge implications for development. The fundamental question of what effects virtual experiences have on people's perception and actions is still open. Studies with appropriate sample size should explore the effect of relevant factors such as age, sensorimotor and cognitive skills on individual variability. More importantly, even if we had a deep understanding of what happens in IVR, we would still need to facilitate the transfer of learning to reality. In fact, the ultimate goal of any intervention is to support people's abilities to optimally interact with their everyday contexts, thus promoting their well-being and quality of life.

Data Availability: All data files are available from the OSF public repository at the following URL (https://osf.io/dyf2t/?view_only=746a9829df784d4f9be1312f4e0aa716).

4 Do we need Agency or Reward? (Study 2)

4.1 Narrative review of behavioural and neural evidence

Abstract: Our ability to perform voluntary actions and make choices is shaped by the motivation from control over the resulting effects (Agency) and from positive outcomes (Reward). We offer an overview of the distinct and common behavioural and neural signatures of Agency and Reward. We discuss their typical and atypical developmental trajectories, thus focusing on Autism Spectrum Disorder (ASD), which is characterised by neurodiverse processes underlying action selection. We propose that reduced sensitivity to Agency and Reward in ASD might be related to atypical multisensory processes and motor planning, with potential for understanding restricted and repetitive behaviours. We emphasise the limitations of the existing literature, and the prospects for future research. Understanding the neurocognitive processes that shape the way people with ASD select actions and perceive their outcomes is essential to support not only learning, but also and especially individuals' volition and self-determination.

4.1.1 A distinction between Agency and Reward

Our ability to perform actions and make choices is fundamental in our daily interaction with the world of physical and social objects. The link between a given action and its effects in the surrounding environment modifies our behaviour, and the underlying cognitive and neural processes, with meaningful effects on our acting, thinking, and learning. We can distinguish between the role played by the mere perception of control over the effects of one's actions (Agency) and that attributable to positive outcomes (Reward). The comprehension of how these two different mechanisms give rise to a person's actions and choices, allows us to understand how to facilitate not only learning, but also volition and self-determination. This might be crucial for interventions that aim to support learning processes for people with neurodevelopmental conditions whereby action selection processes can be affected.

In everyday life, we perform voluntary, goal-oriented actions for which we hold ourselves responsible. Agency can be defined as the perception of control over one's own actions and the external world and can be traced back to the ability to recognize oneself as the cause of an event (Braun et al., 2018; Haggard, 2017; Moore, 2016). Before action execution, the motor system builds a prediction of its sensory consequences. The cortical connectivity between the frontal areas that plan voluntary movements and the parietal areas that monitor outcomes is fundamental to retrospectively (i.e., after action execution) assess the prediction-outcome match (Haggard, 2017). In case of alterations of the spatial and temporal contiguity between action and effect, the mismatch between predictions and actual outcomes would push the individual to search for an external cause of the event (Farrer et al., 2013; Nobusako, Tsujimoto, et al., 2020). On the other hand, processes in the frontal cortex occurring before the initiation of action operate prospectively and underlie the subjective experience of one's own voluntary action (Haggard, 2017). We sometimes consider ourselves authors of an event, even without being directly responsible for it. Whenever an event turns out to be in line with one's intentions, there is a strong tendency to interpret it as self-generated (Moore, 2016). For example, we use to push the crosswalk light buttons because we expect this to reduce the wait before the green light arrives. When the traffic light turns green, after variable and even prolonged time delays, we attribute this event to our action of pressing the button, although there is no evidence of our role in turning the light green.

Agency arises from both implicit and explicit processes and can be distinguished in Feeling of Agency (FoA) and Judgement of Agency (JoA) (Synofzik et al., 2008). FoA comes from implicit sensorimotor representation and can be considered as the preconceptual component of Agency. Altering the spatial or temporal contiguity between action and effect significantly disrupts this level of Agency (Karsh et al., 2016). On the other hand, JoA consists of explicit recognition of oneself as the cause of an event. It is influenced by personal beliefs, contextual and social information (Synofzik et al., 2008), and insensitive to factors of spatial and temporal contiguity between the action and its outcome (Karsh et al., 2016). Different measures have been employed in literature to capture explicit and implicit Agency. Self-reported measures of explicit Agency come from the person’s answer to the question “Did you do that?” (Haggard, 2017). One of the most widely used implicit measures of Agency is the intentional binding effect that consists in the tendency of agents to perceive the time interval between a voluntary action and a sensory stimulus as shorter than it actually is. More specifically, the onset of the voluntary action is reported later in time and awareness of the sensory feedback is temporally anticipated (Haggard et al., 2002).

At the behavioural and motor level, the Control-Based Response Selection framework (CBRS) proposed that producing effects that are perceived as self-caused facilitates action selection and execution (Karsh & Eitam, 2015). Indeed, the way we plan and control our movements is affected by several cognitive and sensorimotor features of actions (Glover, 2004). We more frequently and faster select response options associated with higher probability of producing an effect, compared to no effect, thus being motivated and facilitated by having control (Karsh & Eitam, 2015). At an implicit level, Agency impacts motor parameters of actions (i.e., reducing reaction times), relies on action-effect temporal contingency (i.e., is disrupted by action-effect delays), and goes beyond individuals’ explicit judgements of Agency (Karsh & Eitam, 2015). In everyday life, it could be that fluently selecting an action makes it more likely that our intentions will be realized, and the expected outcome achieved. Individuals report greater perceptions of control over a given event when prime stimuli allow for more fluent and immediate action selection (Wenke et al., 2010). According to this, habitual actions are accompanied by a strong sense of control and could be therefore sustained by Agency mechanisms. Intriguingly, the motor system might be insensitive to abstract representations of the valence of an effect (i.e., receiving a positive or neutral effect does not change motor parameters of action) (Karsh et al., 2020).

Neural underpinnings of Agency

The neural signatures of Agency involve several areas such as the angular gyrus, the temporo-parietal junction, Supplementary and pre-Supplementary Motor Areas, insula, dorsal medial-frontal cortex and precuneus (Sperduti et al., 2011). Importantly, explicit and implicit Agency are differentiated at the neural level, with different areas being involved. As for explicit Agency, the activation of the anterior insula seems to be particularly related to explicit positive Agency ("that was me"), while the inferior parietal cortex is involved during externally driven action (Farrer & Frith, 2002). Several authors reported an increased activation of the angular gyrus in the inferior parietal lobe during explicit judgment of negative Agency ("that was *not* me") (Farrer et al., 2008; (Miele et al., 2011). A recent meta-analysis of neural correlates of Agency highlighted that subjective judgment of negative Agency is associated with neural activity in the right superior temporal gyrus, left inferior parietal lobule and left middle temporal gyrus, whereas no specific underpinnings of positive Agency were found (Zito et al., 2020).

Implicit Agency seems to specifically rely on the activation of Supplementary Motor Area (SMA) and pre-SMA (Cavazzana et al., 2015; Elsner et al., 2002; Kühn et al., 2013; Moore et al., 2010), which are neural circuits responsible for the preparation, execution, and perceptual monitoring of voluntary actions (Nachev et al., 2007). Two neural signatures of implicit Agency have been studied by previous literature, one relative to action preparation processes (Readiness Potential) and the other referring to the processing of action outcomes (N1 and P2). Indeed, intentional actions are preceded by Readiness Potential (RP), a slow build-up of electric potentials associated with the neural activity involved in voluntary movement preparation (Schurger et al., 2021). Readiness potential involves early and late components: the first one is a negative ongoing activity that starts around 1 s before the voluntary movement, it is generated in the pre-SMA/SMA and related to the intention to move. The second component starts 500 ms before the voluntary movement and it is thought to be a more specific motor preparation activity generated in M1 and premotor cortex. Importantly, RP is modulated by stimulus expectancy. For example, expecting sensory feedback in response to a voluntary movement influences RP amplitude and delays the latency of its onset (Vercillo et al., 2018). In the pre-SMA, RP is associated with the preparatory cortical activity that precedes voluntary actions is closely correlated with outcome binding (Moore et al., 2010). These data support the involvement of SMA in predictive processes and suggest that premotor activity in fronto-parietal areas might play a crucial role in prediction and Agency.

The actual sensory feedback to ones' action is reflected by ERP components that have been associated with processing of action outcomes, such as auditory and visual N1 and P2. These components vary in timing and amplitude in response to stimulus generated by voluntary vs externally generated actions (Aytemur et al., 2021; Vercillo et al., 2018). In addition, some authors suggest an involvement of the cerebellum, the posterior parietal cortex (PPC) (Blakemore & Sirigu, 2003), the extrastriate body area (EBA) and superior temporal sulcus (pSTS) (David et al., 2007; Iacoboni et al., 2001; Leube et al., 2003) in the implicit aspects of Agency. The cerebellum is involved in detecting the discrepancies between predicted and actual sensory consequences of a movement (Blakemore et al., 2001). The PPC is a key area for monitoring the concordance between intended and visual consequence of self-produced action. Finally, the EBA is active during self-generated movements (Downing et al., 2001).

Neural underpinnings of Reward

Our actions are certainly shaped by the valence of their consequences. We prefer to perform actions associated with positive effects, which have a motivational value and can be defined as rewards. The neural substrates of reward (Schuetze et al., 2017) are distinguished by the ones devoted to Agency and have been studied for long (Robbins & Everitt, 1996). The ventro-medial prefrontal cortex (vmPFC) is involved in the representation of a stimulus value (Bartra et al., 2013) and plays a critical role in encoding the expected outcome value of different actions. The medial orbito-frontal cortex (mOFC) is specialized in encoding the magnitude and the value of positive and negative rewards and primary reinforcers (Bechara et al., 2000), aids in decision-making processes based on costs-benefit gradients (de Lafuente & Romo, 2006), and has a key role in forming associations between unconditioned stimuli and primary reinforcers (Dichter, Felder, et al., 2012). The anterior cingulate cortex (ACC) is associated with reward anticipation (Dillon et al., 2008) and in mediating cognitive control in uncertain context (Brown & Braver, 2005). The ventral striatum (VS) acquires dopaminergic projection from the ventral tegmental area and is important in reward anticipation and processing of error feedback during learning (O’Doherty et al., 2003), including social learning (Bray & O’Doherty, 2007). The nucleus accumbens (NAc) links reward to behaviour, reward related decision-making and encoding motivational feedback (Balleine et al., 2007). Limbic structures, including the amygdala, that are critical for social cognition and particularly for face processing are also involved when reward stimuli have a social nature (Adolphs, 2010).

Separate cortical processes are devoted to anticipating the reward value or its probability. While reward value (e.g., gain or loss) is associated with a prefrontal P300 ERP component, reward probability is associated with a late prefrontal ERP (Schutte et al., 2019). Moreover, distinct brain mechanisms underlie reward anticipation and consumption. While anticipatory mechanisms seem to be similarly involved for non-social and social rewards, the consumption of different types of positive outcomes may elicit different neural activities. Social rewards are mainly associated with amygdala activation, whereas monetary rewards are particularly associated with the thalamus activity (Rademacher et al., 2010). Other authors found that the magnitude of both monetary and social rewards was related to the activation of the ventromedial prefrontal cortex and striatum (Lin et al., 2012).

In sum, research has extensively investigated Agency and reward as separate mechanisms, showing that they contribute differently to people's action selection, shape distinct aspects of behaviour and emerge from distinct neural bases.

4.1.2 Bridging mechanisms

Although the literature has investigated Agency and Reward separately, these mechanisms are closely interconnected during naturalistic interactions with the outside world. Indeed, when an action that the agent perceives as voluntary has a consequence that is interpreted as self-caused and also positive, the two experiences are concomitant. For instance, people are biased in attributing positive outcomes to themselves (van Elk et al., 2015), suggesting that the motivation derived from the sense of Agency and that derived from the positive valence of the outcome are indeed interconnected. Implicit (intentional binding) and explicit Agency increases when people have a higher number of alternatives to select, they can make free (vs. instructed) choices, the action outcome is positive (Barlas et al., 2018; Barlas & Obhi, 2013). Other researchers found that positive outcomes retrospectively enhance implicit Agency, which is particularly true when the outcome valence is unexpected or unpredictable (Christensen et al., 2016).

Neural evidence suggests that Agency and Reward might act similarly in facilitating people's selection of actions, specifically influencing the motor planning phase. Preparatory neural activity in motor and premotor areas anticipates voluntary movements and contributes to Agency (Moore et al., 2010), which results in a sense of control that makes actions faster (Karsh & Eitam, 2015). Similarly, there is evidence that monetary rewards make actions faster, with reward magnitude being associated with the activation of pre-SMA and SMA brain areas, potentially promoting motor planning prior to action execution (Adkins & Lee, 2021). Reward signals have been also found in monkeys' dorsal premotor and primary motor neurons (Ramkumar et al., 2016). In addition, the reward system activation increases when individuals receive self-caused vs random rewards (Tsukamoto et al., 2006), and can make not simple actions but proper choices (Hassall et al., 2019). This evidence suggests that Agency might modulate the way rewards are processed, thus fostering reinforced learning.

4.1.3 A developmental journey

The mechanisms underlying and associated with Agency and Reward are subject to specialization and tuning throughout child development and may undergo atypical trajectories under specific neurodevelopmental conditions. Decades of research demonstrated that infants learn through embodied sensorimotor contingencies, thus using their bodies to produce effects in the external world (Sen & Gredebäck, 2021), with behavioural and neural markers of action-effect binding at around 3 months of age. After disrupting the action-effect contingency of infants' movements, some of them showed EEG mismatch negativity and a reduction in their movement behaviour, which respectively underpin violation of expectation and behavioural extinction, potentially related to reduced Agency (Zaadnoordijk et al., 2020). Moreover, infants at around 9 months of age are aware of the association between actions and effects, thus responding faster to events that they previously had actively produced than to action-independent events (Verschoor et al., 2010). Other authors question the appropriateness of these methods for studying the sense of Agency in preverbal children and point out that the mere association between stimulus and response is not sufficient to constitute minimal sense of Agency, which should be distinguished from reinforced learning (Bednarski et al., 2022). Additional studies have investigated implicit Agency in school-aged children, who showed reduced temporal binding than adults (Cavazzana et al., 2014, 2017). Other authors found adult-levels of intentional binding in children from 6 years of age (Lorimer et al., 2020).

Notably, the threshold for detecting temporal biases between action and consequence might change during development. From the age of 4 to 15, there is a progressive decrease in the minimum temporal delay necessary for the person to be aware of the action-effect alteration (Nobusako et al., 2018). Overall, the temporal interval within which multisensory stimuli are likely to be perceptually bound (namely, multisensory temporal binding window) gradually decreases up to adolescence (Hillock-Dunn & Wallace, 2012). The time window for intentional binding seems to be associated with manual dexterity and extended in children with Developmental Coordination Disorder (DCD) (Nobusako, Tsujimoto, et al., 2020). In this population, reduced implicit Agency was associated with depressive tendency, thus contributing to children's well-being (Nobusako, Tsujimoto, et al., 2020). Contradictory findings come from adolescence, whereby researchers found both reduced implicit Agency compared to children and adults (Aytemur & Levita, 2021), and greater experience of implicit Agency during mid-adolescence, which was mediated by a neural over-suppression of action outcomes (sensory attenuation), and over-reliance on motor preparation (late readiness potential) (Aytemur et al., 2021). We can conclude that different sensitivity in detecting temporal biases could contribute to differences in implicit mechanisms of Agency and impact on broader dimensions of child development and well-being.

As far as the explicit judgment of Agency, school-aged children and adults seem to be equally accurate in estimating their control over an event as a function of action-outcome congruency (van Elk et al., 2015). However, top-down processes such as metacognition change across the lifespan and affect children's explicit Agency up to later childhood. In particular, the outcome valence influences our causal attributions. A self-attribution bias that over-attributes positive outcomes to oneself and negative outcomes to external factors is pervasive in the general population but greater in children than adults (van Elk et al., 2015). For instance, children from 8 to 10 years-old accurately judged a negative outcome as not self-caused but thought to be responsible for positive outcomes they did not actually cause (Metcalfe et al., 2010b). Overall, school-aged children are happier when allowed to make choices among options, rather than being given only one option, thus being motivated by explicit Agency (Castelli et al., 2017). However, in case of a negative outcome, children's emotions might worsen especially after self-made choices compared to having no choice (Castelli et al., 2017). Moreover, children's academic success is positively associated with their judgment of control, or explicit Agency (i.e., believing that they know how to influence success and failure outcomes in their academic life) (Martin, Burns, et al., 2017). Crucially, the explicit Agency is built on high-level cognitive processes (e.g., expectations, beliefs, attitudes), which may be affected by some neurodevelopmental disorders. For instance, people with Attention Deficit and Hyperactivity Disorder (ADHD) show reduced self-attribution bias (Mezulis et al., 2004), which plays a fundamental role in their well-being (Martin, Cumming, et al., 2017). Moreover, children with ADHD might be more sensitive to their action outcomes valence, with an enhanced sensitivity to positive and negative outcomes and underlying atypicalities in neural reward circuits (Luman et al., 2010; Marx et al., 2021; van Meel et al., 2005).

The nature of rewards may constitute a different degree of motivation depending on the context and the individual characteristics and age of the actor. Toddlers more frequently orient their attention toward social stimuli compared to non-social stimuli that respond to their gaze (Vernetti et al., 2018). Later in childhood, monetary incentives might have stronger reinforcing value as compared to social incentives when children perform cognitive tasks (Kohls et al., 2009). Finally, adolescence might be a critical period whereby social rewards are particularly valued (Foulkes & Blakemore, 2016). However, different personality traits seem to mediate to what extent a child benefits from different types of rewards, with higher reward seeking tendencies and social skills being respectively related to higher benefit from monetary or social rewards (Kohls et al., 2009).

In conclusion, both the mere control feeling arising from Agency, and the positive valence of outcomes drive children's actions. However, these mechanisms undergo developmental trajectories and specialize with age, potentially playing a role in atypical development.

4.1.4 Agency and Reward in Autism

The perception-action processes on which the sense of self is rooted are particularly affected by Autism Spectrum Disorder (ASD). This neurodevelopmental condition is diagnosed from the very first years of children's life based on persistent and pervasive deficits in social communication and social interaction, as well as restricted and repetitive patterns of behaviours, interests, or activities (American Psychiatric Association, 2013). Restrictive and repetitive behaviours might come along with atypical action selection processes, among which Agency and Reward play a crucial role. Understanding these mechanisms in ASD might shed light on how to promote not only learning but also volition and self-determination.

Using implicit measurements of Agency, some researchers found differences in the autistic adult population. Participants were asked to press the spacebar whenever they wanted. Sensory feedback was presented after a variable temporal delay (i.e., 250, 450, or 650 ms), and participants were required to estimate the delay. Despite being overall accurate in time perception, autistic adults showed reduced intentional binding compared to controls (Sperduti et al., 2014b). Another study on explicit Agency in ASD showed that high-functioning autistic and neurotypical adults were equally able to judge whether a visual effect was self-caused or not (David et al., 2008). Participants were asked to move a joystick and its cursor representation on a screen. The authors manipulated the degree of correspondence between participants' actual movement and the visual feedback (i.e., the cursor movement). Half of the trials delivered synchronous visual feedback of participants' real movement. The other half of trials showed pre-recorded cursor movements from a randomly selected previous trial performed by the same participant. When analysing explicit measures of Agency, collected through the question "Did you perform the action on the monitor?", no significant differences emerged between the two groups (David et al., 2008). These findings might suggest a dissociation between explicit and implicit Agency in ASD (Zalla & Sperduti, 2015). Although these considerations are based on very few studies and further investigation is needed, people with ASD might experience reduced sense of implicit Agency, thus being less motivated by the sense of control that accompanies voluntary actions and self-caused events. To the best of our knowledge, there are no previous studies investigating Agency in children with ASD, thus preventing us from understanding the developmental trajectory leading to any atypicalities we can find in adult populations.

To understand Agency in ASD despite the limited research on ASD populations, we can take a hint from studies on other clinical populations, that beyond diagnosis have atypicalities in common with ASD. For instance, Developmental Coordination Disorder (DCD) entails early emerging, persistent difficulties in the acquisition and execution of coordinated movements (American Psychiatric Association, 2013). Motor coordination difficulties seem to be negatively associated with socio-affective abilities, thus being a potential bridge between DCD and ASD (Piek & Dyck, 2004). The sensory processes underlying explicit Agency have been found to be different in children with DCD compared to neurotypical ones. Children were asked to make an action that would cause an effect after a random temporal delay, and then to judge whether the effect was self-caused. The time window for Agency was extended in children with DCD, negatively associated with manual dexterity and positively related to depressive symptoms (Nobusako, Osumi, et al., 2020). As multisensory temporal binding windows are enlarged in ASD (Foss-Feig et al., 2010), that could also impact the emergence of implicit Agency. Looking at the cognitive mechanisms of Agency, some interesting insights come from Attention Deficit Hyperactivity Disorder (ADHD) research. The cognitive mechanisms underlying the inattentiveness and impulsive symptoms that characterize ADHD might also affect Agency. For example, a self-attribution bias that over-attributes positive outcomes to oneself and negative outcomes to external factors is pervasive in the general population but greater in children than adults and reduced in ADHD (Mezulis et al., 2004). However, no difference in self-attribution bias was found in ASD (Kestemont et al., 2016), suggesting that higher-order cognitive mechanisms of explicit Agency might be unaffected.

Extensive literature has investigated the motivation from Reward in people with ASD. Neuroimaging evidence showed that when anticipating monetary reward, NAc activity is reduced compared to neurotypical individuals, while when perceiving the actual reward an hyperactivation of VMPFC is observed, suggesting a reduced motivation from rewards (Dichter, Felder, et al., 2012; Kohls et al., 2013). Reduced motivation from rewards has also been particularly found with respect to social rewards. Among children with ASD, researchers found reduced neural response of VS to social rewards (Scott-Van Zeeland et al., 2010), an attenuated vmPFC response to a presentation of favourite faces (Kishida et al., 2019), reduced activation of frontostriatal networks during socially rewarded learning (Kohls et al., 2012). However, there is also contradictory data on this, which leaves the debate open. Some works have found decreased amygdala activation in children with ASD (Kohls et al., 2013), whereas others report increased amygdala activation during social reward anticipation in adults with ASD (Dichter, Richey, et al., 2012). These results may suggest an atypical developmental trajectory in amygdala reactivity to social incentives (Schuetze et al., 2017).

Underlying mechanisms

The reduced sensitivity to implicit Agency and Reward that can be found in ASD might be related with atypical sensorimotor processes that underlie action-outcome binding and are therefore pivotal for both Agency and Reward. People with ASD show broad differences at the multisensory level (Baum et al., 2015; Hill et al., 2012), with multisensory facilitation and higher reliance on unimodal processing (Collignon et al., 2013), an extended (hence less precise and specialized) multisensory temporal binding window (Foss-Feig et al., 2010), and reduced integration of multimodal (e.g., audio-visual) cues (Feldman et al., 2018). They also experience atypical integration of interoceptive and exteroceptive stimuli (Noel et al., 2018), with delayed or reduced effects of visuo-tactile stimulation on proprioception during the Rubber Hand Illusion (RHI), resulting in less subjective feeling of ownership and self-location drift towards the rubber body (Cascio et al., 2012; Greenfield et al., 2015; Paton et al., 2012; Ropar et al., 2018).

Multisensory development goes hand-in-hand with motor development, in a perception-action cycle that allows the individual to learn from their actions (Kiefer & Trumpp, 2012). From infancy, babies at increased likelihood for a later diagnosis of ASD manifest delayed and qualitatively different motor development (West, 2019). Later in life, children with ASD show a variety of motor difficulties in the domains of praxis and fine and gross motor skills (Kaur et al., 2018), with asymmetrical gait (Esposito et al., 2011), and impaired postural stability (Lim et al., 2017). Difficulties in the underlying motor planning, monitoring and prediction are frequently found in ASD (Cattaneo et al., 2007; Sperduti et al., 2014b). At the neural level, children with ASD showed reduced event-related desynchronization before movements, which is interpreted as a sign of reduced motor preparation (Martineau et al., 2010). Altered movement related potential in people with ASD might reflect abnormal activity of SMA during action planning (Enticott et al., 2009). Moreover, some authors reported altered dACC activity in ASD during response monitoring, which was correlated with repetitive behaviours (Thakkar et al., 2008) and social difficulties (Henderson et al., 2006). Ineffective motor planning seems to be associated with motor stereotypies (Houdayer et al., 2014), which are involuntary, restricted, and repetitive patterns of movements that limit the individual’s resources to learn and practice various, purposeful actions (Mahone et al., 2004, 2014). Motor stereotypies are present in ASD, other neurodevelopmental conditions, and typical development (Ghosh et al., 2013). Notably, motor-related cortical potentials in premotor areas, which anticipate voluntary motor actions, are found to be absent before stereotypy onset in typical development (Houdayer et al., 2014).

Beyond the mechanisms that distinguish Agency and Reward, these two processes share a mutual influence with motor planning. There is still no evidence in the literature that clarifies the link between multisensory and motor planning atypicalities and the sensitivity to Agency and Reward in ASD. Trying to summarize the limited evidence from autism research and drawing on findings on other neurodevelopmental conditions that share differences and similarities with ASD, we can hypothesise that the latter involves differences in low-level sensorimotor mechanisms, which are particularly fundamental to action-outcome binding and motor planning, that are pivotal for experiencing Agency and Reward. We might speculate that reduced Agency and Reward sensitivity in ASD can have huge impacts on the way people learn and perceive their actions in the world. Individuals who are less motivated by the consequences of their actions and choices may experience less opportunities for learning and self-determination.

Intervention perspectives

The investigation of the intra-individual and neuropsychological mechanisms that shape the way individuals with ASD select actions and make choices does not neglect that they are situated and emergent from social, cultural, educational, and political contexts that shape the contours of “ability” and “disability”. Removing barriers to volition and self-determination is crucial when offering support and learning opportunities to people with ASD. From early in life, giving children with ASD a good degree of control over their social and non-social environment might have a great impact on their well-being and quality of life. For instance, Multi-Sensory Environments (also called sensory or Snoezelen® rooms) have been used to give children tools to control and modify their sensory environment. In such spaces, the child having control is a key element that mediates increased attention and reduced repetitive and stereotyped behaviours (Unwin et al., 2021). These findings suggest that providing control over sensory changes to children may create better conditions for learning.

The principle of “following the child’s lead” is also at the core of Naturalistic Developmental Behavioural Interventions (NDBI), in which the adult promotes social engagement and learning by following the child’s initiative and preferred activities (Vivanti & Zhong, 2020). According to these approaches, rather than using extrinsic artificial reinforcers to promote target behaviours, the focus is on leveraging each child's preferred interests and stimuli to provide learning opportunities and broaden the child's range of skills and interests. Although there might be reduced motivation from reward in people with ASD compared to neurotypical individuals (Dichter, Felder, et al., 2012; Kohls et al., 2013; Schuetze et al., 2017), enhancing the positive valence of their actions' outcomes is a well-established method to promote learning (Vivanti & Zhong, 2020). In this perspective, social rewards can be more effective than non-social rewards. When a child with ASD learns new words (e.g., says "train" for the first times while playing with a toy train), having an adult smiling, looking and pointing to the train and saying "yes, it's a train!" facilitates learning more than a non-social reward (the train lights up if the child names it correctly) (Hartley et al., 2019).

4.1.5 Future research perspectives

The literature review reveals how many aspects still need to be investigated in future research. First, the existing literature does not yet offer much information on the interplay of Agency and Reward across child development. Whereas these two mechanisms have been studied separately, Agency and the Reward are closely interconnected. Indeed, when an action that the agent perceives as voluntary and self-driven has a consequence that is interpreted as positive, the two experiences are concomitant. Motivation from Agency and Reward are therefore frequently bounded together (Barlas et al., 2018; Christensen et al., 2016; Tsukamoto et al., 2006). Future research should better disentangle these mechanisms, investigate their specialisation across child development and their potential role in atypical trajectories. This would not only allow us to understand their origins and functions, but also to leverage them to promote the child's development and learning.

The lack of knowledge is particularly relevant for research on Agency, which is still very poorly studied across different age groups and clinical populations. The most popular tasks for studying implicit (i.e., intentional binding) and explicit Agency (i.e., direct questions) are only usable with people who have good verbal skills and understanding of abstract concepts, thus limiting their appropriateness for young children and people with difficulties in verbal communication and abstract reasoning. Other recently proposed paradigms are based on simple tasks of choosing between options and measuring the frequency of choices and kinematic parameters (Karsh et al., 2020). However, it remains to be clarified whether these indices are indeed representative of the sense of Agency, and whether they can be used with populations other than neurotypical adults. Investigating the neurocognitive mechanisms underlying neurodiverse experience of Agency could be particularly relevant to understand several brain disorders (Malik et al., 2022).

In addition, the action-outcome properties that give rise to Agency have been mainly studied using non-social outcomes. Notably, Agency is also crucial during interpersonal exchanges, whereby each partner of the interaction influences the behaviour of the other through his or her own verbal and non-verbal initiatives, and thus feels that he or she has an active role in the exchange (Brandi et al., 2020). Therefore, it would be extremely important for future studies to examine the developmental trajectories of Agency in social and non-social situations and shed light on potential distinctions between social and non-social Agency. Indeed, social characteristics of stimuli involve different neural mechanisms than those devoted to processing non-social stimuli (Johnson et al., 2015).

4.2 A free-choice paradigm to disentangle Agency and Reward

Abstract. The present experiment aimed at disentangling the role of Agency and Reward in driving people's action selection across the lifespan and in ASD. Frequency of choices and reaction times (RT) have been measured while children and adults performed free choices among options with different probability (low, medium, high) of causing an effect. Across two tasks, we separately tested the contribution of Agency (i.e., causing a neutral effect compared to no effect at all) and Reward (i.e., causing a positive compared to a neutral effect). Participants' choices and RT were not affected by Agency, whereas a more frequent selection of the option with higher probability of a positive vs. neutral effect emerged across groups, thus suggesting a Reward effect. Participants with ASD selected less frequently the option with chance level of receiving a neutral or no effect, which could be interpreted as a sign of reduced tolerance of uncertainty. Across tasks, conditions and age groups, participants with ASD presented shorter RT, which is a marker of reduced planning before the action. Future research should deepen how tolerance of uncertainty and action planning impact the way individuals with ASD make choices in everyday life situations, potentially contributing to restricted and repetitive behaviours.

4.2.1 Aim and hypotheses

The present study aimed at investigating the role of Agency and Reward in driving people's free choices across development and exploring potential differences in ASD. Frequency of choices and reaction times have been measured while children and adults performed free-choice tasks whereby the probability of causing an effect and the effect valence (i.e., neutral or positive) were manipulated. We aimed at distinguishing the role of implicit Agency (i.e., causing a neutral effect compared to no effect at all) and Reward (i.e., causing a positive compared to a neutral effect) on action selection. We expect both Agency and Reward to increase the frequency of choices, and affect motor parameters of participants' choices, thus reducing the action time (i.e., RT). We expect adults to be faster in selecting response options with higher probability of causing a neutral (vs. no effect), or a positive (vs. neutral) effect. We also aim to explore developmental differences among children and people with ASD. Younger children and individuals with ASD might be less sensitive to the Agency effect, given their less refined sensorimotor integration system. Children might be also more sensitive than adults to the outcome valence (Reward) and prefer the response options with higher probability of delivering a positive vs. neutral effect. People with ASD might be less motivated by the positive effect, and do not prefer the response options with higher probability of delivering a positive vs. neutral effect.

4.2.2 Procedure and task

Adult participants and children's parents signed a written consent form before taking part in the experiment, which received ethical approval from the Research Ethics Committee of the School of Psychology, University of Padova (protocol no. 3251). The experiment was carried out in accordance with the approved guidelines and regulations.

Participants sat on a desk and were free to play with a reversible laptop with a touchscreen that was set to tablet mode (Lenovo Yoga, 14'' IPS Full HD 1920 x 1080, Intel® Core™-U i7). The experimental paradigm consisted of two tasks: Agency and Reward. On the initial screen of both tasks, participants were presented with three geometric figures positioned in the lower part of the display. After a random temporal delay (ranging from 500 to 1200 ms), a cue stimulus (one of 8 different animals) appeared in the upper central part of the screen. Participants were instructed to freely select and press one of the three geometric figures, as they were candies to feed the animal. As the task is designed to be feasible for people with limited verbal communication skills, in the event that a participant did not communicate verbally, the task was presented without verbal instructions. In this case, the experimenter showed the participant that when an animal appeared, one of the 3 candies could be clicked on. The experimenter demonstrated the game with 3 trials: clicking each of the 3 response options in sequence, from left to right. If a participant was not engaged in this demonstration, the touchscreen was simply made available to the participant to explore freely.

We manipulated the probability of the different response keys to deliver different effects. Crucially, no mention of the effects was made in the instructions, so obtaining or not obtaining the effect was not posited to participants as a purpose nor informed them regarding their performance. The tasks were therefore designed to tap on implicit mechanisms of action selection, which was meant to be driven by the action effect, even beyond explicit judgements, beliefs, or intentions. The paradigm was adapted from that used in Karsh and Eitam's (2015) study that investigated motivation from control (Agency) in neurotypical adults. The advantage of this task is that participants simply make free choices between response options (keyboard keys) when a central stimulus appears. The use of minimal verbal instructions also makes it usable with young children and people with ASD, even with minimal verbal skills or understanding of abstract concepts such as time (necessary in the intentional binding paradigms most commonly used to study implicit Agency). Moreover, paradigms that allow for free choices among alternatives are known to elicit greater experience of Agency than tasks with instructed actions and no alternatives (Barlas & Obhi, 2013; Villa et al., 2021)

Agency task. Participant's response was followed by either the appearance of a neutral effect (the animal immediately disappeared, and a black and white circle became visible for 150 ms), or no effect (the animal immediately disappeared, and nothing is shown for the next 150 ms). Each response key was associated with a different probability (10%, 50% and 90%) of providing the neutral effect.

Reward task. Participant's response was followed by either the appearance of a positive effect (the animal immediately disappeared, and a black and white smile became visible for 150 ms), or a neutral effect (the animal immediately disappeared, and a black and white circle became visible for 150 ms). Each response key was associated with a different probability (10%, 50% and 90%) of providing the positive effect. A schematic representation of the Agency and Reward task is depicted in Figure 4.1.

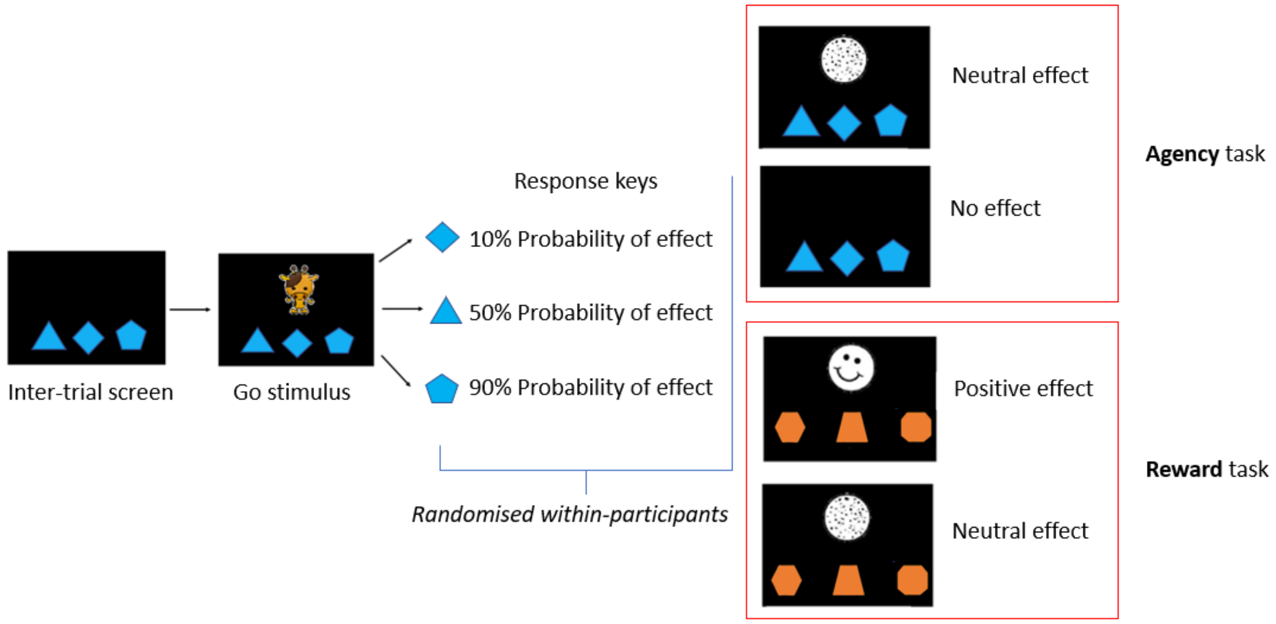


Figure 4.1. Agency and Reward tasks

The smile is meant to have an intrinsic positive value, as it conveys positive, albeit very simplified, social information. The neutral effect has been built from the positive one, so that they have the same degree of black-white percentage to make them equally visible. The combination of shape, position on the screen and probability associated with the response keys was randomised between participants. Within participants, the shape and colour of the response keys varied from the Agency to Reward task, whereas the relative position (left, centre, right) of each probability (10%, 50% and 90%) remained constant. Participants were instructed to reply as quickly as possible. Failure to press any keys within 2,000 ms was marked as “omission” and a drawing of a hand appeared, which had to be clicked to move to the next trial. This caveat allowed the experimenter to briefly pause the task if the participant needed a break. The next trial started after a random delay (ranging from 500 to 1200 ms), which prevented participants from anticipating the onset of the next trial.

All participants firstly performed the Agency task, and then the Reward task, to avoid carryover effects (i.e., a potential reduction of the value of the neutral effect after receiving a positive effect in the previous block of trials). Each task ended upon completion of 104 total trials. The experimental session lasted about 20 minutes.

4.2.3 Participants

Data collection took place between September 2021 and July 2022, as part of a collaborative project with several centres for autism in northern Italy, which offer various services in support of people with ASD and their families. All regular visitors to the centres were offered voluntary participation in the study. The final sample of children and adults with ASD was determined by the number of parents, children and adults who joined and participated. Psychologists confirmed participants' ASD diagnosis. Participants with autism carried out the experiment at their local clinical centre. A convenient control group of children and adults with typical development in the same age range was tested at the University of Padova. Participants in the control group were not recruited on the basis of age range alone, but matched one-to-one with the participants with autism. In this way, despite the breadth of the three age groups, the groups consist of participants matched by exact age (approximate year). According to parent-reports, typically developing children had no medical nor neuropsychological conditions. According to self-reports, typically developing adults had no medical nor neuropsychological conditions. Participants older than 16 years of age completed the Autism-spectrum Quotient - AQ questionnaire to assess the presence of autistic traits (Baron-Cohen et al., 2001). Since ASD is an inherently heterogeneous condition, we have not established inclusion or exclusion criteria based on IQ, level of support needed, or possible presence of co-occurring medical or neuropsychological conditions. Thus, we aimed to include participants along the whole spectrum.

Our sample constitutes of 55 participants with ASD and 55 neurotypical controls, across 3 age groups: younger children (from 6 to 10 years of age), older children (from 11 to 16 years of age), and adults (from 17 to 35 years of age). We established to exclude participants who would have demonstrated (verbally or non-verbally) that they were unwilling or unable to continue until the end of the tasks (with less than 50% valid trials in each task), and/or never selected some of the response options, thus being unable to learn its action-effect characteristics. Five additional participants (n=3 ASD, n=2 TD) were tested but have not been included in the final sample due to inability/unwillingness to perform the task. Among the 110 participants included, 1 TD adult was excluded from the Agency analysis as he never chose 1 of the 3 response keys. Moreover, 1 ASD adult was excluded from the Reward analysis, as he ended up with less than 50% valid trials (after removal of anticipations and omissions). Group size, female:male ratio, means and standard deviations of age are reported in Table 4.1 for included participants.

Group	Younger children		Older children		Adults	
	n (F:M)	Age mean (SD)	n (F:M)	Age mean (SD)	n (F:M)	Age mean (SD)
ASD	13 (1:12)	8.5 (1.2)	17 (0:17)	13.0 (2.0)	25 (4:21)	23.2 (4.9)
TD	17 (6:11)	8.4 (1.1)	14 (5:9)	12.7 (1.8)	24 (6:8)	23.5 (4.9)

Table 4.1. Sample description

4.2.4 Statistical approach

Data pre-processing. Participants completed n = 11,132 trials in the Agency task and n = 11,240 trials in the Reward task. Raw data were first cleaned from omissions (i.e., participants' response not within 2000 ms from stimulus presentation), with 1.79% trials being rejected in Agency task and 0.84% trials being rejected in Reward task. Afterwards, we applied a filter on Reaction Time (RT). Specifically, we excluded those responses whereby RT was less than 100 ms, being ascribable to anticipations. Filtered responses (Agency: 406/10,404 = 3.90%; Reward: 768/10,876 = 7.06%) were removed and not further analysed. Final dataset included n = 9,998 observations in the Agency task and n = 10,108 observations in the Reward task.

Variables. To analyse participants' responses, we considered 2 dependent variables. Choices indicate which response key was selected in each trial. RT is a continuous non-normally distributed variable that measures the time from the appearance of the central stimulus to the response. For all analyses, data were used in the long form, with as many lines as many valid trials were included for each participant. An exploratory approach was elected to test different potential hypotheses linking each dependent variable to the predictors of interest. Button probability is a within-subjects 3-level categorical factor that indicates the probability of each response button to deliver the effect (low, medium, high). Group is a between-subjects 2-level categorical factor that indicates participants' group membership (ASD or TD). Age group is a between-subjects 3-level categorical factor that indicates participants' age (younger children, older children, adults).

Model comparisons. All analyses have been run in R, version 4.0.2 (R Core Team, 2020). Through separated sets of model comparisons, different research hypotheses were specified as statistical models, and their statistical evidence was evaluated. For each dependent variable, a set of models were compared through the Akaike Information Criteria Weights (AICcWt) (i.e., the probability of each model, given the data and the set of considered models), using the 'AICcmodavg' (Mazerolle, 2020) R package. Then, likelihood ratio tests were used to compare the different models ('*anova*' R function), and test the effects predicted by the best model ('*summary*' R function).

Choices:

Multinomial logistic models were used to identify associations between explanatory factors (group, age group) and participants' choices among the 3 response options. To this end, we used the *'gam'* function from the *'mgcv'* R package (Wood, 2011). The response option with low (10%) probability of delivering the effect was held as a reference category. ASD group and Younger children were held as reference categories for the Group and Age group factors, respectively. As such, the multinomial logistic model makes two logistic regressions, comparing the baseline with each of the other 2 categories (e.g., if the baseline is set at "low" it makes one logistic with "low" and "medium" and one with "low" and "high"). The probability that the participant's response falls into each of the categories is thus estimated. We compared the models that follow.

- **m0** specified the hypothesis of no difference due to the independent variables and only accounted for individual variability
- **m1** specified the hypothesis of a Group effect
- **m2** specified the hypothesis of additive Group and Age group effects
- **m3** specified the hypothesis of a two-way interaction effect between Group and Age group

Reaction time (RT):

Generalised mixed-effects models were employed to analyse the associations between explanatory factors (button probability, group, age group) and RT, thus specifying its gamma distribution (i.e., positively skewed). To this end, we used the *'glmer'* function of the *'lme4'* R package (Bates et al., 2015). All models accounted for the random effect of participants (i.e., interpersonal variability). We compared the models that follow.

- **m0** (null model) specified the hypothesis of no difference due to the independent variables and only accounted for individual variability
- **m1** specified the hypothesis of differences due to the probability of each response option to deliver a neutral (Agency task) or positive (Reward task) effect
- **m2** specified the hypothesis of differences due to the probability of each response option to deliver a neutral (Agency task) or positive (Reward task) effect, with the additive contribution of Group membership

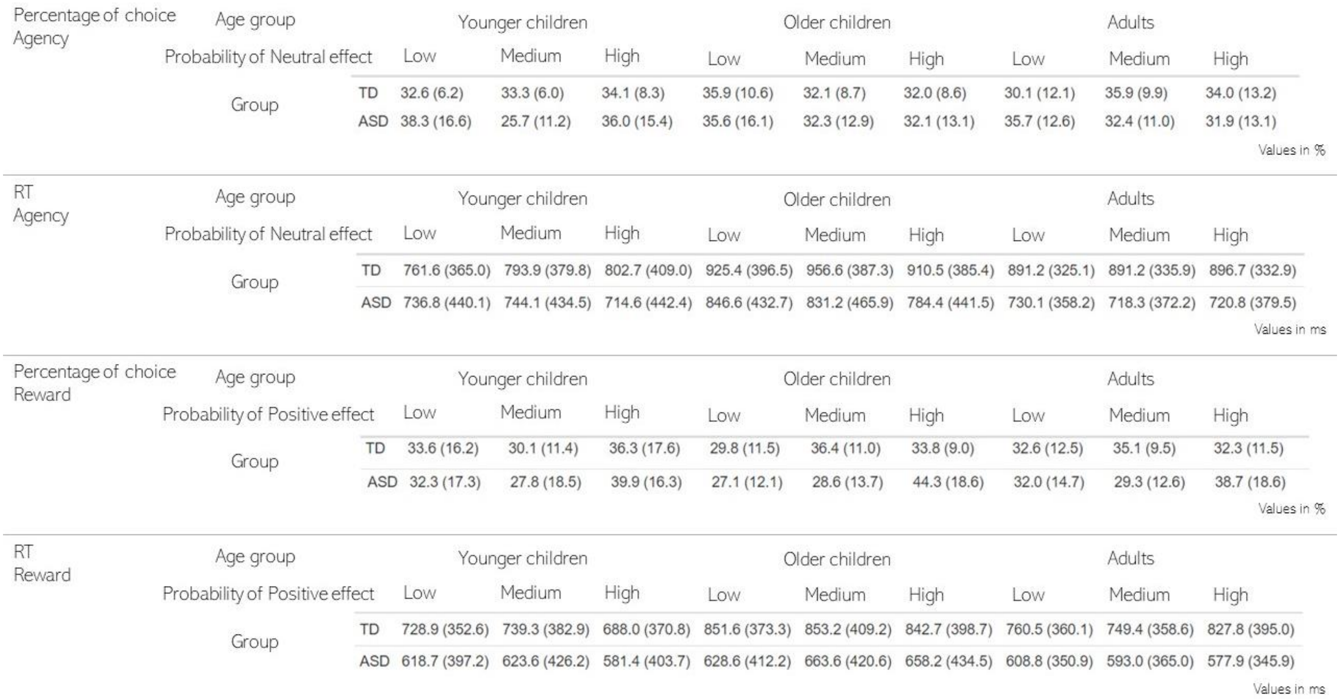
- **m3** specified the hypothesis of differences due to the probability of each response option to deliver a neutral (Agency task) or positive (Reward task) effect, with the additive contribution of Group and Age group membership

- **m4** specified the hypothesis of differences due to two-way interaction between the probability of each response option to deliver a neutral (Agency task) or positive (Reward task) effect and Group membership, with the additive contribution of Age group membership.

4.2.5 Results

4.2.5.1 Descriptive statistics

Descriptive statistics (means and standard deviations) are reported in Figure 4.2.



Percentage of choice Agency	Age group		Younger children			Older children			Adults		
	Probability of Neutral effect		Low	Medium	High	Low	Medium	High	Low	Medium	High
	Group	TD	32.6 (6.2)	33.3 (6.0)	34.1 (8.3)	35.9 (10.6)	32.1 (8.7)	32.0 (8.6)	30.1 (12.1)	35.9 (9.9)	34.0 (13.2)
		ASD	38.3 (16.6)	25.7 (11.2)	36.0 (15.4)	35.6 (16.1)	32.3 (12.9)	32.1 (13.1)	35.7 (12.6)	32.4 (11.0)	31.9 (13.1)

Values in %

RT Agency	Age group		Younger children			Older children			Adults		
	Probability of Neutral effect		Low	Medium	High	Low	Medium	High	Low	Medium	High
	Group	TD	761.6 (365.0)	793.9 (379.8)	802.7 (409.0)	925.4 (396.5)	956.6 (387.3)	910.5 (385.4)	891.2 (325.1)	891.2 (335.9)	896.7 (332.9)
		ASD	736.8 (440.1)	744.1 (434.5)	714.6 (442.4)	846.6 (432.7)	831.2 (465.9)	784.4 (441.5)	730.1 (358.2)	718.3 (372.2)	720.8 (379.5)

Values in ms

Percentage of choice Reward	Age group		Younger children			Older children			Adults		
	Probability of Positive effect		Low	Medium	High	Low	Medium	High	Low	Medium	High
	Group	TD	33.6 (16.2)	30.1 (11.4)	36.3 (17.6)	29.8 (11.5)	36.4 (11.0)	33.8 (9.0)	32.6 (12.5)	35.1 (9.5)	32.3 (11.5)
		ASD	32.3 (17.3)	27.8 (18.5)	39.9 (16.3)	27.1 (12.1)	28.6 (13.7)	44.3 (18.6)	32.0 (14.7)	29.3 (12.6)	38.7 (18.6)

Values in %

RT Reward	Age group		Younger children			Older children			Adults		
	Probability of Positive effect		Low	Medium	High	Low	Medium	High	Low	Medium	High
	Group	TD	728.9 (352.6)	739.3 (382.9)	688.0 (370.8)	851.6 (373.3)	853.2 (409.2)	842.7 (398.7)	760.5 (360.1)	749.4 (358.6)	827.8 (395.0)
		ASD	618.7 (397.2)	623.6 (426.2)	581.4 (403.7)	628.6 (412.2)	663.6 (420.6)	658.2 (434.5)	608.8 (350.9)	593.0 (365.0)	577.9 (345.9)

Values in ms

Figure 4.2. Descriptive statistics of choices and RT: mean (standard deviation).

Graphical visualisations of raw data, means and 95% CI are depicted below and distinguished by Group (TD, ASD) and Age group (Younger children, Older children, Adults). Figure 4.3 represents percentage of choices in the Agency task. Figure 4.4 represents RT in the Agency task. Figure 4.5 represents percentage of choices in the Reward task. Figure 4.6. represents RT in the Reward task.

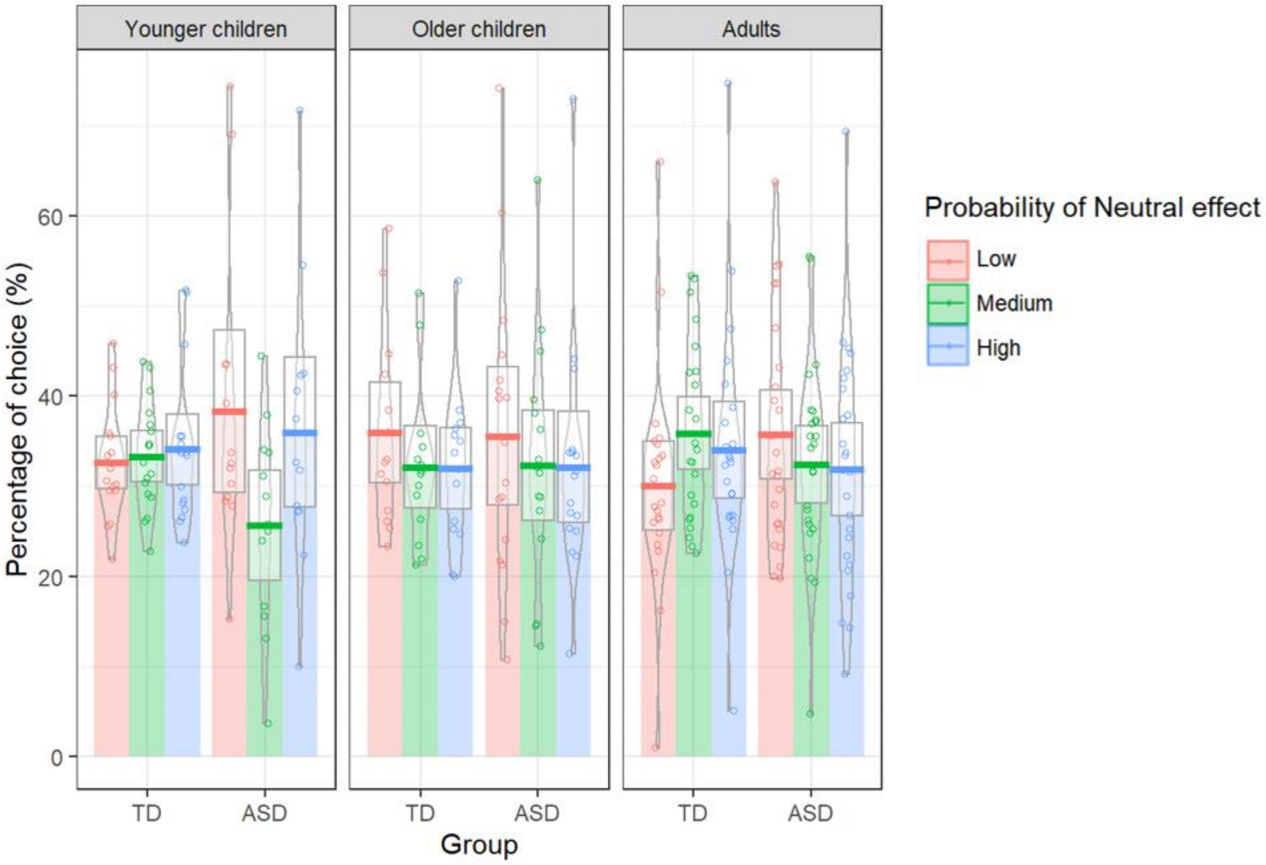


Figure 4.3. Visualisation of percentage of choice for each response option, according to its probability of delivering a neutral vs. no effect (raw data points, horizontal lines that represent means, boxes that represent 95% confidence intervals). Percentages are calculated on the total of valid answers, excluding omissions and anticipations.

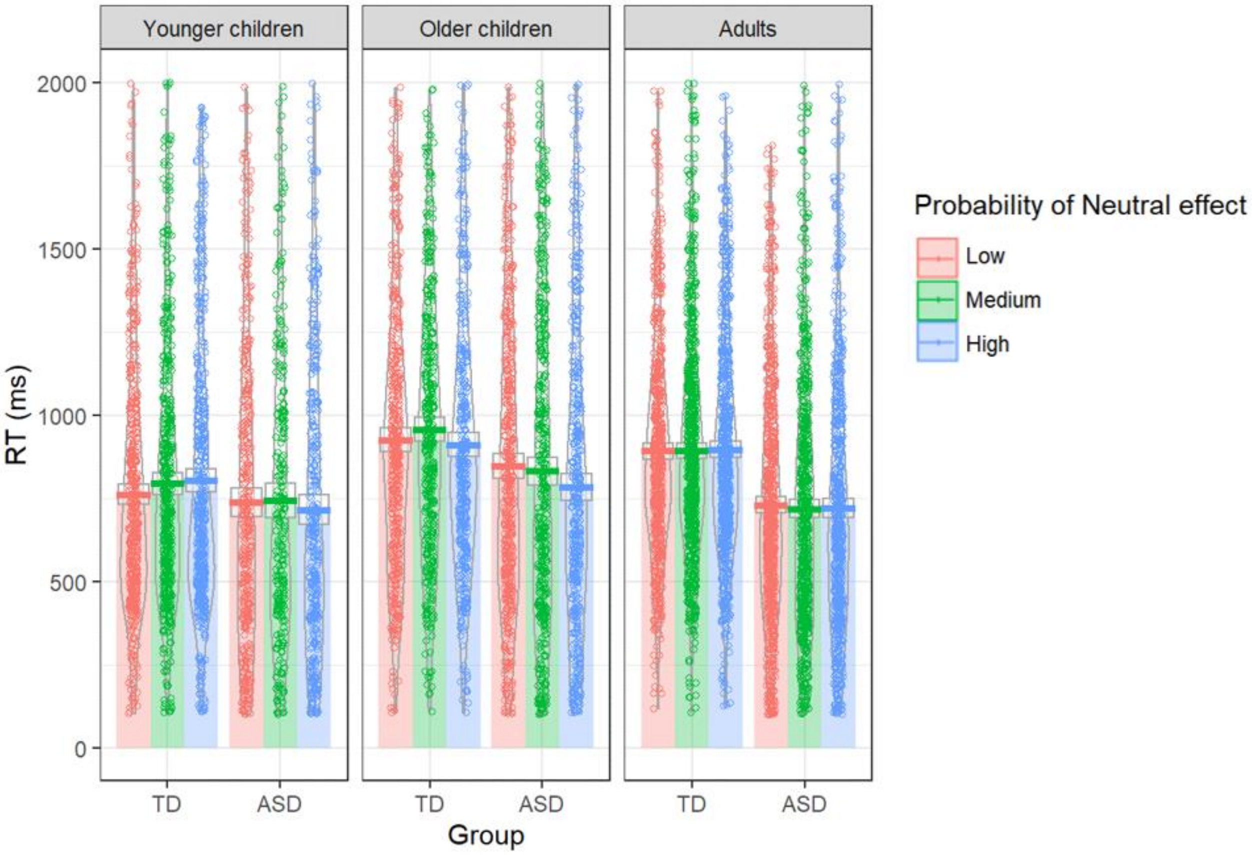


Figure 4.4. Visualisation of RT for each response option, according to its probability of delivering a neutral vs. no effect (raw data points, horizontal lines that represent means, boxes that represent 95% confidence intervals).

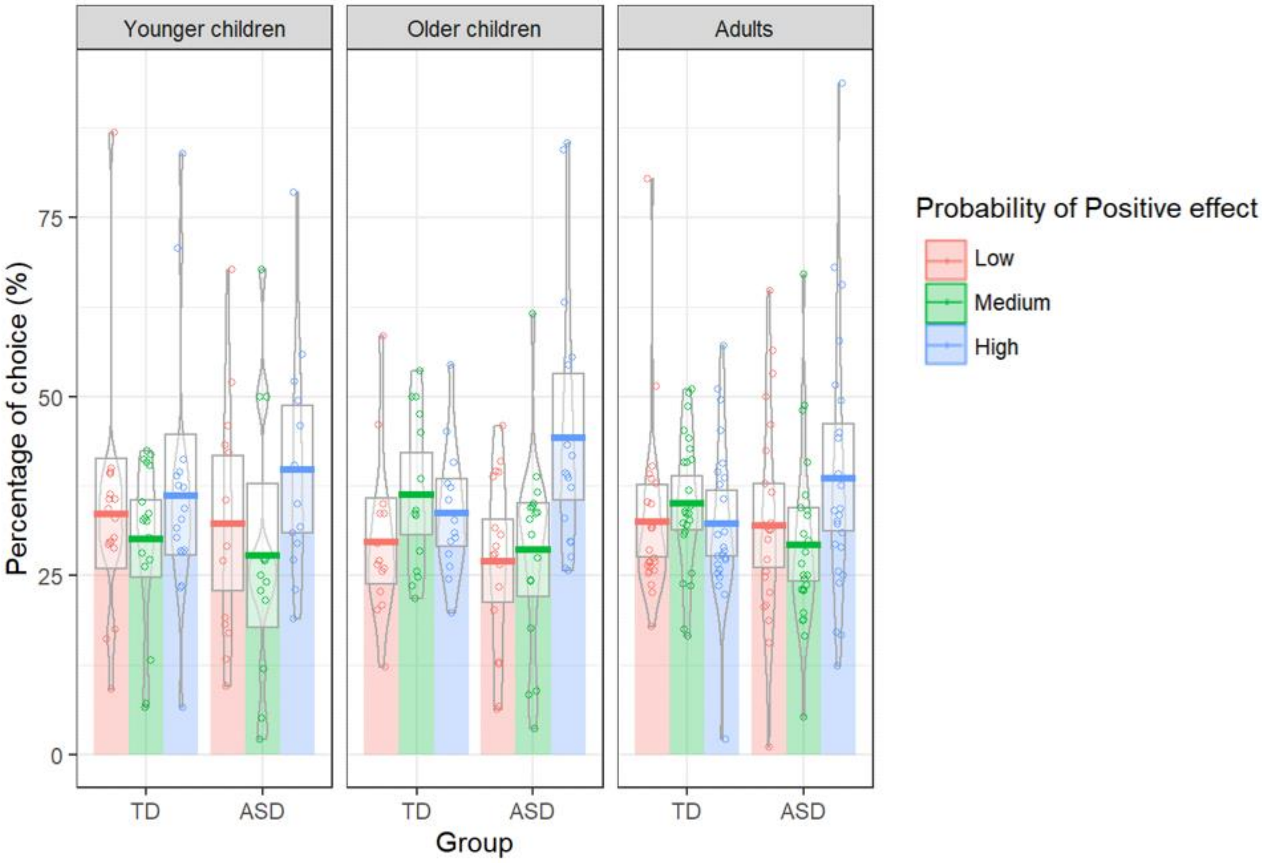


Figure 4.5. Visualisation of percentage of choice for each response option, according to its probability of delivering a positive vs. neutral effect (raw data points, horizontal lines that represent means, boxes that represent 95% confidence intervals). Percentages are calculated on the total of valid answers, excluding omissions and anticipations.

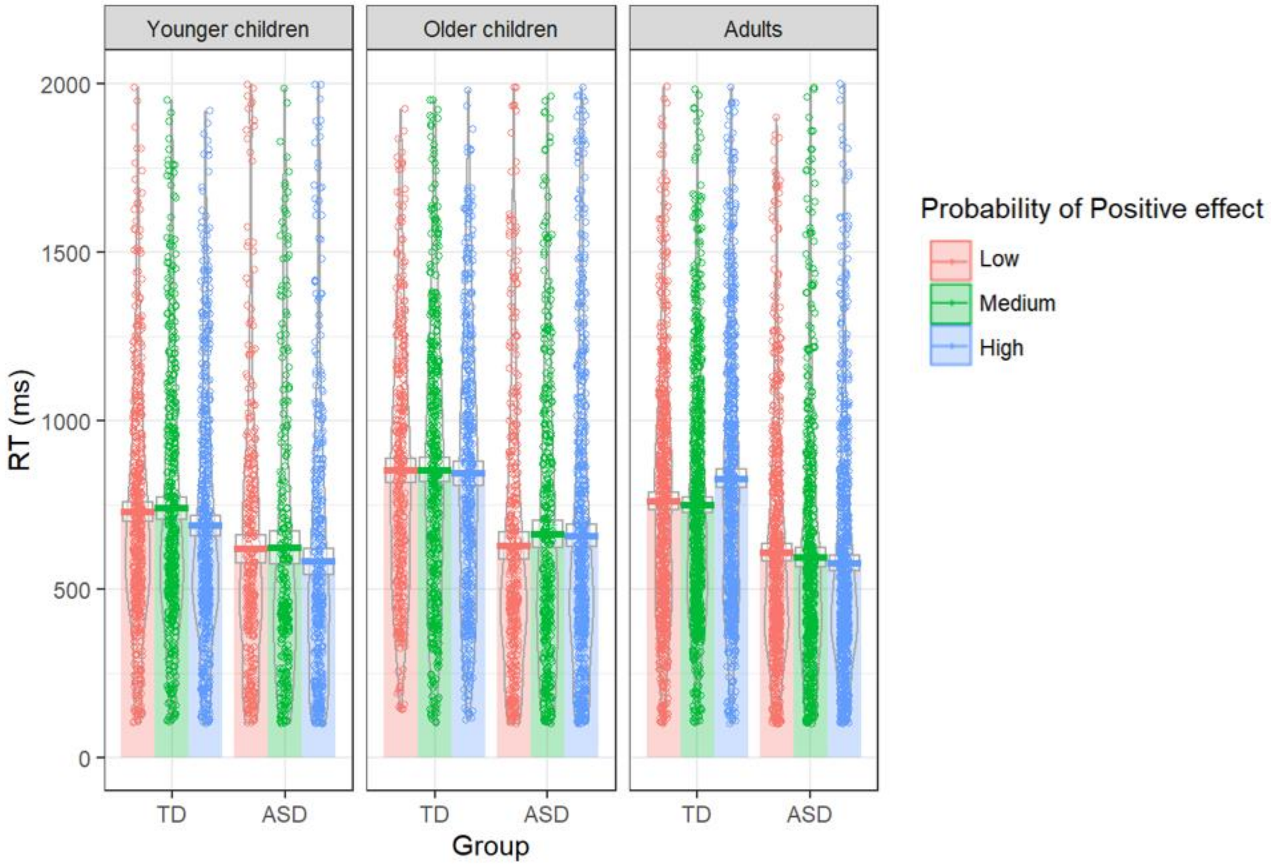


Figure 4.6. Visualisation of RT for each response option, according to its probability of delivering a positive vs. neutral effect (raw data points, horizontal lines that represent means, boxes that represent 95% confidence intervals).

4.2.5.2 Model comparisons

Agency

Choices

According to AIC weights (AICWt_m0 = .22; AICWt_m1 = **.29**; AICWt_m2 = .25; AICWt_m3 = .24), the most plausible model is **m1** (deviance explained = 5.13%), which revealed a significant Group effect in the difference between participants' choices of the response option with low or medium probability of delivering a neutral vs. no effect (z = 2.07; p = .04). A graphical representation of this effect is displayed in Figure 4.7. We can observe that the TD group equally selected the low- and medium-probability response option (CI includes 0 values). On the other hand, the ASD group selected the low-probability option more frequently than the medium-probability one.

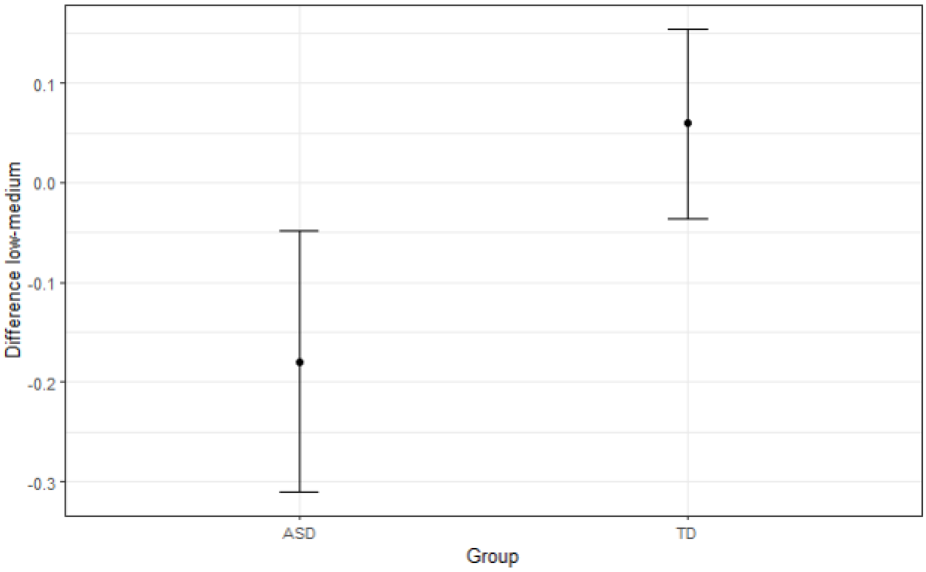


Figure 4.7. Group effect predicted by **m1** (relative choice of the response with medium - vs. low - probability of delivering a neutral vs. no effect, with whiskers representing 95% confidence intervals).

RT

According to AIC weights (AICWt_m0 = .22; AICWt_m1 = .05; AICWt_m2 = **.46**; AICWt_m3 = .23; AICWt_m4 = .04), the most plausible model is **m2** ($R^2 = .05$), which is significantly different from m0 ($\chi^2 = 6.66$; p = .01) and reveals a significant effect of Group (t = 2.624; p = .009). As visualised in Figure 4.8, the ASD group can be expected to show an overall shorter RT. Predicted RT [95% CI] for the TD group is 0.80 s [0.88, 0.74], whereas for the ASD group is 0.69 s [0.75, 0.65].

Figure 4.8. Group effect on RT (Agency task), as predicted by **m2** (estimated marginal means with whiskers representing 95% confidence intervals).

Reward

Choices

According to AIC weights (AICWt_m0 = .26; AICWt_m1 = .26; AICWt_m2 = **.29**; AICWt_m3 = .20), the most plausible model is **m2** (deviance explained = 7.92%), whereby no effects are significant. The second most plausible model (together with m0) is **m1**, which compared to **m2** has similar probability of being the best model and explains the same amount of deviance (AICWt = .26; deviance explained = 7.91%). **M1** reveals a significant difference in participants' choices of response options with low or high probability of delivering a positive vs. neutral effect (z = 2.72; p = .01). A graphical representation of this effect is displayed in Figure 4.9. Participants seem to more frequently select the response option with high (vs. low) probability of delivering a positive vs. neutral effect.

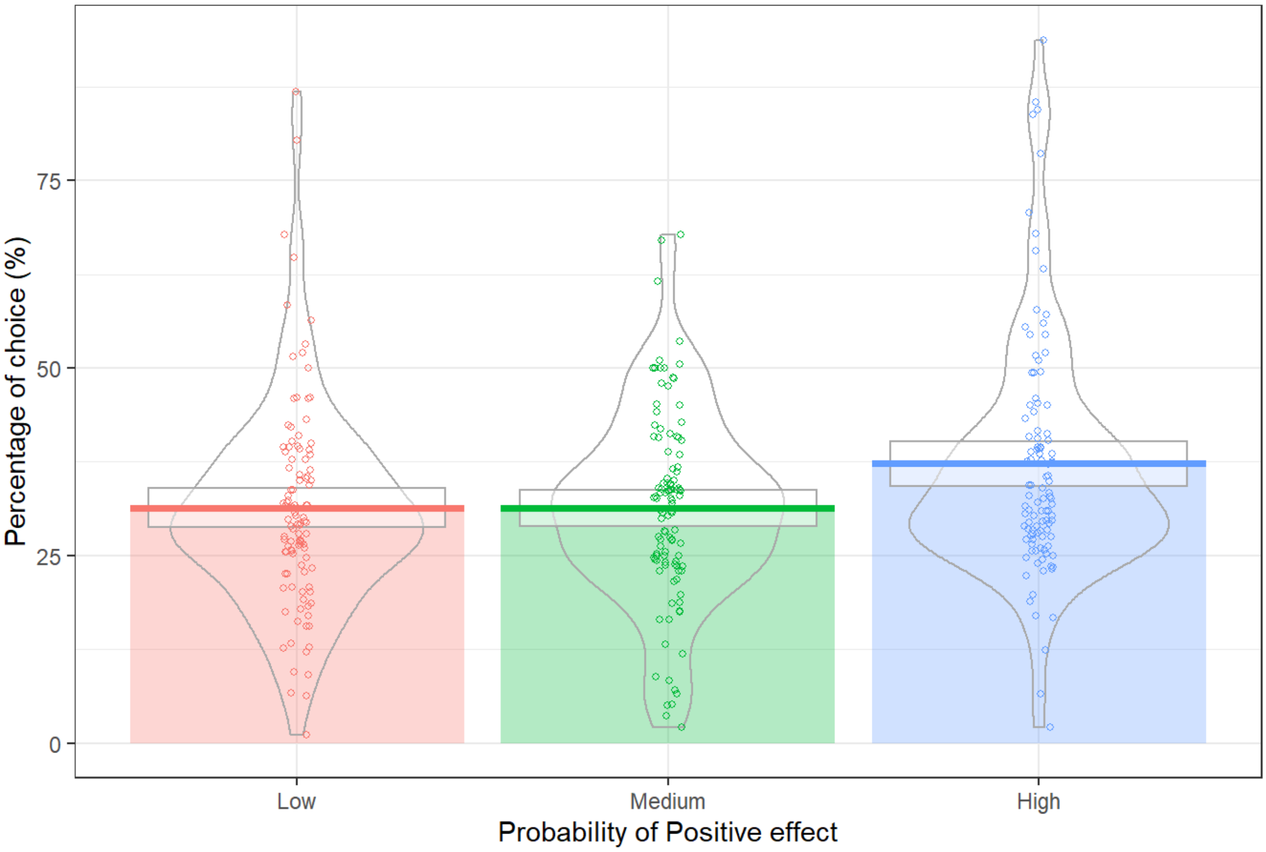


Figure 4.9. Visualisation of percentage of choice for each response option, according to its probability of delivering a positive vs. neutral effect (raw data points, horizontal lines that represent means, boxes that represent 95% confidence intervals). Percentages are calculated on the total of valid answers, excluding omissions and anticipations.

RT

According to AIC weights (AICWt_m0 = .02; AICWt_m1 = .01; AICWt_m2 = .71; AICWt_m3 = .15; AICWt_m4 = .11), the best model is **m2** ($R^2 = .07$), which is significantly different from m0 ($\chi^2 = 10.54$; p = .001) and predicts a significant effect of Group (t = 3.33; p < .001). As depicted in Figure 4.10, the ASD group can be expected to show an overall shorter RT. Predicted RT [95% CI] for the TD group is 0.68 s [0.75, 0.62], whereas for the ASD group is 0.55 s [0.60, 0.51].

Figure 4.10. Group difference in RT (Reward task), as predicted by model **m2** (estimated marginal means with whiskers representing 95% confidence intervals).

4.2.5.3 Exploratory correlations with AQ

In order to assess possible relationships between the results obtained from the model comparison and individual differences, we decided a posteriori to conduct a correlation analysis of certain indices of interest and the autistic traits measured through the AQ questionnaire. Across both the TD and ASD groups, the AQ was compiled by participants above 16 years of age (n = 42). The matrix in Figure 4.11 shows the pairwise correlations between:

- AQ: scores from the self-reported questionnaire on autistic traits among adults (min = 5; max = 35). Higher values indicate more pronounced autistic traits

- Percentage_Medium_Agency: percentage of choice for the response option with medium probability of delivering a neutral vs. no effect. Percentages for each participant are calculated over their total number of trials.

- Percentage_High_Reward: percentage of choice for the response option with high probability of delivering a positive vs. neutral effect. Percentages for each participant are calculated over their total number of trials.

- RT_Agency: average RT in the Agency task

- RT_Reward: average RT in the Reward task

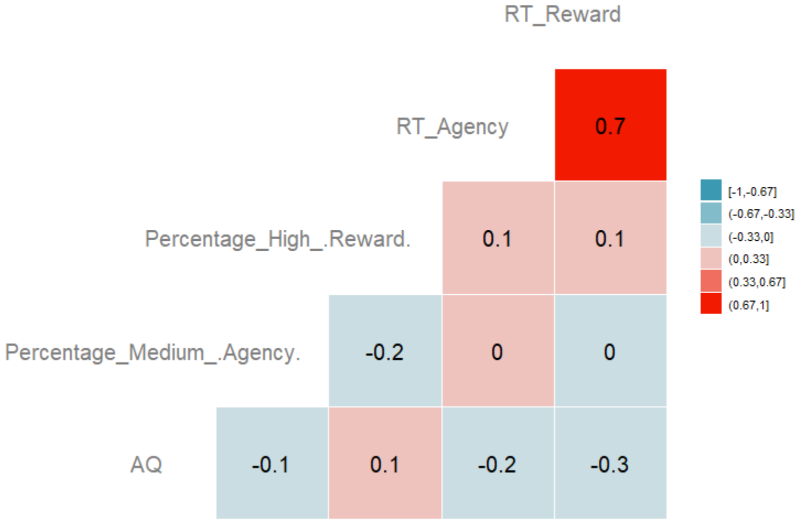


Figure 4.11. Correlation matrix (n = 42)

Apart from the RTs that are highly correlated across the two tasks, correlations are overall low or null. Negative correlations between AQ and RTs are appreciated, indicating that individuals with more pronounced autistic traits show slightly shorter RTs.

4.3 Discussion

Our ability to perform actions and make choices is fundamental in our daily interaction with the world of physical and social objects. The link between a given action and its effects in the surrounding environment modifies our behaviour, and the underlying cognitive and neural processes, with meaningful effects on our acting, thinking, and learning. Perception of control over the effects of one's actions (Agency) and sensitivity to positive outcomes (Reward) increase action frequency and have potential to facilitate action planning. These mechanisms undergo developmental changes that can contribute to typical and atypical developmental trajectories. We experimentally investigated the role of Agency and Reward in driving people's action selection across the lifespan and in ASD. Frequency of choices and reaction times (RT) have been measured while children and adults performed free choices among options with different probability (low, medium, high) of causing an effect. Across two tasks, we separately tested the contribution of Agency (i.e., causing a neutral effect compared to no effect at all) and Reward (i.e., causing a positive compared to a neutral effect).

Agency. Our data showed no preference for participants in choosing response options with a higher probability of giving a neutral versus no effect. In fact, we found no Agency effect on the frequencies of choice among the different options, nor on reaction times. Consequently, our results are not in line with the Control-Based Response Selection theory (CBRS) (Karsh et al., 2020) that proposes that the mere action-effectiveness facilitates action selection and speed when people make free-choices among options. To explain the discrepancies between the predictions of the CBRS model (Karsh et al., 2020) and our data we should consider some specific features of our experimental adaptation. While the original study explicitly required participants to perform random response selection (Karsh & Eitam, 2015), we used a cover story designed to engage younger children. Therefore, during the instructions, we told participants to use the response options as if they were candies to feed the animals that appeared on the screen. It is possible that this instruction drove attention towards finding matches between animals and candies, and away from the effects of the selected action. However, this should not be a limitation since the original task, like ours, is designed to elicit mechanisms of implicit Agency, which goes beyond conscious intentions and evaluations. It is also possible that such a simple and un-naturalistic task has limited potential in capturing the essence of Agency (and driving people's choices depending on mere action-effectiveness manipulations), which should be further explored in ecological situations where the action-consequence link takes on real relevance for the person. Agency is also crucial during interpersonal exchanges, whereby each partner of the interaction influences the behaviour of the other through his or her own verbal and non-verbal initiatives, and thus feels that he or she has an active role in the exchange (Brandi et al., 2020). Whereas Agency research has focused on the use of non-social effects of action, it would be extremely important for future studies to examine the developmental trajectories of Agency in social and non-social situations.

Reward. We found a general preference for choosing the option with a higher probability of a positive versus neutral effect. However, the effect valence did not affect reaction times, thus failing to facilitate motor preparation and execution in our task. Previous literature offers contradictory findings on whether positive outcomes can actually facilitate actions at the motor level. The CBRS literature found that monetary outcomes of adults' free choices do not decrease RTs (Karsh et al., 2020). Other authors found evidence that monetary rewards make actions faster, with reward magnitude being associated with the activation of pre-SMA and SMA brain areas, potentially promoting motor planning prior to action execution (Adkins & Lee, 2021). Differently from these previous studies, we used a Reward stimulus (smiley) with immediate positive value even for people with a limited concept of the value of money (i.e., very young children and some participants with ASD). It is possible that the social characteristics of our Reward stimulus involved different mechanisms than those devoted to processing non-social rewards. Indeed, even very simplified stimuli that resemble the global structure of faces activate specific subcortical and cortical routes of the social brain (Johnson et al., 2015). Interestingly, different types of feedback can have a different motivational effect for people with different ages and developmental trajectories. The literature points out that neurotypical children are differently motivated by social and non-social rewards in different situations (Dubey et al., 2022). Autism research, on the other hand, presents evidence on possible differences in neural reward circuits (Dichter, Felder, et al., 2012; Kohls et al., 2013; Scott-Van Zeeland et al., 2010), with potential reductions in the motivation from and search for social outcomes (Dichter, Richey, et al., 2012; Vernetti et al., 2018).

Autism. The experimental study has an exploratory intent with regard to the mechanisms of interest in the population with ASD. Little is known about how these processes function and develop across typical development, so it is risky to draw definitive conclusions about autism. However, we believe it is of interest for autism research to make some preliminary and speculative observations from the data we have analysed, bearing in mind that those should be taken with caution and further studied in future research. First of all, we found a group difference in the Agency task. While the TD group equally selected the response option regardless of their probability of a neutral vs. no effect, the ASD group seemed to avoid the response option with chance probability (50%) of giving a neutral vs. no effect. Since that response option can be seen as the one with highest level of uncertainty, we can interpret this finding in light of the evidence on the intolerance of uncertainty in people with ASD (Vasa et al., 2018), who might overestimate the volatility of the environment and be more prone to expect the unexpected (Arthur et al., 2021). In this sense, people with ASD may have avoided choosing the response key associated with higher uncertainty about the outcome. Intolerance for uncertainty is a potential mechanism underlying the presence of restricted and repetitive behaviours in ASD (Hwang et al., 2020; Wigham et al., 2015). However, among adult participants with or without a diagnosis of autism, the frequency of choosing that response option did not correlate with autistic traits.

Second, we did not find any Reward-specific differences between TD and ASD groups: they more frequently selected the option with higher probability of a positive vs. neutral effect. We can interpretate this finding as a sign of sensitivity to and motivation from reward. This is not in line with previous literature on reduced motivation from reward in people with ASD (Dichter, Felder, et al., 2012; Kohls et al., 2013; Schuetze et al., 2017).

Notably, participants with ASD, across all age groups and the two tasks, showed shorter reaction times than TD participants. Moreover, we found a small negative correlation between autistic traits and RTs, with more pronounced autistic traits being associated with shorter RTs (the analysis was run on data from all participants older than 16, regardless of their formal ASD diagnosis). These findings may indicate the presence of a general propensity for more automatic responses, with less time spent planning the action (Glover, 2004). In everyday life, people constantly perform actions that require planning and control. Previous findings suggested that when people with ASD perform self-generated movements, their performance can become stereotyped (Glazebrook et al., 2008). Stereotypies are involuntary, restricted, and repetitive patterns of movements that limit the resources to learn and practise various, purposeful actions (Ghosh et al., 2013; Mahone et al., 2004, 2014). Ineffective motor planning seems to be associated with motor stereotypies (Houdayer et al., 2014), which are present in ASD, other neurodevelopmental conditions, and typical development (Ghosh et al., 2013). Notably, motor-related cortical potentials in premotor areas, which anticipate voluntary motor actions are found to be absent before stereotypy onset in typical development (Houdayer et al., 2014). We can speculate that reduced action planning in ASD is related to reduced reliance on predictions about the action outcomes (C. J. Palmer et al., 2017), potentially contributing to difficulties in learning from the action consequences. In this perspective, sub-optimal predictive processes and action planning could be associated with reduced sensitivity to Agency and Reward. That is suggested by previous literature but not clearly emerged from the current study. Further research is needed to investigate these aspects in ASD, digging into the implications on the individuals' daily life and well-being.

Limitations and future perspectives

Our model comparisons suggest that there are in fact some differences in the extent to which participants select response options according to their probability of producing specific effects. Specifically, the ASD group seemed to avoid selecting the response option with chance level of producing a neutral or no effect. Moreover, all groups more frequently selected the response option with higher probability of a positive vs. neutral effect. We found group differences in overall reaction times, with the ASD group showing shorter RT. These considerations are supported by the information criteria that led to the selection of the most plausible model in explaining our data. However, the models explained a limited amount of variability within the data, as suggested by the deviance explained for the 'choices' variable, and the R^2 for the RT variable, with the most plausible models only explaining from 5 to 7% of variability. Therefore, our results should be interpreted with caution, and future work should investigate additional latent variables that may contribute to the phenomena under study.

A limitation of the current study is sample size, which was determined by the number of families that agreed to participate in the study. While the original CBRS studies on neurotypical adults used a much larger sample (Karsh et al., 2020; Karsh & Eitam, 2015), it is possible that our study was under-powered to detect Agency and Reward effects that might be actually small in the general population. Given the paucity of prior evidence on children and autistic populations, we were not able to a-priori estimate expected effect sizes and appropriate sample sizes, resulting in a sample size that may be insufficient to reveal further patterns within the data. Relatedly, although participants over the age of 16 filled out the AQ questionnaire, thus providing a measure of the presence of autistic traits, participants were not characterized in terms of cognitive and verbal functioning, that is a standard practice in experimental research involving participants with autism. The heterogeneity within the autism spectrum along the cognitive and verbal dimensions, might have contributed to between-group differences (for example in reaction times) that go beyond autism-specific characteristics. For these reasons, our results should be considered as a first exploratory step towards investigating how Agency and Reward drive free-choices across different developmental trajectories.

The literature review and discussion of the experimental results open the door to challenging perspectives for future research. During naturalistic interactions with the outside world, a sense of Agency and the Reward derived from the positive consequences of one's actions are closely interconnected. Indeed, when an action that the agent perceives as voluntary has a consequence that is interpreted as self-caused and also positive, the two experiences are concomitant. Motivation from Agency and Reward are therefore frequently bounded together (Barlas et al., 2018; Christensen et al., 2016; Tsukamoto et al., 2006). To better disentangle these mechanisms, the use of neural measures of Agency and Reward will offer unique possibilities. Distinct and shared components of neural activity are associated with the sense of Agency and sensitivity to Reward. For example, preparatory neural activity in motor and premotor areas anticipates voluntary movements and contributes to implicit Agency (Moore et al., 2010) but is also affected by Reward (Adkins & Lee, 2021). Distinct neural components are instead in charge of processing what happens after the action and its outcomes. While sensory-related activity is associated with the sense of Agency in response to expected self-caused outcomes (Aytemur et al., 2021; Vercillo et al., 2018), neural activity in amygdala and thalamus areas underlie Reward consumption (Rademacher et al., 2010).

We are far from understanding how these different mechanisms specialise during the course of child development and may be involved in atypical trajectories. Our behavioural task is a first attempt to establish a paradigm suitable for young children and people with limited verbal abilities, which can be integrated with neural measures to shed light on the deep mechanisms underlying motivation from Agency and Reward. Nevertheless, the extant literature and the present study mainly employed simple and un-naturalistic tasks that might have limited potential in capturing the essence of Agency and Reward, and their role in driving people's actions and choices, which should be further explored in ecological situations where the action-consequence link takes on real relevance for the person.

Interesting prospects also open up for autism research and interventions. Leveraging both Agency and Reward might be crucial for enhancing the action-outcome binding that is pivotal for a person to learn from their own actions, while also fostering self-determination. From early in life, the child having the control over the environment is a key element that mediates increased attention and reduced repetitive and stereotyped behaviours (Unwin et al., 2021). Providing control over sensory changes to children may create better conditions for learning. On the other hand, there are different ways of using rewards to facilitate the child's learning. Behavioural interventions for children with ASD often employ "artificial" rewards (e.g., food or tokens) to reinforce behaviours during adult-determined activities. Instead, recently operationalised, evidence-based interventions that follow under the umbrella category of Naturalistic Developmental Behavioural Interventions (NDBIs), recommend reinforcing the child's behaviours with "natural" consequences (Vivanti & Zhong, 2020). Using the example of language learning, when a child says "train" to express their intention to play with a toy train, the adult can reinforce this behaviour with affective facial and vocal expressions (smiling and saying "yes, a train!"), and body language (pointing to the train). Those naturalistic reinforcements that are related to the activity and foster social engagement should be preferred to artificial rewards (e.g., giving chocolate or tokens to reinforce target behaviours). Importantly, the adult should "follow the child's lead", creating learning opportunities from the child's initiative, interests, and preferred activities (Vivanti & Zhong, 2020).

Part II

5 Inhibition of prepotent responses: motor planning and control (Study 3)

5.1 Introduction

The actions we perform voluntarily are what enable us to be active agents in interacting with the environment. Performing a specific action requires both a pre-planning and an on-line control of the desired motor output. Understanding the way we plan and control our movements across different tasks help shedding light on which motor strategies individuals adopt to select and execute different goal-oriented actions. Such two mechanisms are settled in distinct brain regions, respectively intervene in either the early or later movement time and appear influenced by different sensorimotor aspects and cognitive processes (Glover, 2004). Indeed, the role of motor networks go beyond the action specification that answers to the "how to do it" and contribute to the simultaneous process of action selection, which addresses the "what to do" issue and chooses among currently available options (Cisek, 2007).

Performing cognitive operations and motor actions can be considered two faces of the same coin, as they vastly rely on shared mechanisms that allow us to produce appropriate responses with respect to goals and context (Koziol et al., 2012). Action processes specialize with experience across the life span, with motor and cognitive development being closely connected and inter-related in a dynamic process of exploring and adjusting to the demands of the external physical and social environment (Thelen, 1995). Although cognitive and motor difficulties often co-occur in neurodevelopmental conditions, they have been extensively studied as separate processes (Sokhadze et al., 2016; Wilson et al., 2020), and their common underlying mechanisms are still to be furthered. An integrated approach could provide a more complete understanding of the interplay between low-level sensorimotor processes and high-level executive functioning. Indeed, executive functions are those top-down processes (i.e., working memory, inhibition, shifting) that enable people to plan, monitor and control sensorimotor, socio-affective and cognitive processes, being fundamental to mental and physical wellbeing (Diamond, 2013b).

Cognitive control is fundamental to the process of action selection, including the ability to flexibly adjust to environmental changes and demands, and inhibit inappropriate or incorrect responses (Ridderinkhof et al., 2004). Rather than a unitary process, inhibition is a multifaceted skill that comprehends sensory, cognitive, behavioural and motor sub-components (Friedman & Miyake, 2004), such as the ability to stop prepotent motor activities. The ability to inhibit automatic and highly probable responses and let less probable alternatives successfully compete for control of cognition and behaviours, ensures that we are flexible and open to learning from the surrounding environment (Leisman et al., 2016).

Inhibition of prepotent responses is a well-studied process being affected by neurodevelopmental conditions such as Attention Deficit and Hyperactivity Disorder (ADHD) (Barkley, 1999), which is diagnosed based on inattentiveness, impulsiveness, and hyperactivity symptoms (American Psychiatric Association, 2013). At the cognitive level, it is established that people with ADHD, despite the wide variability that characterizes developmental trajectories, are overall impaired in executive functions (Doyle, 2006). ADHD can entail several aspects of cognitive and motor impulsivity, that consists of nonreflective stimulus-driven processes and manifests itself through inhibitory difficulties, distractibility, faster and less accurate responses to neuropsychological tests (Nigg, 2017).

At the motor level, it is still debated whether motor signs of atypical development can be detected from infancy and interpreted as early risk factors for the following development of ADHD cognitive and behavioural symptoms (Athanasiadou et al., 2020). Some co-occurrent difficulties in motor skills (e.g., fine motor precision, manual dexterity, bilateral coordination, balance, and postural control, running speed and agility, limb coordination, strength) can be found in about 50% of individuals with ADHD (Farran et al., 2020). However, those are not a diagnostic criterion and there is no evidence so far supporting the link between motor impairments and ADHD-specific symptoms such as inhibitory deficiencies (Farran et al., 2020). To shed light on this, an approach that studies these two aspects in an integrated manner could provide an innovative perspective on difficulties with inhibition and behavioural hyperactivity. Potential underlying mechanisms of inhibition difficulties relate to motor planning, which is responsible for selecting the action target and the timing of movements (e.g., reaction times, movement times, and acceleration/velocity parameters) (Glover, 2004).

Adults with ADHD have been found to show atypical motor planning, with longer reaction times to start moving after a “Go” cue and higher variability in the velocity shape along time (Dahan & Reiner, 2017). It is interesting to note that there is a kind of slowness in sensorimotor and cognitive processes that underlie behavioural manifestations of impulsivity, hyperactivity, and inattention. A developmental perspective is needed to understand how these atypicalities have emerged and are maintained from childhood to adulthood. This would help us design targeted and age-appropriate interventions to promote a change on the mechanisms underlying the cognitive and behavioural difficulties of ADHD. Notably, purely cognitive training specifically targeting executive functions such as working memory, attention, inhibition, and shifting rarely result in cognitive nor behavioural or academic improvements, with scarce effect on ADHD core symptoms (Cortese et al., 2015; Rapport et al., 2013). It has been speculated that leveraging embodied cognition and cognitive-motor approaches could boost training efficacy (Moreau, 2015). This multidimensional perspective would eventually chart the way to define and test both motor and cognitive interventions to strengthen inhibition by passing through multidimensional doorways. Despite their presence and impact, motor difficulties of people with ADHD often end up being overlooked by research and clinical practice. Previous studies mainly based on correlational analysis of motor skills and purely cognitive performance at inhibition tasks, and failed to find clear relationships (Farran et al., 2020). On the other hand, investigating inhibition without dissociating motor and cognitive aspects that are deeply interrelated offers further insights on the underlying processes.

5.2 Measuring the motor parameters of inhibition

Different paradigms are commonly used to measure the inhibition of prepotent responses (e.g., Stroop, Stop-signal and Go/No-Go tasks), with diverse versions that rely on mainly cognitive processes or entail varying degrees of motor components, and activate both distinct and shared neural areas (Henry et al., 2012; Rubia et al., 2001). For instance, cognitive inhibition of prepotent responses is conceived as the ability to focus on the task and ignore irrelevant distractors, as in the case of reading the world "blue" written in red ink. The motor component comes into play when the response requires some sort of movement (from pressing a button to reach a target), which sometimes has to be voluntarily stopped before or during its execution (Henry et al., 2012). Usually, these motor executions are not main targets of study, as they are considered only a way to obtain from individuals a response that is believed to reflect certain cognitive mechanisms. However, the very planning of this motor response could reveal important information about the processes at play. Thus, a deeper understanding of motor responses in cognitive tasks needs an improved consideration, leading to a new perspective on the shared mechanisms that underpin adaptive behaviours.

One of the most commonly used tasks to assess motor inhibition of prepotent responses is the Go/No-Go paradigm (Simmonds et al., 2008). The "Go" trials require participants to provide a fast response (i.e., do something) as soon as a dominant cue appears. On the other hand, the "No-Go" trials require to inhibit the response and not answer (i.e., do nothing) when another non-dominant cue appears (the latter usually appears less frequently than the dominant one) (Wessel, 2018). However, the classical task is unable to investigate the different motor strategies individuals may adopt to perform either a prepotent or an alternative response. To further distinguish between planning and control aspects, kinematic measures have been included with adapted Go/No-Go paradigms that asked participants to perform either a prepotent action elicited most of the time (dominant), or an alternative less frequent one (non-dominant). In one adaptation of the Go/No-Go, both Reaction Time (RT) and Movement Duration (MD) were analysed, whereby the non-dominant action might be performed with a longer RT or a longer MD depending on whether the actor required either a longer planning phase before the movement onset or a greater control and adjustment during its execution (Trewartha et al., 2011).

Nevertheless, it is worth noting that motor planning is not relegate to RT but also overlaps with motor control during the MD. Indeed, "as planning is generally operative early and control late in a movement, the influence of each will rise and fall as the movement unfolds" (Glover, 2004, pag. 5). Therefore, kinematic indices other than RT and MD would be more informative to further clarify the mechanisms beneath distinct movements, with promising possibilities to distinguish the specific inhibitory impairments that are common of several neuro-psychological conditions (Wright et al., 2014). As planning seems to be primarily devoted to process cognitive information, whereas control is dedicated to homing in on a target with specific spatial features (Glover, 2004), the inhibition of prepotent motor responses evoked by Go/No-Go tasks would likely load on planning mechanisms.

Researchers have extensively debated regarding the distinctive meaning of different motor indices, which are affected by different factors, thus providing insights on distinct neuro-psychological mechanisms underlying motor activities. Acceleration, in particular, discloses the movement smoothness, whereby an optimal reaching is ideally (for instance in experimental contexts and robotics) the one with the minimum jerk, namely, the rate of acceleration changes in time (Flash & Hogan, 1985; Iuppariello et al., 2019). The smoothness of a reach-to-grasp movement might depend on whether the target object is present, imagined, or absent, on how it is oriented, or on which is the plane of movement (e.g., horizontal, or vertical plane) (Wisneski & Johnson, 2007).

Neuro-imaging studies collected evidence of distinct cortical networks being related to distinct kinematic features. Bourguignon et al. (2011) studied the fast repetitive voluntary hand movements of neuro-typical adults and revealed that movement acceleration was mainly coupled with a coherent activation of contralateral primary motor (M1) hand area at around 3 Hz and 6 Hz of movement frequencies. Only when the hand movement aimed at touching its own fingers, the primary somatosensory (S1) hand area became the most coherent brain area at around 3 Hz of motion frequency. In addition, the activation of DLPFC (dorsolateral prefrontal cortex, which is responsible for goal-directed action planning) and PPC (posterior parietal cortex, which is responsible for sensorimotor integration and movement monitoring) areas were coherent with movement acceleration (Bourguignon et al., 2012).

Focusing on velocity, the minimum-jerk model predicts that reaching trajectories starting and ending at full rest will show a symmetric, bell-shaped velocity path, with 50% of MD spent both accelerating and decelerating. However, MD and velocity across time are shaped by several factors, such as the individual developmental trajectory (Thelen et al., 1996), the affordances of the target object (e.g., a cup or a spoon) (Wisneski & Johnson, 2007), and social intentions during interactions with others (Becchio et al., 2008). On this matter, the Time to Peak Velocity percentage (TPV%) is a relative asymmetry index whereby the ideal symmetrical value of 50% would indicate an equivalent acceleration/deceleration phase. Given that whether a kinematic parameter occurs earlier or later over the MD would reflect more either planning or control (Glover, 2004), a small TPV% resulting in a longer deceleration phase may indicate a greater need for control and adjustment of the ongoing movement. On the other hand, a big TPV% resulting in a shorter deceleration phase may indicate a greater need for motor planning.

The compelling possibility of integrating kinematic measures to the traditional neuropsychological evaluation is strongly limited by the need of sophisticated motion capture systems. Those used for research purposes are often expensive and bulky, thus being hardly affordable for most clinical centres. In order to use low-cost portable solutions and boost the applicability of motion analysis, inertial sensors have been recently recommended for their good measurement reliability and validity (Cahill-Rowley & Rose, 2017). Adopting this technology in clinical practice would allow for a more detailed analysis of the mechanisms underlying the child's performance on tests of interest. It could be used during assessment for setting specific intervention goals, for monitoring treatment effects, and as a training tool itself when used as biofeedback.

5.3 Aims

The present work aimed at disentangling the contribution of motor planning and control in the selection or inhibition of a prepotent response (provided through a reaching movement). To effectively inhibit a prepotent response and select an alternative one, individuals might employ different strategies, such as devoting more time to either the first (planning) or last (online control) movement phases.

The first experiment aimed at adapting a Go/No-Go task to study kinematics of responses in dominant and non-dominant (i.e., inhibition is required) conditions. We assessed the feasibility of using a low-cost portable motion tracking system to capture the timing of the peak velocity. The resulting percent Time to Peak Velocity index would help disentangling motor planning and control, being more informative than just response time, which is the most common measure of Go/No-Go performance. Moreover, using a low-cost portable technology is meant to boost the applicability of our method to a broad range of research and clinical contexts.

The second experiment aimed at using the same method to explore the different strategies used by children with ADHD or typical development when providing a dominant or non-dominant response. Combining cognitive and kinematic measures has potential for assessment and intervention of subtle differences in executive processes such as inhibition, going deeper than is possible based on accuracy alone.

5.4 Procedure and task

Participants sat on a desk and wore an accelerometer sensor on their dominant wrist. They were instructed to place the dominant hand at a specific starting position, monitored by a presence sensor, and completely extend their arm to tap on the response touchscreen. A Go/No-Go paradigm was adapted to assess the inhibition of a prepotent response. Upon comparison of a central stimulus (red/green, upwards/downwards arrow), participants were asked to select, reach, and press one of two response keys (either a red or green circle) placed one on the left and one on the right side of the central stimulus, following specific instructions. Before the start of the next trial, participants had to return their hand on the sensor. As soon as the hand was in place, the next trial started after a random delay (range = 0:2 seconds), which prevented participants from anticipating the onset of the next trial. We will refer to this variable as StimulusRandomTime and analyse its effect on participants' performance. Indeed, this variable manipulated the time available to pre-activate the sensorimotor system and predict the incoming occurrence of the central stimulus, potentially affecting the response timing (Vallesi et al., 2013). The set-up and procedure are illustrated in Figure 5.1.

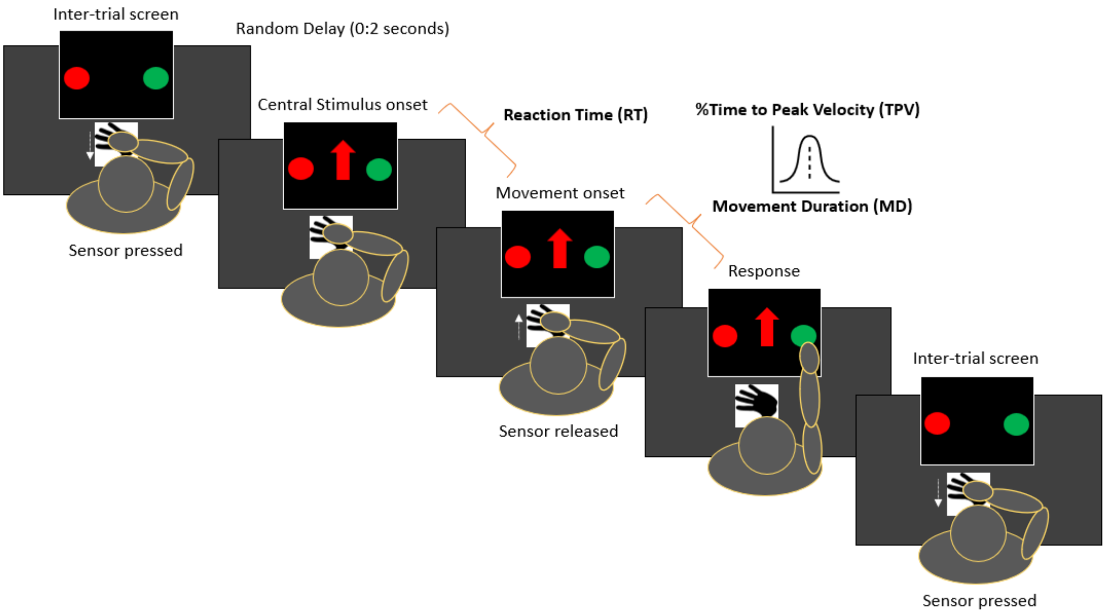


Figure 5.1. Set-up and procedure.

More in detail, participants were told to select the response key of the same colour of the central stimulus when it was an upwards/downwards (counterbalanced between participants) arrow (*dominant condition*). On the other side, they were told to select the response key of the different colour when the central stimulus was an averted (either upwards or downwards, counterbalanced between participants) arrow (*non-dominant condition*). We elicited a prepotent response for the same-colour action (occurring the 75% of times), and an inhibitory response for the alternative different-colour action (occurring the 25% of times). Two blocks were administered, with the red/green response keys being located once on the right and once on the left side of the touchscreen. To maintain participants' engagement during the task, a short (30 seconds on average) video from well-known movies appeared every 40 trials. The task lasted about 15 minutes.

Participants were instructed to reply as quickly and accurately as possible. Failure to press any keys within 2,000 ms was marked as "omission". Movements starting before the cue stimulus onset were tagged as "anticipation" (the program aborted the trial by showing no cue stimulus). Omissions and anticipations were considered invalid trials, therefore excluded from the analysis. The task ended upon completion of 160 valid trials (i.e., trial with correct/incorrect answer) or a maximum of 180 total trials (in case omissions and anticipations occurred). We then planned to exclude those responses whereby either RT or MD was less than

100 ms, being them ascribable to anticipation. We only included responses whereby the TPV was within the 5-95% range, thus considering extremes as due to extra-task movements.

5.5 Apparatus

Although motor analysis is highly informative both in research and clinical settings, kinematic studies often reneactely on expensive, bulky, and sophisticated motion capture systems which may not be affordable in most operative and experimental contexts. In order to use low-cost portable solutions and boost the applicability of motion analysis, both custom-made (Ertzgaard et al., 2016) and commercial tools have been recently evaluated. One extensively used commercial option is the Leap Motion Controller system, a small compact device containing two cameras and three infrared light diodes which has, however, spatial, and temporal limits compared to motion capture systems (Niechwiej-Szwedo et al., 2018). Another commercial possibility that seems more promising in terms of measurement reliability and validity are the inertial sensors built with 3-axis accelerometers, gyroscopes, and magnetometers. In particular, Cahill-Rowley and Rose (2017) analysed human reaching kinematics through both inertial sensors and gold standard motion capture systems. The two methods provided consistent measures of displacement, peak velocity magnitude and timing. In light of this encouraging evidence, the time is ripe for the use of low-cost accelerometers to investigate distinct neuropsychological mechanisms beneath action selection.

In the present study, we employed the GENEActiv Original 3-axis wrist worn accelerometer (size: 43 mm × 40 mm × 13 mm, weight without the strap: 16 g) to monitor participants' arm movements. The device measured accelerations through a MEMS sensor, within a range of +/− 8 g, at a 12 bit (3.9 mg) resolution with a 100 Hz logging frequency (Activinsights Ltd, 2019).

The task was implemented resorting to a JavaFX based application. To run the experiment, we employed a laptop Lenovo G50–80 (Intel Core i5–5200U (2.2 GHz), 4 GB DDR3L SDRAM, 500 GB HDD, 15.6" HD LED (1366 × 768), Intel HD Graphics 5500, Windows 10 64-bit).

The analysis of the resulting data was performed resorting to Python and primarily to "pandas" (McKinney & al., 2010), "numpy" (C. R. Harris et al., 2020), and "scipy" (Virtanen et al., 2020) libraries.

Participants responded by tapping on a 19-inch touchscreen (LG-T1910BP, response time 5 ms). The presence-absence of the participant's hand on the starting position was detected through a custom-made presence sensor based on Arduino Leonardo which sent the hand detection data to the laptop via one of its USB ports. It was connected to a ground capacitor (100 pF) and a capacitive sensor, which consisted of a copper foil wrapped with plastic film (dimension 20 cm × 12 cm, thickness 0.1 mm). The presence sensor program was written using the Arduino Capacitive Sensing Library.

5.6 Kinematic indices extraction

For each valid trial (i.e., no anticipation, no omission) we captured the following time instants:

sensor Pressed; Stimulus appeared; sensor Released; Answer given;

which from now on we will refer to as P, S, R, A.

To obtain these data, we synchronized the software logs and the accelerometer with the computer local time, thus combining the accelerometer data with the task outputs.

The time intervals that are related to the kinematic measures of interest were [S, R] which defined RT and [R, A] that corresponded to the MD and was used to compute the TPV%. In addition, the interval [P, S] determined the StimulusRandomTime.

As described in detail in S1 Appendix, the effective acceleration was individuated by means of raw accelerometer data calibration and pre-processing. Subsequently, we computed velocity and Time to Peak Velocity percentage (TPV%), which is the percentage of time spent from R to maximum peak velocity in the time interval from R to A (i.e., the MD). In the following, we walk through the methodology adopted to compute the TPV% value.

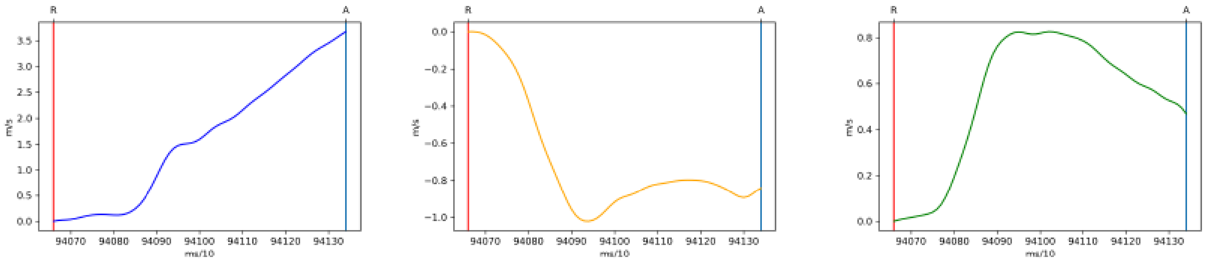
From a theoretical and mathematical point of view, the most direct way to start computing the TPV% is by applying an integration in time and obtain velocity from acceleration. In particular, let *a(t)* be the acceleration signal on one axis, the related velocity signal *v(t)* can be computed as follows:

$$v(t) = \int_{t_i}^{t_f} a(dt)dt + C,$$

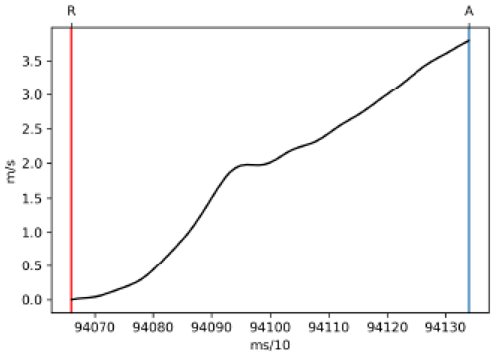
where t_i and t_f are the initial and final time instants of the movement and C is an integration constant.

However, when facing with real data and numerical functions (e.g., numerical integration), numerical errors can return unreliable velocity values.

Considering the calibrated and pre-processed acceleration (S1 Appendix), let *accRA* be the signal related to the time interval [R, A] of a specific valid trial, we applied the cumulative trapezoidal numerical integration function in order to compute velocity. In Figure 5.2, we reported the velocity components obtained by applying this function to the acceleration values of a trial. After this step, we computed the magnitude (which represents the velocity module) from its components, also shown in Figure 5.2.



x component y component z component



magnitude

Figure 5.2. Velocity signals of a trial where the error due to the acceleration bias is visible in both the x component and the magnitude (increasing monotonous curves that do not represent the expected bell shape).

Notably, the application of an integration function could lead to an incremental numerical error due to a possible bias (i.e., additive noise) present in the acceleration, visible in Figure 5.2, whereby the x component and magnitude of velocity present increasing monotonous curves rather than the expected bell shape. Such phenomenon, may lead to the creation of a “new” and “false” maximum peak at the end of MD, making the computation of the central “true” peak quite challenging. To overcome this issue, we applied the detrend function to the velocity magnitude, thus removing the signal linear trend and reducing the numerical error described above (further details are reported in S2 Appendix). While the velocity values could change due to the detrend function application, the position in time of the peak velocity appeared stable, thus allowing us to calculate the TPV% (“when”). On the other hand, we were not able to further investigate those indices based on the velocity value (“how fast”, e.g., mean velocity, value of peak velocity), as supported also by the supplementary analysis described in S3 Appendix.

Ultimately, we aimed to exclude possible extreme TPV% values that would be due to numerical errors, in cases where the detrend function was not sufficient to remove their effect on the signal. Moreover, we aimed to remove those observations with TPV% values that were unlikely related to task-related human reaching movements, but rather potentially ascribable to extra-task movements. For these reasons, the a-priori inclusion criteria for valid TPV% values comprehended those between 5% and 95%.

5.7 A kinematic adaptation of the Go/No-Go paradigm (Experiment A)

Abstract. The present work explores the distinctive contribution of motor planning and control to human reaching movements. In particular, the movements were triggered by the selection of a prepotent response (*dominant*) or, instead, by the inhibition of the prepotent response, which required the selection of an alternative one (*non-dominant*). To this end, we adapted a Go/No-Go task to investigate both the dominant and non-dominant movements of a cohort of 19 adults, utilizing kinematic measures to discriminate between the planning and control components of the two actions. In this experiment, a low-cost, easy to use, 3-axis wrist-worn accelerometer was put to good use to obtain raw acceleration data and to compute and break down its velocity components. The values obtained with this task indicate that with the inhibition of a prepotent response, the selection and execution of the alternative one yields both a longer reaction time and movement duration. Moreover, the peak velocity occurred later in time in the non-dominant response with respect to the dominant response, revealing that participants tended to indulge more in motor planning than in adjusting their movement along the way. Finally, comparing such results to the findings obtained by other means in the literature, we discuss the feasibility of an accelerometer-based analysis to disentangle distinctive cognitive mechanisms of human movements.

5.7.1 Participants

For this study, we recruited 19 neuro-typical adults aged from 18 to 26 years old (M = 22.3, SD = 1.9), among them 5 men. Recruitment took place among university students with no past or present history of clinical conditions (self-reported). They voluntarily participated in the study and did not receive compensation. All participants signed a written consent form to take part in the study, which was approved by the Ethics Committee of Psychology Research, University of Padova.

5.7.2 Statistical approach

In light of the novelty of our paradigm, an exploratory approach was elected to test different potential hypotheses through a model comparison. We investigated whether the TPV% was influenced by the random effect of participants (i.e., interpersonal variability), as well as the fixed effect of condition (within-subjects, two levels categorical factor: dominant versus non- dominant). Moreover, we checked for the effect of the random time before the central stimulus onset. The latter was a continuous independent variable that we named StimulusRandomTime. Each research hypothesis was specified as a statistical model, such that the statistical evidence of the formalised models was evaluated using information criteria (Wagenmakers & Farrell, 2004).

Mixed-effects models were employed to account for the repeated measures design of the experiment (i.e., trials nested within participants). In particular, generalized mixed-effects models were used considering the Beta distribution (with logit link function) of our dependent variable (TPV%). Indeed, the TPV% contained continuous proportions on the interval (0, 100), easily rescaled in the interval (0, 1) (TPV), and can be approximated by a Beta distribution (Douma & Weedon, 2019). The statistical analyses were conducted using the R version 4.0.2 (R Core Team, 2020), with the "glmmTMB" package (Brooks et al., 2017) to run the model comparison.

To the end of exploring our data, we specified four nested models with the TPV as dependent variable and the random effect of participants:

- **mb0** specified the hypothesis of no difference due to the independent variables and only accounted for the random effect of participants
- **mb1** specified the hypothesis of a difference due to the condition effect
- **mb2** specified the hypothesis of a difference due to the additive effect of condition and StimulusRandomTime
- **mb3** specified the hypothesis of a difference due to the interaction effect of condition and StimulusRandomTime.

The details of the model specification are depicted in Table 1. Therefore, the four models were compared through the Akaike weights (i.e., the probability of each model, given the data and the set of considered models) (Wagenmakers & Farrell, 2004), using the R package "AICcmodavg" (Mazerolle, 2020). Moreover, the models were compared using a likelihood ratio test (anova (mb0, mb1, mb2, mb3)).

Model	**Dependent variable**	**Random effect**	**Fixed effects**
`mb0`	TPV	Participants	–
`mb1`	TPV	Participants	Condition
`mb2`	TPV	Participants	Condition + StimulusRandomTime
`mb3`	TPV	Participants	Condition × StimulusRandomTime

Table 5.1. Model specification

5.7.3 Results

The 19 participants provided 2,962 correct responses, 54 incorrect ones (24 in the *dominant condition* and 30 in the *non-dominant condition*), 107 omissions (78 in the *dominant condition* and 29 in the *non-dominant condition*) and 22 anticipations. From correct responses, 59 out of 2,962 observations were discarded, since their TPV% was not comprehended within the 5-95% range. Minimum and maximum values, means and standard deviations of RT, MD, and TPV% of correct responses in each condition are reported in Table 5.2. The distribution of TPV values in each condition is shown in Figure 5.3.

RT					
Condition	n_{trials}	**min**	**max**	**M**	**SD**
Dominant	2,253	62 ms	1,373 ms	558 ms	136 ms
Non-dominant	709	335 ms	1,365 ms	601 ms	163 ms
MD					
Condition	n_{trials}	**min**	**max**	**M**	**SD**
Dominant	2,253	266 ms	1,562 ms	500 ms	167 ms
Non-dominant	709	291 ms	1,562 ms	591 ms	207 ms
TPV%					
Condition	n_{trials}	**min**	**max**	**M**	**SD**
Dominant	2,213	5.04%	94.36%	40%	15%
Non-dominant	690	6.9%	94.31%	45%	17%

Table 5.2. Descriptive statistics ($n_{participants} = 19$). Note: TPV% includes less trials due to the exclusion of extreme values.

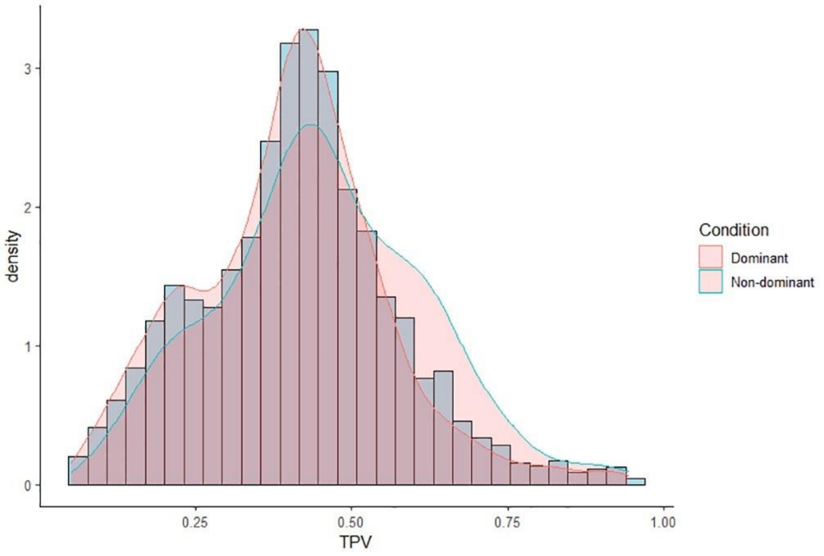


Figure 5.3. Distribution of the TPV values ($n_{trials} = 2, 903$).

The model comparison outputs, namely the degree of freedom (*Df*), the Akaike weights (*AICcWt*), the chi-squared test statistic values (χ^2) and the p-values (*p*) are reported in Table 5.3.

Model	*Df*	*AICcWt*	χ2	*p*
`mb0`	3	0.00		
`mb1`	4	0.20	49.70	<.001
`mb2`	5	0.44	3.58	.06
`mb3`	6	0.36	1.63	.20

Table 5.3. Model comparison

The most plausible model given the data and the set of considered models was **mb2** (AICcWt = 0.44), which included the random effect of participants, the additive effects of condition (statistically significant according to $p < .001$) and StimulusRandomTime (statistically non-significant according to $p = .08$). The condition effect, predicted by model **mb2**, is depicted in Figure 5.4.

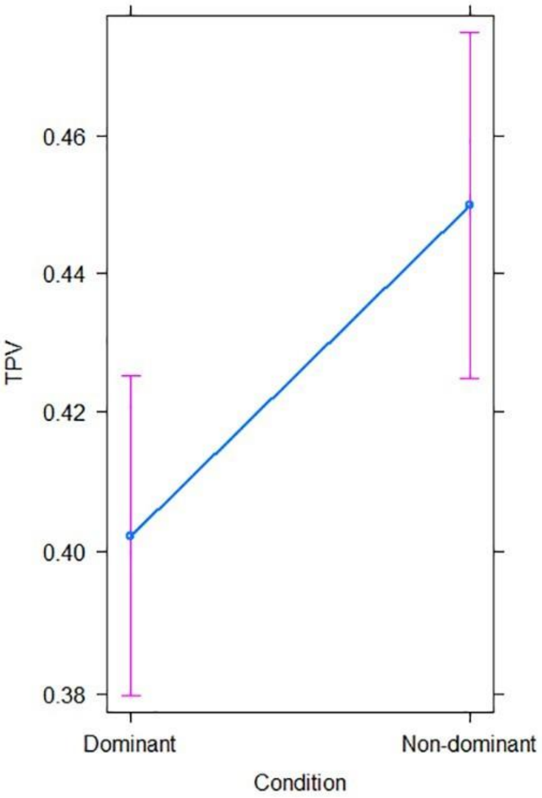


Figure 5.4. Model **mb2**: Condition effect on the TPV ($n_{participants} = 19$, $n_{trials} = 2{,}903$).

5.7.4 Discussion

The present study investigated the relative contribution of motor planning and control to the inhibition of a prepotent response. We explored neuro-typical adults' movements in a task that required a reaching either to select a prepotent, dominant response or to inhibit the dominant and select the non-dominant alternative. The descriptive statistics indicated that participants performed the non-dominant response (compared to the dominant one) by increasing both the RT (time devoted to motor planning prior to movement onset) and MD (time of motor execution). However, these two indices are not sufficient to disentangle the planning and control phases of the movement. Indeed, given that motor planning and control overlap during the MD (Glover, 2004), we analysed the Time to Peak Velocity (TPV) to further distinguish these two mechanisms. As a relative asymmetry index, whether the TPV occurred earlier or later over the MD would reflect more either planning or control. From our exploratory model comparison, we can expect people to show bigger TPV in the non-dominant compared to the dominant condition. This evidence supported the idea that adults require a greater motor planning rather than online adjustment to inhibit a prepotent response, select and perform an alternative one. Our results are consistent with the extant literature, whereby planning is devoted to process cognitive information, and control is dedicated to get on a target and adjust to its specific spatial features (Glover, 2004).

The present work also employed a low-cost wearable 3-axis accelerometer to investigate human motor inhibition. The inertial sensors built with 3-axis accelerometers, gyroscopes, and magnetometers have been indicated as promising commercial tools to study the kinematics of human movements and overcome the constraints of expensive motion capture systems. Although they have the potential of being portable and wearable, they appeared to provide accurate and reliable data only for some kinematic indices, such as the value and timing of peak velocity (Cahill-Rowley & Rose, 2017). Based on our kinematic measurements and analyses, the kinematic indices built upon the velocity value did not appear sufficiently reliable and valid (as reported in S3 Appendix). On the other hand, those related to the velocity shape over time seemed to be valid indices. Indeed, our average Time to Peak Velocity percentage (TPV%) was consistent with those reported by previous studies, similar tasks and motion capture systems with highest level of precision (Domellöf et al., 2020). Therefore, we support the use of a commercial and low-cost 3-axis accelerometer to calculate the TPV% and compare participants' performance.

It is worth mentioning that the present study has some limitations. Firstly, our sample did not include a balanced number of women and men, thus preventing us from controlling for potential gender differences, which are beyond the scope of this study. Secondly, we could not base our sample size specification on previous literature that tested motor inhibition through the TPV%. Therefore, our findings should be interpreted as preliminary and exploratory indications to develop future confirmatory studies. Moreover, future studies might include video recordings and offline coding of the experimental sessions, thus checking for potential cases where participants show extra-task movements that could result in anomalous trials. Ultimately, from a methodological point of view, to further increase the accuracy of the pre-processing, in particular to remove the gravity component from the acquired acceleration, future studies could use a combination of accelerometer and gyroscope. In this way, data related to the orientation of the accelerometer would be available in order to remove the gravitational acceleration. However, the gyroscope would not solve the numerical errors driven by possible accelerometer bias and numerical mathematical functions. These issues could be addressed from an algorithmic point of view, with the evaluation of other methods and models in order to process raw accelerometer data in a way that could reduce the numerical errors. An algorithm class that could obtain promising results with huge amount of raw data is the learning class. Machine and deep learning algorithms could study different input signals and learning information from all the data. In this case, a supervised data set would incrementally improve the results but also an unsupervised approach could be taken into consideration.

Overall, this study expands on our understanding of which motor strategy is successful for neurotypical adults to inhibit prepotent reaching movements. This would lay the foundations for investigating the atypical strategies implemented by individuals and clinical groups with inefficient motor inhibition. Although motor inhibition is affected in a number of neurodevelopmental disorders, the underlying multifaceted mechanisms shape unique phenotypes that require appropriate and specific interventions (Mirabella, 2021). For instance, inhibitory skills are linked to individual traits such as impulsiveness (Aichert et al., 2012), and inhibitory control deficits have been found through Go/No-Go tasks in autism spectrum disorder (Uzefovsky et al., 2016), whereby difficulties in inhibiting prepotent responses seem to be associated with higher-order repetitive behaviours (Mosconi et al., 2009). Moreover, inhibition is part of a broader category of control processes named executive functions, which are distinguished but correlated (Miyake & Friedman, 2012), and play a fundamental role in everyday action selection and execution. Indeed, although difficulties and impairments in the action domain are common to several clinical conditions (i.e., multiple sclerosis, Alzheimer's disease, Parkin- son's disease), the underlying sensory, motor, and cognitive mechanisms might dramatically differ among patients (Bisio et al., 2017; Forti et al., 2011; Schröter et al., 2003; Smiley-Oyen et al., 2007). Future studies could utilise the present method and apparatus to disentangle the planning and control mechanisms of motor actions that involve different neuropsychological abilities, thus providing fundamental insights on the design of motor and psychological interventions.

5.8 Beyond accuracy: reduced motor planning in children with ADHD (Experiment B)

Abstract. To flexibly regulate their behaviour, children's ability to inhibit prepotent responses arises from cognitive and motor mechanisms that have an intertwined developmental trajectory. Subtle differences in planning and control can contribute to impulsive behaviours, which are common in Attention Deficit and Hyperactivity Disorder (ADHD) and difficult to be assessed and trained. We adapted a Go/No-Go task and employed a portable, low-cost kinematic sensor to explore the different strategies used by children with ADHD or typical development to provide a prepotent response (*dominant* condition) or inhibit the prepotent and select an alternative one (*non-dominant* condition). Although no group difference emerged on accuracy levels, the kinematic analysis of correct responses revealed that, unlike neurotypical children, those with ADHD did not show increased motor planning in non-dominant compared to dominant trials. In our simple task, motor control could have compensated leading to good accuracy. However, this strategy might make inhibition harder in more naturalistic situations that involve complex actions. Combining cognitive and kinematic measures has potential for assessment and intervention of subtle differences in executive processes such as inhibition, going deeper than is possible based on accuracy alone.

5.8.1 Hypotheses

In Experiment A, we have found that, to correctly inhibit a prepotent response and select the instructed alternative, neurotypical adults show longer RT and MD, as well as increased TPV, overall dedicating more resources to motor planning than monitoring and control of ongoing movements (Angeli et al., 2021). Assuming that this is the motor strategy that has been established as most effective in adults, a developmental perspective is needed to understand how it specializes during childhood and is potentially subject to deviation in cases of atypical development. We therefore expect age-related differences in the kinematic profile of motor planning and control necessary to inhibit prepotent responses. Moreover, we hypothesize that children with ADHD, compared to neurotypical controls, would show greater difficulties inhibiting the prepotent response, which the literature also refers to as motor impulsivity (Lage et al., 2012). We expect children with ADHD to make more errors than controls in the non-dominant condition, and show an atypical motor profile, with reduced or less effective motor planning. As markers of motor impulsivity, we particularly expect reduced RT and TPV in the group of children with ADHD.

5.8.2 Participants

We recruited 17 children with ADHD (4 female children) from 6 to 15 years of age (M =9.4, SD = 2.2), and 26 children with Typical Development (TD control group; 10 female children), from 6 to 13 years of age (M = 9.2, SD = 2.1). Three additional participants (2 in the ADHD and 1 in the TD group) were excluded due to technical issues that prevented them from completing at least 50% of the trials.

Data collection was planned to take place between December 2019 and April 2020, as part of a collaborative project with a clinical centre in northern Italy, which is specialised in ADHD diagnosis and intervention. Data collection was interrupted at the beginning of the Covid-19 pandemic and resumed when the centre was authorised to reopen to external operators (i.e., the investigators). Thus, a further phase of data collection was carried out between October and December 2021. The partner centre had an average intake of 60 children, and all were offered voluntary participation in the study. The final sample of children with ADHD was determined by the number of parents and children who joined and participated. Since ADHD is an inherently heterogeneous condition (Sonuga-Barke & Thapar, 2021; Wåhlstedt et al., 2009), we have not established inclusion or exclusion criteria based on IQ, level of support needed, or possible presence of co-occurring medical or neuropsychological conditions. Thus, we aimed to include participants from the heterogeneous ADHD population. Psychologists confirmed children's diagnosis and provided IQ assessments through the WISC-IV scale. Moreover, we collected parent-reported questionnaires on the child's executive (Executive Functions Questionnaire – Q.FE (Schweiger & Marzocchi, 2008)) and sensory profile (Short Sensory Profile – SSP (McIntosh et al., 1999)), as well as the presence and severity of restricted and repetitive behaviours (Repetitive Behavior Scale-Revised – RBS-R) (Fulceri et al., 2016). A convenient control group of children with typical development in the same age range was tested at the University of Padova. According to parents' reports, typically developing children had no medical nor neuropsychological conditions.

Characteristics of the ADHD group are provided in Table S3 of S4 Appendix, which includes IQs, and scores from the parent reported assessment. Diagnostic subtypes and comorbidities are also described in S4 Appendix. All children's parents signed a written consent form. All experimental methods received ethical approval from the Research Ethics Committee of the School of Psychology, University of Padova (protocol no. 3251). The experiment was carried out in accordance with the approved guidelines and regulations.

5.8.3 Results

To analyse children's performance, we considered 4 dependent variables. Accuracy indicates the percentage of correct responses out of the total number of valid responses (after discarding anticipations and omissions). RT measures the time from the appearance of the central stimulus to the onset of movement (the time when the hand is raised by the presence sensor). MD measures the duration of the movement (from when the sensor is released to when a response is given). We then computed the percent Time to Peak Velocity (TPV), which is the percentage of MD spent from movement onset to maximum peak velocity. Our previous work describes the rationale behind the selection of these kinematic variables and their reliability, the steps for data calibration and pre-processing of raw acceleration data, as well as the computation of TPV values (Experiment A) (Angeli et al., 2021).

TD children provided 4,104 valid responses out of 4,526 total trials (91%). Children with ADHD provided 2472 valid responses out of 3,023 total trials (82%). This demonstrates both successful task competition (with our task being adequate for both groups), and low rate of discarded data. From valid trials performed by both groups, we excluded 217 out of 6,576 responses (3.3%), whereby either RT or MD was less than 100 ms, or the TPV was out of the 5-95% range. Excluded responses were not further analysed. Final dataset comprehended 6,359 observations.

An exploratory approach was elected to test different potential hypotheses linking each dependent variable to the predictors of interest. Through separated sets of model comparisons, different research hypotheses were specified as statistical models, and their statistical evidence was evaluated using information criteria (Wagenmakers & Farrell, 2004). Generalized mixed-effects models were employed to account for the repeated measures design of the experiment (i.e., trials nested within participants, which has been included as a random effect in the analyses) and specify the distribution of each dependent variable. For each dependent variable, a set of models were compared through the Akaike weights (AICWt) (i.e., the probability of each model, given the data and the set of considered models) (Wagenmakers & Farrell, 2004), using the *AICcmodavg* (Wagenmakers & Farrell, 2004) R package. Then, likelihood ratio tests were used to compare the chosen models, and test the effects predicted by the best model.

As an index of goodness of prediction, conditional R^2 (the ratio of variance explained by fixed and random effects over total variance) and marginal R^2 (the ratio of variance explained by fixed effects over total variance) were calculated to quantify the variance explained by the whole model (including the contribution of individual variability) or the fixed effects only (excluding the contribution of individual variability) (Nakagawa & Schielzeth, 2013). Higher percentages of explained variance indicates a stronger strength of association between the dependent variable and the predictors, with the selected model making better predictions. The analyses have been run with R, version 4.0.2 (R Core Team, 2020).

We separately investigated whether each dependent variable (Accuracy, RT, MD, TPV) was influenced by the fixed effects of Condition (within-subjects, two levels categorical factor: dominant versus non-dominant), Group (between-subjects, two levels categorical factor: ADHD versus TD), and Age (continuous numeric variable). All models accounted for the random effect of participants (i.e., interpersonal variability). We considered the five models that follow.

- **m0** (null model) specified the hypothesis of no difference due to the independent variables and only accounted for individual variability
- **m1** specified the hypothesis of a Condition effect
- **m2** specified the hypothesis of additive Condition and Group effects

- **m3** specified the hypothesis of additive Condition, Group and Age effects
- **m4** specified the hypothesis of a two-way interaction effect between Condition and Group, with the additive Age effect.

Accuracy

After excluding omissions and anticipations, children with ADHD provided 2,234 correct and 137 incorrect (i.e., the wrong answer was provided) responses. TD children provided 3,777 correct and 211 incorrect responses (percentages of correct responses according to Group and Condition are reported in Table S1, S4 Appendix). Model comparison was run with the *glmmTMB* (Brooks et al., 2017) R package. The binomial distribution was specified to account for the binary nature of the dependent variable (1 = correct; 0 = incorrect). According to AIC weights (AICWt_m0 < .01; AICWt_m1 = .39; AICWt_m2 = .14; AICWt_m3 = .15; AICWt_m4 = .14), the best model was **m1** (39% probability of being the best model; $\chi^2 = 369.3$; $p < .001$), which revealed a significant effect of Condition ($p < .001$). As visualized in Figure 5.6, accuracy was reduced in the non-dominant condition.

Conditional R^2 (the ratio of variance explained by fixed and random effects over total variance) indicates that **m1** explains 33% of variance, whereas marginal R^2 (the ratio of variance explained by fixed effects over total variance) indicates that Condition explains 19% of variance. Therefore, 14% of variance was explained by individual variability (i.e., the random effect of participants).

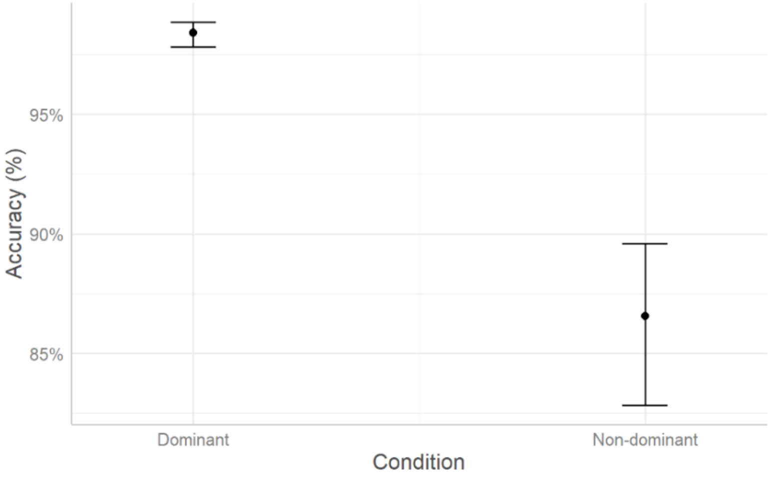


Figure 5.6. Predicted effect of Condition on Accuracy ($n_{trials} = 6,359$, $n_{ADHD} = 17$, $n_{TD} = 26$, estimated marginal means with whiskers representing 95% confidence intervals).

Kinematics

We further explored kinematic features of correct responses to investigate whether, beyond accuracy, children with ADHD would show subtle motor atypicalities. Means and standard deviations of RT, MD, and TPV of correct responses in each condition and group are reported in Table S2, S4 Appendix. In S4 Appendix, we have also conducted a visual inspection of the velocity shape and trend across movement time, describing group and individual differences. At the group level, children with ADHD show a flatter velocity profile over the time course of the movement, with a less evident peak velocity at the beginning of the movement.

RT. Model comparison was run with the *glmer* function of *lme4* (Bates et al., 2015) R package. The gamma distribution was specified to account for the positively skewed nature of the dependent variable. According to AIC weights (AICWt_m0 < .001; AICWt_m1 < .01; AICWt_m2 < .01; AICWt_m3 = .19; AICWt_m4 = .80), the best model is **m4** (80% probability of being the best model; $\chi^2 = 4.9$; $p = .03$), which reveals a significant interaction between Condition and Group ($p = .03$), and a significant effect of Age ($p < .001$). As visualized in Figure 5.7, TD children showed increased RT in the non-dominant compared to the dominant condition, thus devoting more time to motor planning when the response required inhibition. This pattern was not present in children with ADHD, who did not differentiate RT depending on Condition. Moreover, there is a negative association between RT and Age, with RT decreasing at older ages, regardless of group.

Conditional R^2 (the ratio of variance explained by fixed and random effects over total variance) indicates that **m4** explains 37% of variance, whereas marginal R^2 (the ratio of variance explained by fixed effects over total variance) indicates that Condition*Group and Age explain 28% of variance. Therefore, 9% of variance is explained by individual variability (i.e., the random effect of participants).

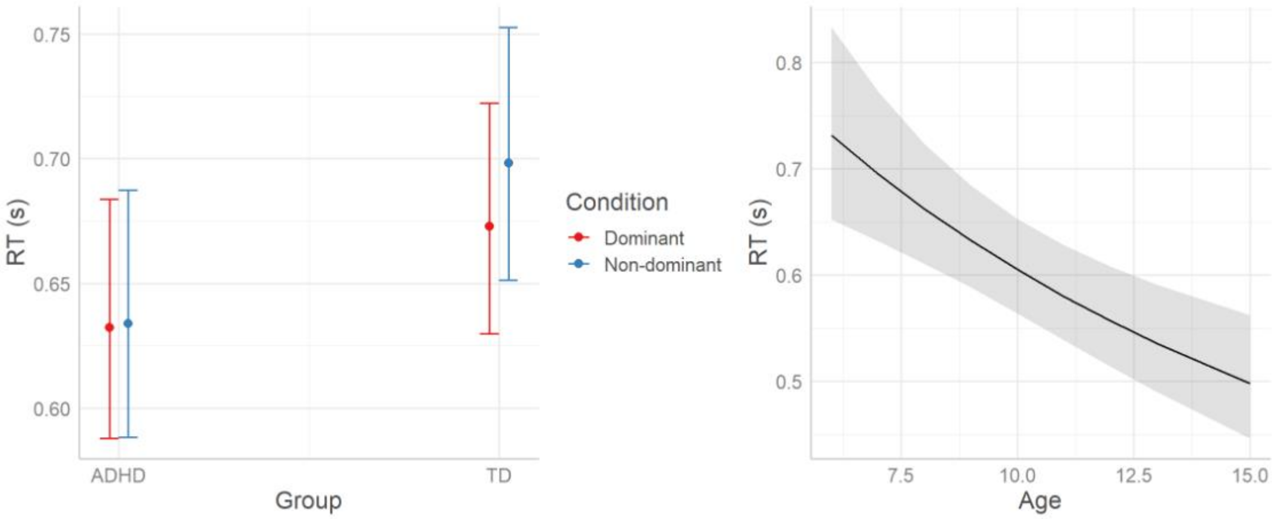


Figure 5.7. Predicted effects of Condition*Group and Age on RT ($n_{trials} = 6011$, $n_{ADHD} = 17$, $n_{TD} = 26$, RT is expressed in seconds, estimated marginal means with whiskers representing 95% confidence interval; for the Age effect, shaded area represents the 95% confidence interval).

MD. Model comparison was run with the *glmer* function of *lme4* (Bates et al., 2015) R package. The gamma distribution was specified to account for the positively skewed nature of the dependent variable. According to AIC weights (AICWt_m0 < .001; AICWt_m1 < .29; AICWt_m2 < .41; AICWt_m3 = .22; AICWt_m4 = .08), the best model is **m2** (41% probability of being the best model; $\chi^2 = 2.7$; $p = .1$), which reveals a significant effect of Condition ($p < .001$), and a non-significant effect of Group ($p = .09$). As visualized in Figure 5.8, MD increased in the non-dominant condition compared to the dominant condition.

Conditional R^2 (the ratio of variance explained by fixed and random effects over total variance) indicates that **m4** explains 38% of variance, whereas marginal R^2 (the ratio of variance explained by fixed effects over total variance) indicates that Condition and Group explain 20% of variance. Therefore, 18% of variance is explained by individual variability (i.e., the random effect of participants).

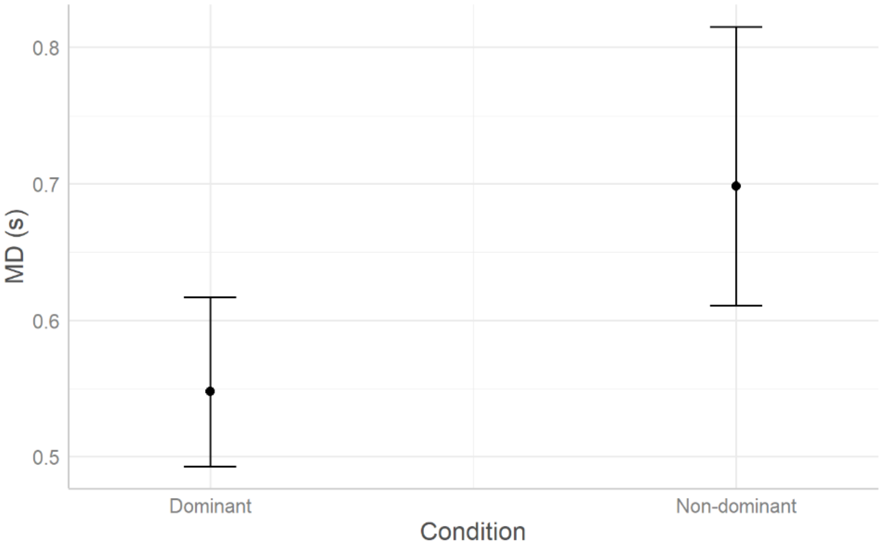


Figure 5.8. Predicted effects of Condition on MD (n_{trials} = 6011, n_{ADHD} = 17, n_{TD} = 26, MD is expressed in seconds, estimated marginal means with whiskers representing 95% confidence interval).

TPV. Model comparison was run with the *glmmTMB* (Brooks et al., 2017) R package. The beta distribution was specified to account for the nature of the dependent variable (continuous proportions on the interval 0:1). According to AIC weights (AICWt_m0 < .01; AICWt_m1 = .08; AICWt_m2 = .06; AICWt_m3 = .04; AICWt_m4 = .83), the best model is **m4** (83% probability of being the best model; χ^2 = 8.3; p = .004), which reveals a significant interaction between Condition and Group (p = .004), and a non-significant effect of Age (p = .3). As visualized in Figure 5.9, TD children showed increased TPV in the non-dominant compared to the dominant condition, thus devoting more time to motor planning when the response required inhibition. This pattern was not present in children with ADHD, who did not differentiate TPV depending on Condition. At both the group and individual level, further graphical inspection of velocity shape across time is described in S4 Appendix.

Conditional R^2 (the ratio of variance explained by fixed and random effects over total variance) indicates that **m4** explains 71% of variance, whereas marginal R^2 (the ratio of variance explained by fixed effects over total variance) indicates that Condition*Group and Age explain 9% of variance. Therefore, 62% of variance is explained by individual variability (i.e., the random effect of participants).

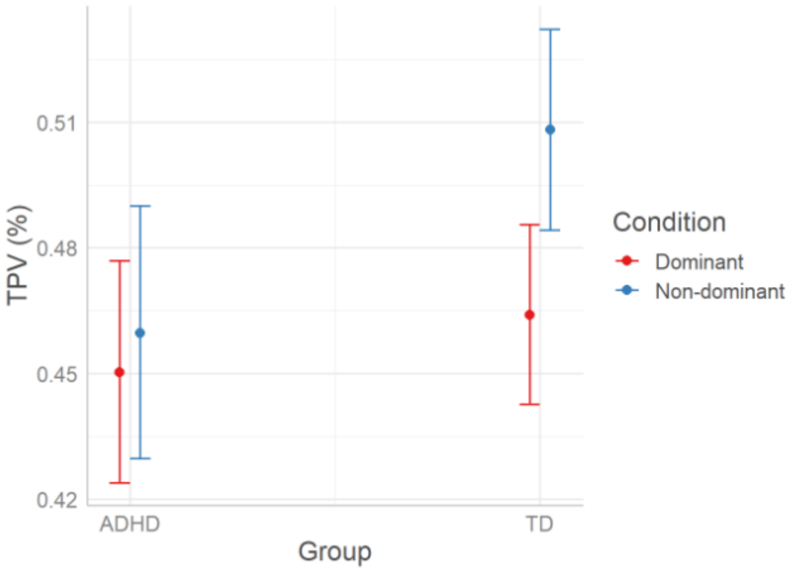


Figure 5.9. Predicted effects of Condition*Group and Age on TPV ($n_{trials} = 6011$, $n_{ADHD} = 17$, $n_{TD} = 26$, TPV is expressed as a percentage within the 0:1 range, estimated marginal means with whiskers representing 95% confidence interval).

5.8.4 Discussion

The present experiment explored the mechanisms underlying the inhibition of a prepotent motor response, which is frequently reported to be impaired in children with ADHD. The performance of the ADHD and TD groups at our motor adaptation of the Go/No-Go task, showed both similarities and differences.

Accuracy. Both ADHD and TD children made more errors in the non-dominant compared to the dominant condition. This indicates that the task was effective in inducing a prepotent response in the dominant condition, which was the more frequent one, and facilitated by the requirement to match the Go stimulus and the response option by colour. Children with ADHD and typical development were equally accurate in selecting the correct response, so that no group difference was found on accuracy levels. This unexpected result could be due to the ease of the task, which required a rather simple motor response, as also evidenced by the high percentages of correct responses. In tasks with greater time pressure or greater complexity of the motor action required to answer, we could expect more marked differences between the two groups. Although the task was based on the central properties of Go/No-Go (i.e., more frequent administration of the dominant condition), some differences may have made our task easier than traditional ones at the level of inhibition of prepotent responses. In particular, responding by reaching rather than quickly pressing a button may have allowed participants more time to process the cue, recall the instructions, and redirect their response during movement. On the one hand, this may explain the high accuracy, and at the same time allowed us to study not only reaction time (movement pre-planning), but also movement duration (online control of the response).

Motor planning. The main findings of this study revealed that, beyond accuracy, the ADHD group showed different motor patterns that possibly indicate reduced motor planning compared to the TD group. In the non-dominant condition compared to the dominant condition, TD children spent more time planning the movement, which resulted in longer Reaction Time (RT) and greater percent Time to Peak Velocity (TPV). Indeed, a higher relative time to peak velocity (i.e., greater TPV) is an efficient strategy of the motor system, that reduces the time and resources needed for online movement correction (Lage et al., 2013). On the other hand, children with ADHD did not modulate RT and TPV according to condition, not dedicating more time to motor planning when needed to inhibit the prepotent response. This subtle lack of flexibility in adjusting the motor and cognitive strategies to the task demands can be interpreted as a marker of motor and cognitive impulsivity. Our findings are in line with previous literature showing that atypical activation of premotor systems may contribute to impaired response inhibition in children with ADHD (Suskauer et al., 2008). There is an interesting debate in the literature on the link between motor preparation and spatial attention (Craighero & Rizzolatti, 2005; Smith & Schenk, 2012), which could be further explored to understand the link between cognition and movement in ADHD.

Motor control. Across both groups, children showed increased Movement Duration (MD) in non-dominant versus dominant condition. Despite being non statistically significant, the more plausible model to explain our data also included the Group effect, with children with ADHD, compared to controls, having longer MD. This tendency potentially indicates that they are controlling their movement along the way, instead of preplanning. This is also suggested by the smaller TPV captured in the ADHD group across conditions, with higher portion of movement being dedicated to the deceleration phase, that usually stands for motor control (Glover, 2004). We might speculate that children with ADHD employ different motor and cognitive strategies, with greater reliance on ongoing monitoring and readjustment than planning of movements and actions. This result can contribute to shedding light on previous findings that reported increased movement variability in children with ADHD (Demers et al., 2013). This has often been interpreted as an indication of poor motor control, when instead it could be a compensatory strategy that, given a reduced planning, requires more online adjustments during movement execution. Previous evidence suggests that increased activation of prefrontal areas can help children with ADHD compensate for atypical activation of premotor areas in Go/No-Go tasks (Suskauer et al., 2008). Online control might help children with ADHD compensate for planning difficulties, which may be sufficient to achieve good accuracy in very simple tasks as the one employed in our work. Indeed, they chose between two alternatives that differed only in one motor (i.e., the movement direction: reaching the key to the right or to the left of the central stimulus) and cognitive (i.e., the response key colour) parameter. However, this might not be sufficient in more naturalistic situations, in which alternative choices differ in more complex kinematic parameters (e.g., using the right arm or the left arm to respond), or require finer cognitive processing (e.g., selecting the most appropriate behaviour according to a specific social context). Future studies would benefit from the use of additional kinematic indices that capture online motor correction more precisely (e.g., number of direction changes and acceleration/deceleration units).

Age. We can also see a progressive reduction in RT as the age of the participants increases, which is consistent with decades of findings from developmental studies (Eckert & Eichorn, 1977). This suggests that motor planning becomes globally more effective and rapid with age, and therefore requires fewer cognitive resources. Given the low sample size, the statistical models tested included the age variable as an additive effect (i.e., irrespective of experimental condition and group membership). Thus, we accounted for the differences attributable to the age of participants in the accuracy and overall kinematic profile. However, we did not specifically assess the role of age in interaction with the other predictors (i.e., experimental condition and group membership). Future studies with appropriate sample sizes and broader age ranges may further investigate developmental changes in inhibitory strategies, also exploring potential ADHD-related differences.

Limitations. It is worth mentioning that the present study has some limitations. As we were not interested in assessing gender differences, our sample is not balanced by participant gender, which reduces its representativeness of the general population. In addition, the sample size was determined by the number of families that agreed to participate in the study. Given the complexity of the experimental design (i.e., multiple dependent and independent measures are of interest), its exploratory nature, and the paucity of prior evidence on which to estimate expected effect sizes and appropriate sample sizes, our sample size may be insufficient to reveal further differences between groups. Further inferential research will be needed to confirm the considerations presented in this paper. Moreover, research on developmental populations with specific conditions frequently suffers from small sample sizes and even single-case studies. Replication of studies, meta-analyses and multi-lab projects would help deal with this issue in the long run of knowledge acquisition, whereby every study contributes to a piece of the puzzle.

Future perspectives. In everyday life, children constantly perform actions that require planning and control, as well as inhibition of automatic behaviours as the demands of their environment change. Further research is needed to investigate the implications of atypical motor and cognitive inhibition on the daily life, learning, and social skills of children with ADHD. For instance, some children with ADHD show stereotypies, which are involuntary, restricted and repetitive patterns of behaviours that limit the child's resources to learn and practice various, appropriate and goal-directed actions (K. M. Harris et al., 2008; Mahone et al., 2004, 2014). Specifically, motor stereotypies are present in both neurodevelopmental conditions and typical development (Ghosh et al., 2013), and might be related to ineffective motor planning (Houdayer et al., 2014) and inhibitory difficulties (Mirabella et al., 2020). Indeed, motor-related cortical potentials in premotor areas, which anticipate voluntary motor actions, are found to be absent before stereotypy onset in typical development (Houdayer et al., 2014). Stereotypies are mostly studied in Autism Spectrum Disorder (ASD), as they are core symptoms of those conditions (American Psychiatric Association, 2013). However, they are frequently found in ADHD, and show similar characteristics across ASD and ADHD (Brierley et al., 2021), which often co-occur, share clinical manifestations, and entail impairments in overlapping mechanisms (Jang et al., 2013; Sokolova et al., 2017). Notably, stereotypies can be related to cross-diagnostic sensory, motor, and cognitive mechanisms. Atypical inhibition of prepotent responses is correlated with repetitive behaviours, with differences between higher-order (preoccupations, restricted interests, compulsive routines, ritualistic behaviours) and sensorimotor (repetitive movements and sensory preoccupations) stereotypies (Faja & Nelson Darling, 2019; Mosconi et al., 2009). Moreover, stereotypies are associated with sensory difficulties (Fetta et al., 2021), that can be present in ADHD (Fuermaier et al., 2018; Little et al., 2018; Shimizu et al., 2014), and are bounded to motor and cognitive processes through complex, dynamic, and multidirectional relationships. We can speculate that those children with greater stereotypies could have less effective sensory and executive profiles, as well as motor planning difficulties. They might need to devote more resources to motor control to effectively inhibit a prepotent response. Future studies may employ our paradigm to better understand whether atypical cognitive and motor inhibition may contribute to broader individual differences in everyday sensory, cognitive, and social functioning. Studies with more hypothesis-driven approaches and appropriate sample size would allow to draw clearer, more inferential conclusions on the complex relationships between these variables.

This study opens the door to important application challenges in bringing these methods and knowledge into clinical practice. It would be crucial to integrate the kinematic analysis to the classical neuropsychological tests that evaluate executive functions, to better understand how a response to a given test is planned and adjusted along the way. In this regard, the distinction between reaction time and movement duration is a promising perspective for neuropsychological research, as it allows a distinction to be made between two different mechanisms underlying a response (i.e., planning and control). These nuances are often obscured by the use of total response time in the literature. Moreover, this method would facilitate not only the identification of specific difficulties and the monitoring of the treatment effects, but also serve as an intervention tool itself. For instance, using kinematic measures as biofeedback could promote patients' awareness of their behaviours and facilitate learning strategies to modify them. Although the use of inexpensive and portable kinematic sensors removes one of the barriers to its use in the clinic, the difficulty of analysing and interpreting the raw data obtained with such instruments remains. To overcome this obstacle, it will be necessary for researchers to develop and make available user-friendly software that process the raw kinematic data and calculate performance indices that are interpretable by clinicians. To this end, we first need large-scale validation studies that provide normative values and risk indices to evaluate an individual's performance.

5.9 Conclusions

Integrating kinematic measures to traditional neuropsychological tests has potential to surface motor planning and control aspects beneath responses, being more informative than accuracy alone in understanding individuals' performance. The use of low-cost, portable, commercially available motion tracking systems is a feasible and promising way to apply this method to broad research and clinical settings, being also affordable for local services that conduct diagnoses and intervention. We specifically investigated the way people inhibit a prepotent response, select and execute an instructed alternative. However, this approach can be implemented to understand the motor underpinnings of a vast range of cognitive mechanisms that are pivotal to action.

To accurately inhibit a prepotent response and perform an alternative, neurotypical adults rely more on motor planning than in adjusting their movement along the way. Children with ADHD can exhibit similar accuracy than neurotypical controls in simple tasks tapping on the inhibition of prepotent motor responses. However, accurate inhibition appears to be achieved through different mechanisms, including less motor planning and greater ongoing control of movements. Although online control of one's own responses may be sufficient to compensate for planning difficulties in simple experimental tasks, this could profoundly impact the behaviour of children with ADHD in everyday life contexts, which involve very complex choices among numerous possible alternatives.

General conclusions and future perspectives

Having a body means perceiving what is happening inside and outside us, moving to act on the environment, using cognitive resources to monitor the process. To be meaningful, experiences must comply with the physical rules of multisensory interactions, elicit a sense of Agency, and pass the scrutiny of the cognitive processes that run the mind. These are the foundations for embodied experience, they evolve throughout the life span and undertake atypical developmental trajectories.

In the first study of this thesis, I highlighted the role of perceptual and multisensory characteristics of the environment in the way an individual situates his or her body and self in space. I emphasised that virtual reality and head-mounted displays have different visuo-proprioceptive characteristics from reality and therefore alter the mechanisms underlying self-location. On the one hand, this different perceptual functioning reduces self-location accuracy of children and adults with typical development. On the other hand, the multisensory diversity of virtual environments may facilitate individuals with different multisensory development and functioning, as in the case of autism. This tells us that, although we still know little about it, virtual reality can be used to understand (and perhaps change) the way people with different multisensory profiles perceive their bodies in space.

In the second study of this thesis, I emphasised the importance of the sense of agency that an individual perceives when their actions are followed by congruent effects on the external world. This central mechanism in the construction of the concept of self is still little studied in child development, especially in cases of atypical trajectories and neurodiversity. Above all, the sense of agency is studied through laboratory experiments and tasks that are far from capturing the essence of this construct in ecological and naturalistic contexts. To further study this phenomenon, analysing its components of multisensory congruence (on a temporal, spatial and semantic level) between action and affect, virtual reality has the advantage of immersing the user in controlled and experimentally manipulable situations, which nevertheless achieve greater levels of ecology than the classical experimental tasks used in psychology.

In the third study of the thesis, I investigated the link between movement and cognition in a prepotent response inhibition task. Inhibition is part of the category of executive functions and is a fundamental component of the top-down control with which people direct their actions. I have emphasised the advantages of using portable motion capture tools to reveal the motor strategies underlying cognitive responses. This perspective can be further enhanced by using virtual reality headsets, which increasingly include motion sensors (of the body, eyes, facial muscles) that provide unique information on how individuals interact with environments designed to resemble reality. The additional advantage is the possibility of exposing the person to cognitive tasks that are a good approximation of the everyday tasks we solve at any given time and are a far from what traditional tests used in neuropsychology require.

It seems clear that a major limitation to the potential of virtual reality to test (and train) human perception, action, and cognition is its actual ability to resemble reality (and therefore engage similar neuropsychological functions). The field of human-computer interaction has for many years posed the problem of creating embodiment in technology-mediated experiences. Embodiment is what blurs the neural distinction between real and virtual and opens the way for the integration of experience into the self, and thus for change and learning. The joint objective is to have tools that expands our possibilities for research, education, and intervention. The question is certainly a technical one: how to create technologies that are 'good enough'. However, there has been little progress in studying the way people with different profiles perceive, interact, and learn within virtual environments. Perhaps what we need is not a 'perfect' virtual reality (i.e., faithful reproduction of reality). Perhaps what we should try to understand is what are the things that we can only do in virtual reality and not in reality. And above all, which of these that we can only do in virtual reality will benefit the individual? We will never have 'good' technology solutions if we do not bring the focus back to the 'human' side of the interaction (or maybe relationship). It is essential to assess the subjective, behavioural, psychophysiological, and neural responses that are elicited by technology-mediated experiences, and ultimately take individual differences (and needs) into proper consideration.

This is particularly critical when moving from research to clinical practice. We are still far from developing applications that go beyond the fascination of technology and rather spring from a deep understanding of the specific neuropsychological processes to be nurtured in individuals. Most importantly, we cannot risk applications of technology that are theoretically promising being considered as proper interventions before we have substantial evidence of their short- and long-term effects, and effectiveness in promoting the person development and well-being.

Ultimately, if we forget that human beings are social beings, perception, action, and cognition are baseless pillars of human-computer interactions. Connection with others is at the foundation of our physical, psychological, and social health. The challenge is not in the future but in the present: how do we use technology to feel close to each other? How can we feel co-present even at a distance? Do we want to make virtual experiences with others as close to reality as possible? Do we want to touch and be touched in virtual worlds?

Asking ourselves these questions is fundamental to understanding not only 'what' we can do with technology, but more importantly 'how' and 'why’ and constitutes a collective responsibility to shape the humanity of the future.

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Appendices

S1 Appendix

Acceleration calibration and preprocessing

The acceleration calibration and preprocessing analysis has been run on the data collected by an external experimenter (not part of the cohort involved in the trials) who repeated multiple selection tasks, just as a participant. Within each task, the experimenter answered to a central cue stimulus by tapping a central response key below the cue. In this way, the displacement remained roughly the same for each trial. In particular, the experimenter performed 40 trials: 1 anticipation, 2 omissions, 37 valid answers. The subsequent analysis focused on the raw acceleration signals that started when the sensor was pressed for the first trial and ended when the last valid answer was given.

The accelerometer data were sampled at 100 Hz (i.e., data sampled every 10 ms) and data were stored in g units for offline analyses.

Considering the 3-axis accelerometer, the principal output was, for each axis, the measured signal, which may be broken into the following components [1]:

$$\textit{acquired acceleration} = \textit{effective acceleration} + \textit{gravity acceleration} + \textit{noise}.$$

In order to examine the true movements of the participants, we processed the *acquired acceleration* components to obtain their corresponding *effective acceleration* ones, as raw acceleration signals also contained noise, which could include an offset error, and gravity. In particular, the separation of the latter components becomes increasingly difficult during rotational movements. In fact, in the case of rotational movements (which were observed during our experimental task), the frequency domains of the movement-related component and the gravitational component can overlap, thus their separation can become challenging [1].

Resorting to state of the art approaches [1], the effective acceleration was extracted implementing the following two key steps (Table 1): (a) a band-pass filter, and, (b) an offset estimation and subtraction step. We now proceed expanding the discussion regarding their use in this work.

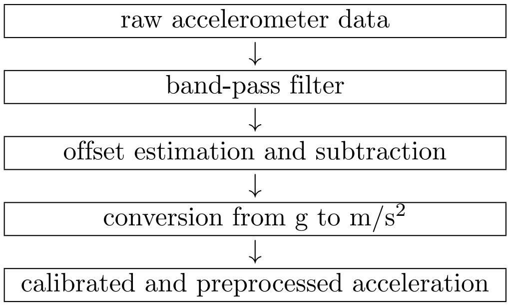
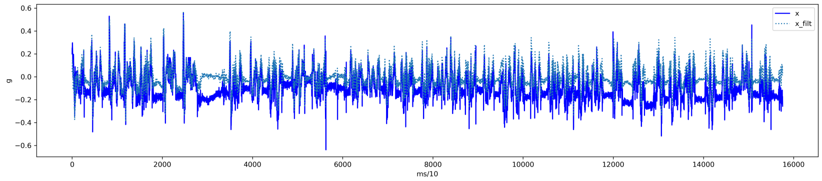


Table 1. Acceleration calibration and preprocessing.

Following [1], a 4th order Butterworth band-pass filter with cut-off frequencies equal to 0.2-15 Hz was applied to the signal. The filter cut-off frequency of 0.2 Hz was chosen on the presumption that most daily movements of human body parts occur at frequencies higher than 0.2 Hz. The cut-off frequency of 15 Hz was instead chosen to remove the effect of high-frequency noise. Also the 1-20 Hz cut-off frequencies were evaluated, considering other choices made in literature [1–4], however it was not possible to observe any meaningful difference with respect to the 0.2-15 Hz band. Comparing now the acceleration signals in Figure 1, it is possible to see that the raw acceleration components were shifted with respect to 0 g because of gravity. The z component, for example, would fall as low as −g. After applying the band-pass filter, all acceleration components adjusted to lie around 0 g.



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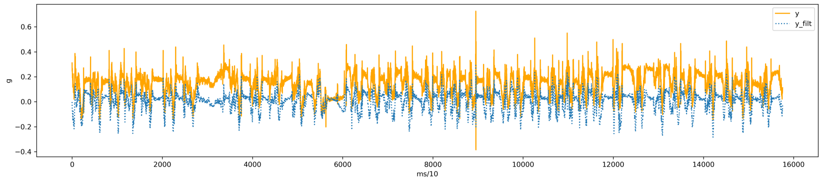
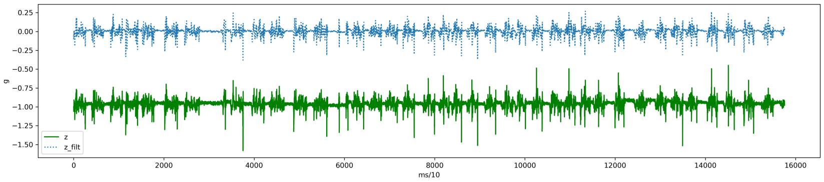


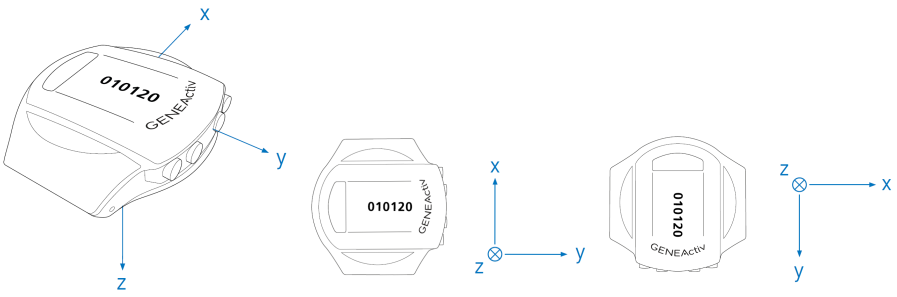
y component



z component

Fig 1. Acceleration signals before (x, y, z) and after the band-pass filter (x_filt, y_filt, z_filt) application.

To estimate the offset error, data was collected from the accelerometer while at rest with the x, y and z axes pointing towards the ground (Figure 2).



position 1 position 2 position 3

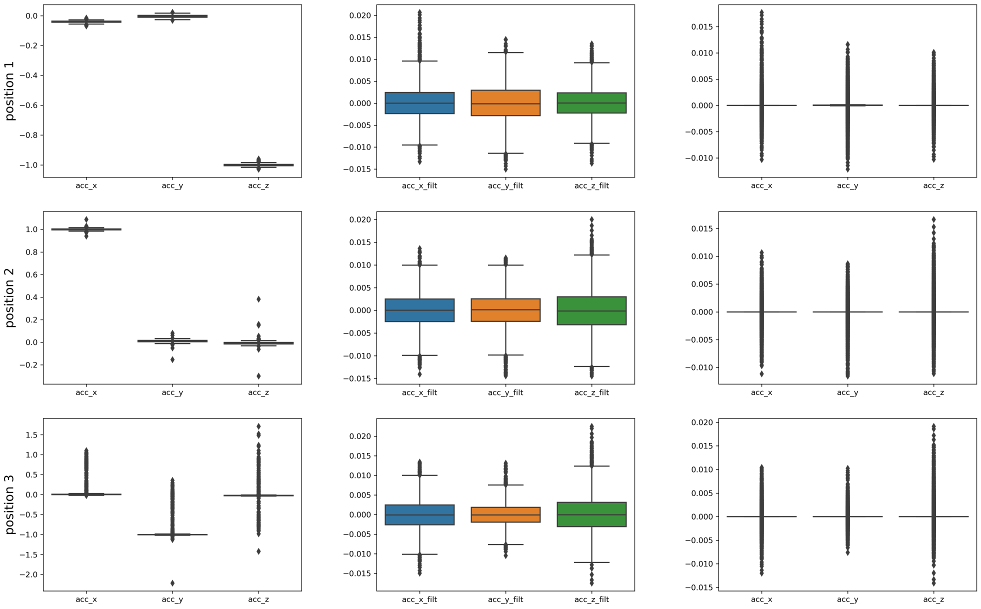
Fig 2. Accelerometer at rest positions [5].

From the filtered signal, for each of the three components, we computed the mean of the differences between actual accelerometer readings and the 0 g value expected from an accelerometer at rest. We hence obtained an offset value for each of the three axes. Successively, such values were removed from the acceleration data components, according to the pseudocode reported in Algorithm 1.

Algorithm 1 Accelerometer offset

```
procedure (for each axis x, y, z)
    $i$ in $(x, y, z)$
    $df\_filt\_acc \leftarrow$ DataFrame with filtered acceleration
    $df\_offset\_acc \leftarrow$ new DataFrame for offset acceleration
    $epsilon_i \leftarrow$ offset value for axis i
    for $j$ in range (0, len($df\_filt\_acc$)): do
        if $df\_filt\_acc[j, acc_i] < (epsilon_i * (-1))$ then
            $df\_offset\_acc[j, acc_i] = df\_filt\_acc[j, acc_i] + epsilon_i$
        else if $df\_filt\_acc[j, acc_i] > epsilon_i$ then
            $df\_offset\_acc[j, acc_i] = df\_filt\_acc[j, acc_i] - epsilon_i$
        else
            $df\_offset\_acc[j, acc_i] = 0$
```

The visualisation of the signal from the accelerometer at rest fixed in the three different positions shows the filter effect and the presence of a offset error (Figure 3a and Figure 3b). Indeed, the offset removal led to data closer to zero (Figure 3c).



(a) (b) (c)

Fig 3. Acceleration values in g sampled at 100 Hz from the accelerometer at rest: (a) no filtering, (b) band-pass filtering, (c) band-pass filtering and offset removal (n_{data} for each position $= 6,960$).

Finally, we obtained an estimate of the effective acceleration, adopting g = 9.80665 m/s^2 for the conversion from g to m/s^2 units.

S1 References

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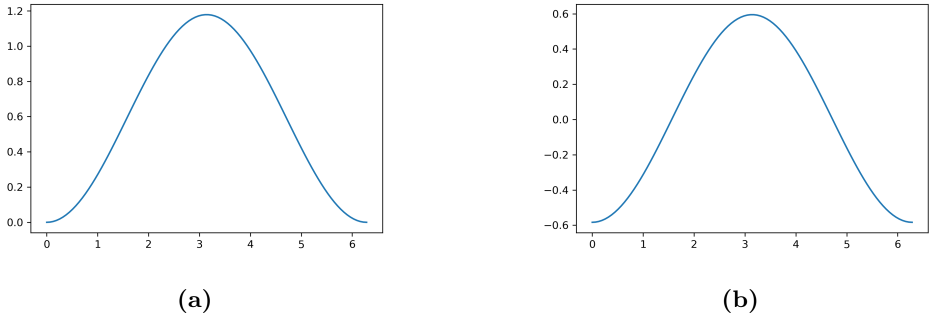
S2 Appendix

The detrend function application to velocity

In the following analysis, with no loss of generality with respect to the aims of the procedure here described, we considered the exemplar waveforms $sin(t)$, $2 \cdot sin(t)$, $3 \cdot sin(t)$ as acceleration components signals. Therefore, we proceeded computing the velocity components integrating the acceleration ones and obtaining the velocity magnitudes reported in Figure 1a. After that, we applied the detrend function to the velocity magnitude, as shown in Figure 1b.

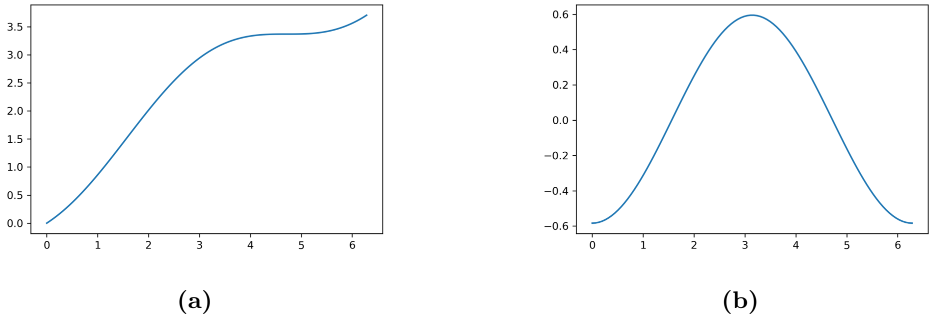


(a) **(b)**

Fig 1. Velocity magnitudes obtained from the integration of the acceleration vector components when no constant bias is present: (a) before applying the detrending and (b) after applying the detrending.

From these result it is possible to see that the application of detrend function only modified the signal respect to the ordinate axis but did not change the signal shape. This result is due to the fact that the velocity magnitude is computed from acceleration components characterized by neither trend nor bias.

Nevertheless, repeating the same analysis but starting from acceleration components, each of these with a constant bias, we obtained the velocity magnitude, before the application of detrend function, as shown in Figure 2a and, after the application of detrend function, as shown in Figure 2b.



(a) **(b)**

Fig 2. Velocity magnitudes obtained from the integration of the acceleration vector components when a constant bias is present: (a) before the detrending and (b) after the detrending.

In Figure 2a it is possible to see an incremental numerical error due to the presence of the acceleration bias, as this is amplified by the application of the numerical integration function. Both the signal shape and the signal peak changed. Nevertheless, after the application of the detrend function, some of the signal changes due to this numerical error were removed, as reported in Figure 2b. In particular, it is important to note that comparing velocity signals in Figure 1b and Figure 2b: (i) the peak values changed, but (ii) the peak position in time is the same.

From the exploratory analyses on the signals, it is possible to draw the conclusion, hence, that although the velocity values could change due to the detrend function application, the position in time of the peak velocity remains stable. This property meets the requirement of individuating the TPV value set in this work.

S3 Appendix

Reliability and validity of acceleration and velocity values

Ultimately, we adopted a mathematical approach to assess the reliability and validity of the calibrated and preprocessed acceleration and the computed velocity values.

As for the calibration and preprocessing analyses (S1 Appendix), we considered the data collected by an experimenter not belonging to the cohort involved in our trials. We measured the distance between the sensor and where the response keys appear on the touchscreen, corresponding to the actual hand displacement required to reach the screen. We then compared such displacement to the one computed from the acceleration data.

In particular, we calculated the displacement of interest (i.e., from R to A) in three different ways. Under the hypothesis of constant acceleration, for each trial, we computed the mean acceleration from R to A and the displacement as the product between the mean acceleration and the square of time required to cover the distance of interest divided by 2 (i.e., according to the equation of uniformly accelerated motion). Under the hypothesis of constant velocity, for each trial, we calculated the mean velocity from R to A and computed the displacement as the product between time ($[R, A]$) and mean velocity (i.e., according to the equation of uniform motion). In addition, we computed the displacement by applying a double numerical integration to acceleration, using the cumulative trapezoidal numerical function, that does not rely on any hypothesis regarding acceleration or velocity.

It should be noted that to compute the displacement following the aforementioned procedures, the signal was not subject to detrending as in S2 Appendix. The detrending, in fact, can affect velocity component values, which is not acceptable when aiming to compute its magnitude. For this reason, the contribution of the numerical errors may be expected to appear in the displacement. The boxplot of the displacement values is visualised in Figure 1.

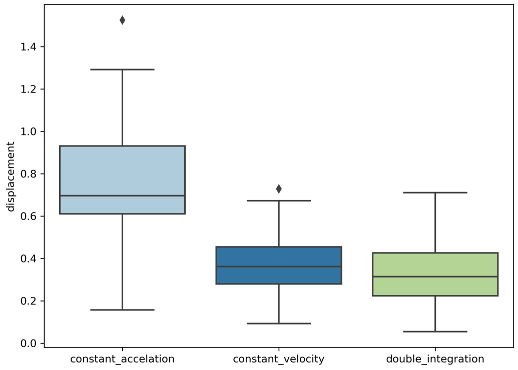


Fig 1. Displacement values in m computed from the acceleration values with different methods.

Then, we computed the mean and the standard deviation among all trials (37 trials with answer). For each method, these results are reported in Table 1 and compared to the actual displacement.

Notably, the mean values are distant from the actual displacement and the standard

Method	**Mean**	**Standard Deviation**	**Measured Displacement**
Constant acceleration	0.76 m	0.28 m	0.46 m
Constant velocity	0.38 m	0.15 m	
Double integration	0.34 m	0.16 m	

Table 1. Computed and actual displacement values ($n_{trials} = 37$).

deviations are quite high, especially under the hypothesis of constant acceleration. This could be due to the fact that the assumption of neither a constant acceleration nor a constant velocity are really appropriate to the actual characteristics of our task. Moreover, a double integration to compute displacements from acceleration can lead to large numerical errors, making this a weak method to assess the reliability and validity of velocity values. Indeed, this computation could be principally impeded by the accumulation of the numerical errors discussed so far.

Concluding, with this work we were not able to confirm nor disprove the reliability and validity of acceleration and velocity values obtained from a setting based on a wrist worn sensor. Nevertheless, we were able to show that such approach may be put to good use to instead obtain the peak velocity timing ("when" in time, e.g., time to peak velocity), information that may be fruitfully used to analyze the response of a subject.

S4 Appendix

Descriptive statistics

Accuracy

Children with ADHD provided 2,234 correct and 137 incorrect responses. TD children provided 3,777 correct and 211 incorrect responses (percentages of correct responses according to Group and Condition are reported in Table S1).

		Accuracy	
Group	**Condition**	Mean	SD
ADHD	Dominant	98	3
	Non-dominant	82	16
TD	Dominant	98	2
	Non-dominant	85	11

Table S1. Descriptive statistics of accuracy levels, % of correct responses ($n_{ADHD} = 17$, $n_{TD} = 26$).

Kinematics

Means and standard deviations of RT, MD, and TPV of correct responses in each condition and group are reported in Table S2.

		RT		**MD**		**TPV**	
Group	**Condition**	Mean	SD	Mean	SD	Mean	SD
ADHD	Dominant	652	211	565	217	447	182
	Non-dominant	653	217	734	242	456	228
TD	Dominant	691	198	514	190	460	175
	Non-dominant	716	217	656	242	504	215

Table S2. Descriptive statistics of correct responses, values in ms ($n_{trials} = 6{,}011$, $n_{ADHD} = 17$, $n_{TD} = 26$).

Demographic information

Characteristics of the Attention Deficit and Hyperactivity Disorder (ADHD) group are provided in Table S3, which includes IQs, and scores from the parent reported assessment.

	IQ	**RBS Tot**	**Low-level RRB**	**High-level RRB**	**Q-FE Tot**	**SSP Tot**
M	107.2	21.8	7.8	14.0	90.6	136.4
SD	17.6	15.5	6.5	11.8	20.9	26.2

Table S3. ADHD group characterisation ($n_{ADHD} = 17$). Mean (M) and Standard Deviation (SD) of:

IQ: total score from the WISC-IV scale. RBS Tot: total score from the RBS-R; higher scores indicate a more severe profile of restricted and repetitive behaviours. Low-level RRB: scores from Stereotyped, and Self-Injurious subscales of the RBS-R. High-level RRB: scores from Compulsive, Ritualistic, Sameness and Restricted Interests Behaviours subscales of the RBS-R. SSP Tot: total score from the SSP; higher scores indicate better sensory profile. Q.FE Tot: total score from Q.FE; higher scores indicate better executive functions.

Twelve children were diagnosed with the combined subtype of ADHD, 2 with the inattentive subtype, and 3 with the impulsive/hyperactive subtype. Moreover, 6 children received a comorbid diagnosis of Specific reading disorders (from moderate to severe), 2 children received a diagnosis of Specific spelling disorder (moderate), and 4 were diagnosed with other behavioural and emotional disorders.

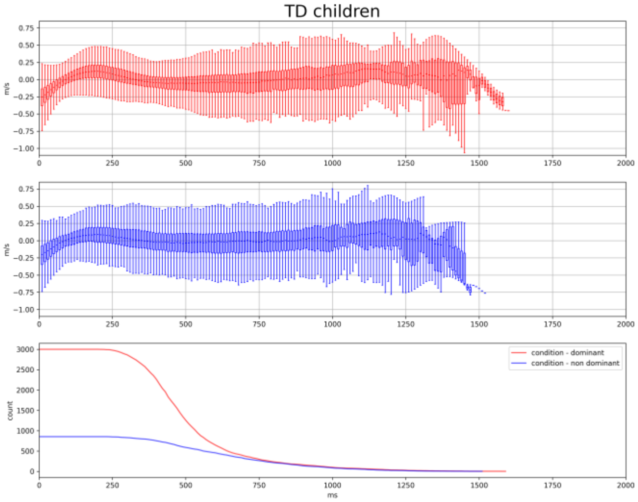
Velocity shape and trend

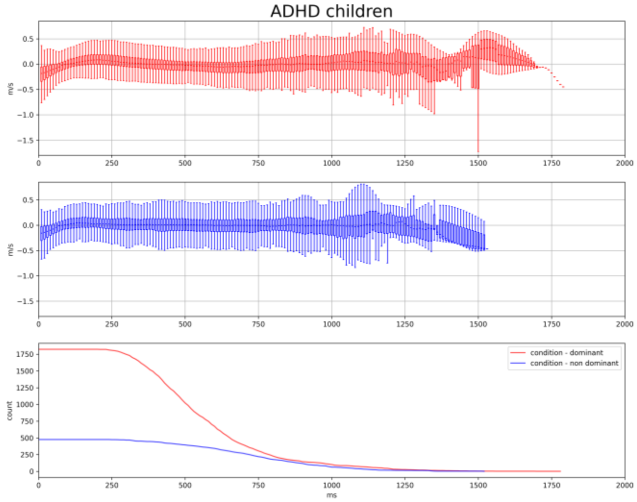
We here conduct a visual inspection of our data, with a specific focus on velocity shape and trend across movement time. Notably, only correct trials (i.e., trials in which the participant gave the correct answer) are considered. Firstly, we plotted the data of the two groups separately (**TD children** and **ADHD children**), then we plotted individual data to explore individual variability. As explained in our previous work [1], we do not look at velocity magnitude values, but rather focus on its curve shape and trend in time.

At the group level, each Figure is composed by 3 graphs, one for each row. The first and second graphs constitute of a boxplot composition from trials in either the dominant (red) or non-dominant (blue) condition, respectively. The x-axis represents the movement time (in ms), whereby the instant in which the participant starts moving is aligned with the 0 value. The y-axis shows the velocity values (in m/s). For each 10 ms of movement time (corresponding to the accelerometer sampling rate), we plotted a boxplot composed by data from all equivalent time points of the different trials. Although, the y-axis value ranges were affected by outliers, they were excluded from visualization for the sake of graphic clarity and readability. For instance, in case some blank spaces appear in the superior and inferior parts of a boxplot, some invisible outliers are present. As we focus on the velocity shape and trend across time, and do not aim to compare its magnitude across different graphs, we did not set a fixed y-axis range for all the Figures. We have therefore avoided a flattening of the boxplots resulting from variability between participants. As not all the trials have the same movement duration, the boxplots are composed by varying amount of data. We take this into consideration in the third graph, which represents the number of trials contributing to each time instant of each boxplot in either the dominant (red) or non-dominant (blue) condition, respectively.

At the individual level, we also reported a plot representing velocity in all single trials. Each curve corresponds to a single trial and is visualized in red for the dominant condition, and in blue for the non-dominant condition. The x-axis represents the movement time (in ms), while the y-axis shows the velocity values (in m/s). In addition, a vertical green line marks the time instants when the participant ended its movement in each trial (namely, touched the response screen and provided an answer). Green lines make it easier to capture movement duration in each trial.

1. TD and ADHD groups

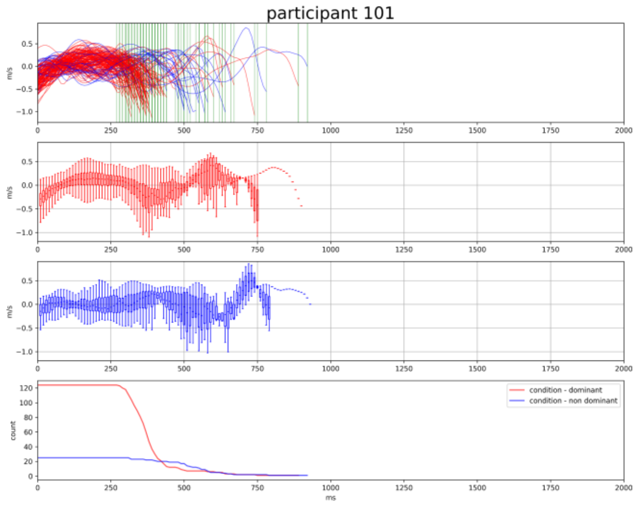




From a group level visualisation of the boxplot composition graphs, we observe that the **TD group** showed a more pronounced bell-shaped velocity pattern at the beginning of movements, as represented by the time-ordered set of boxplots. This seems in line with previous literature suggesting that children with ADHD do not show a typical bell-shaped velocity profile, which indicates impaired motor planning [2].

2. TD children

Here we report graphical visualisations of individual data from the **TD group**. For this cohort of 26 participants, numbers ranging from 101 to 126 are reported in the Figure title as participants' identification code.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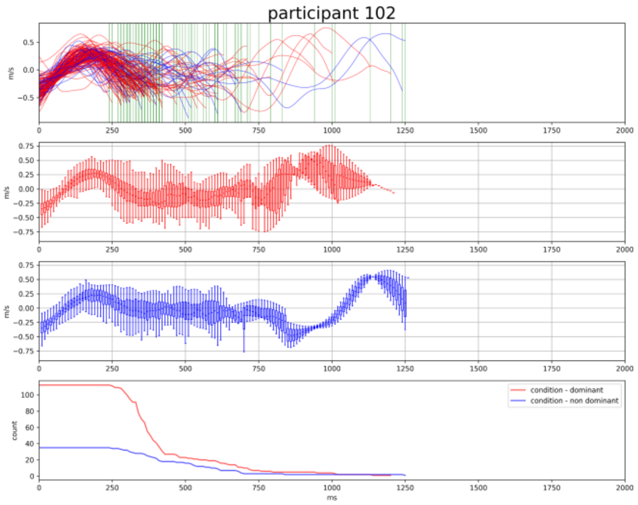
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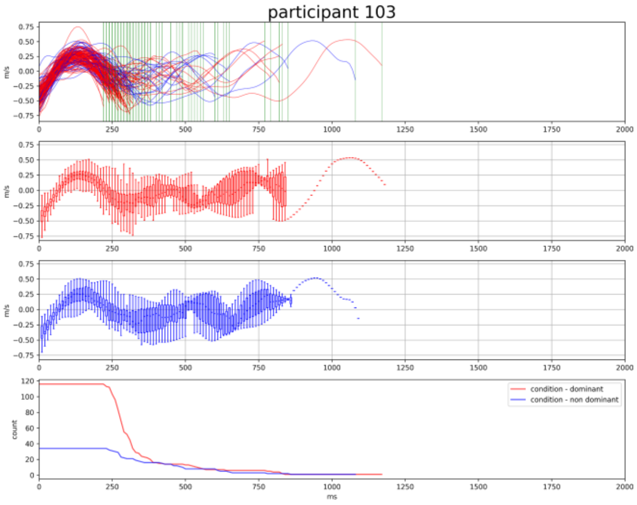
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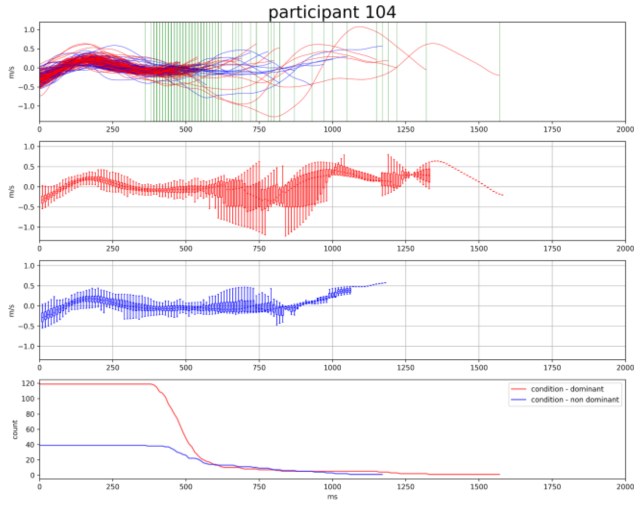
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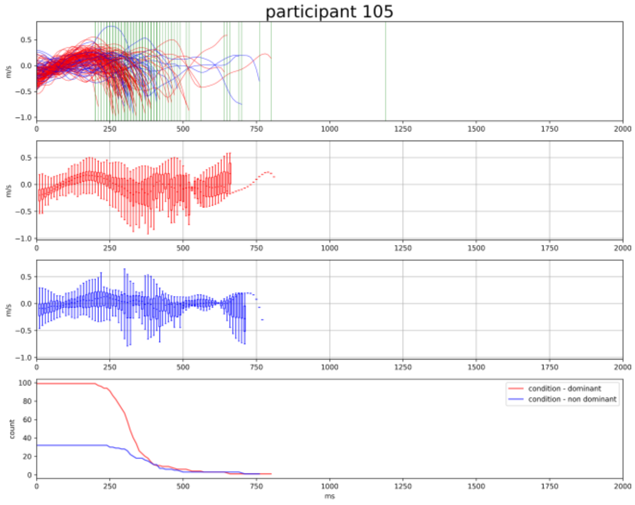
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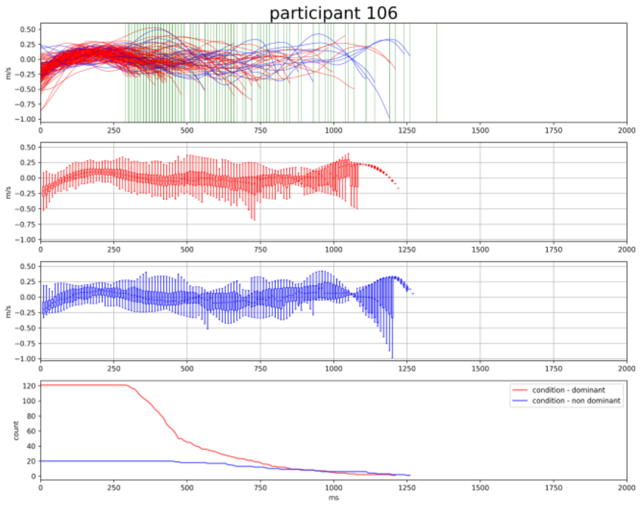
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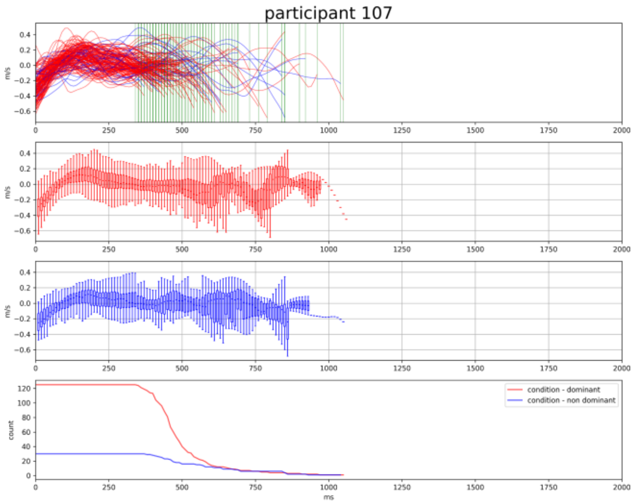
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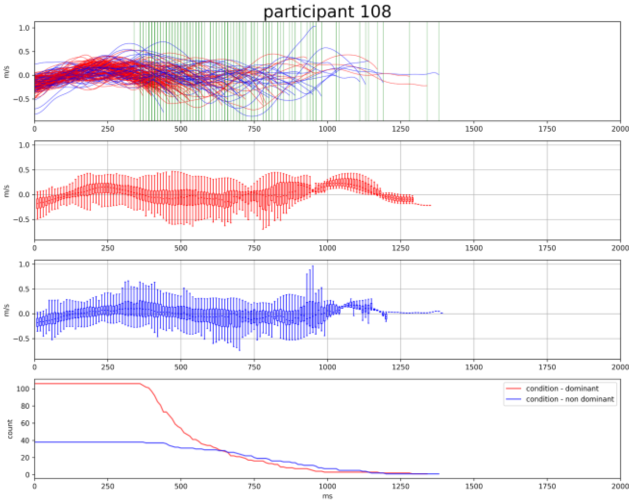
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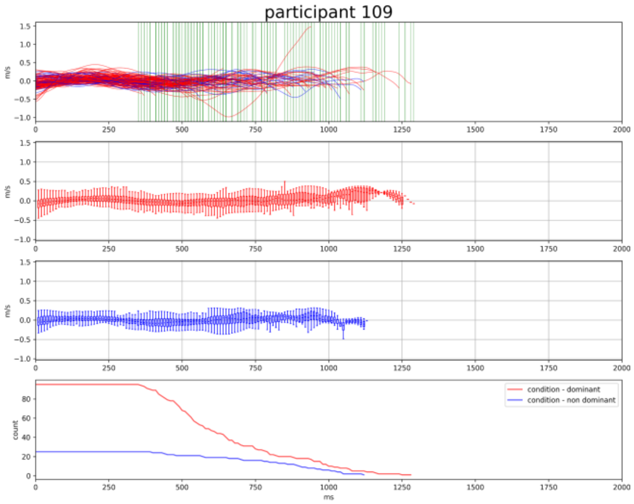
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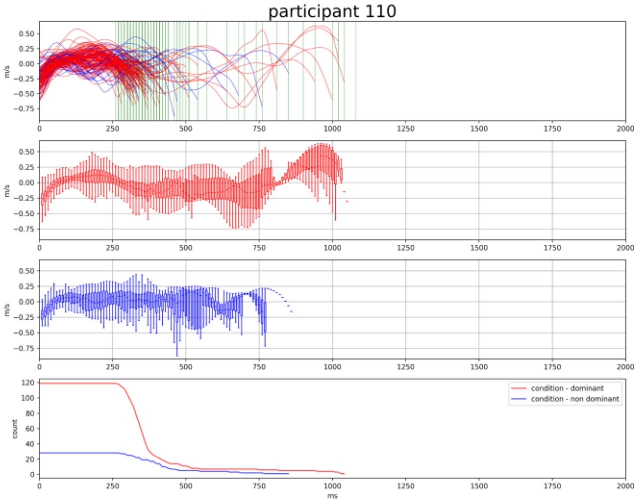
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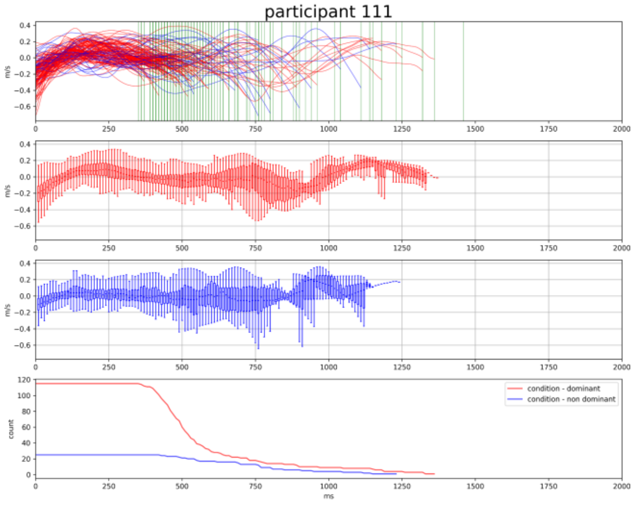
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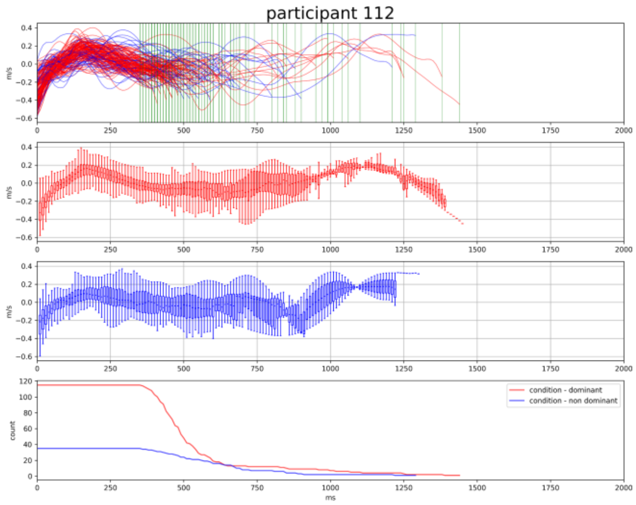
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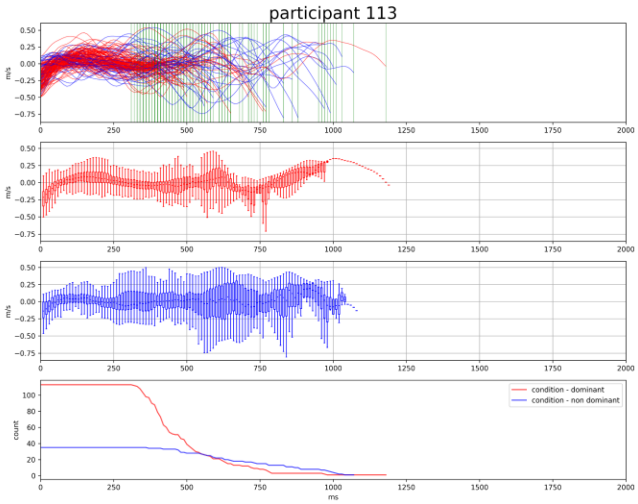
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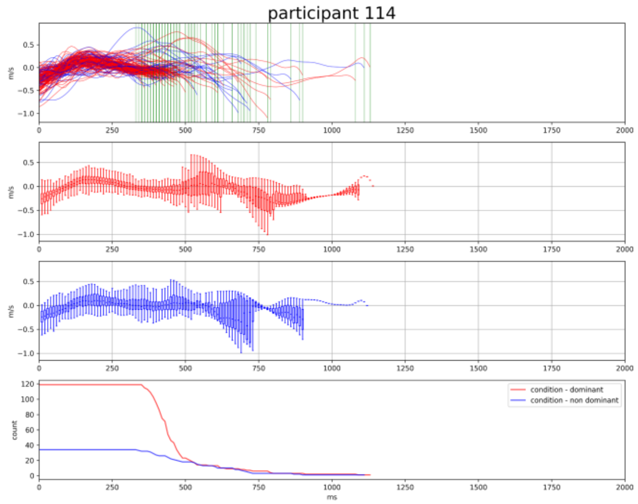
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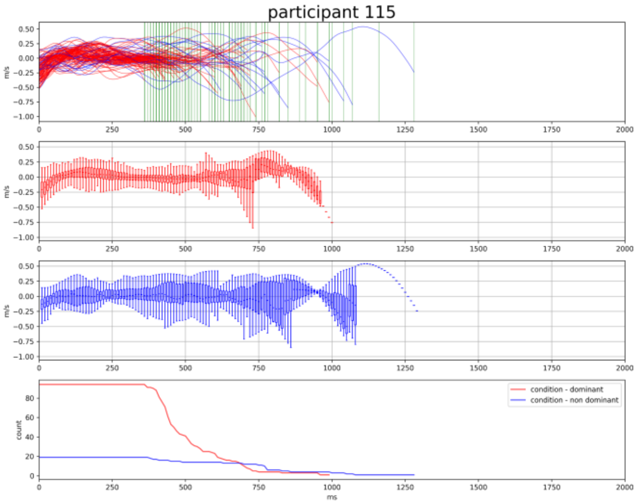
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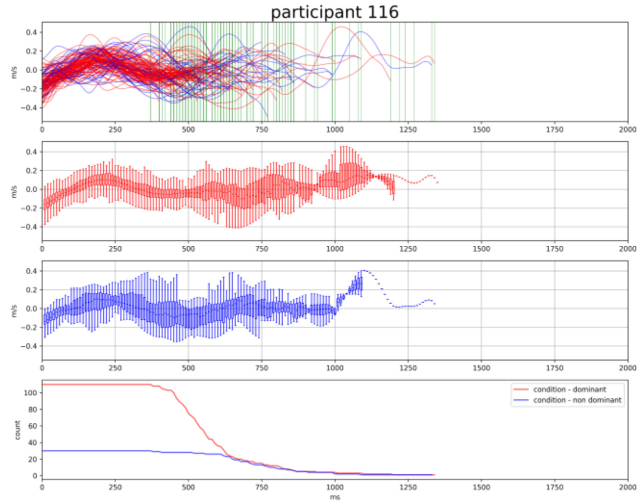
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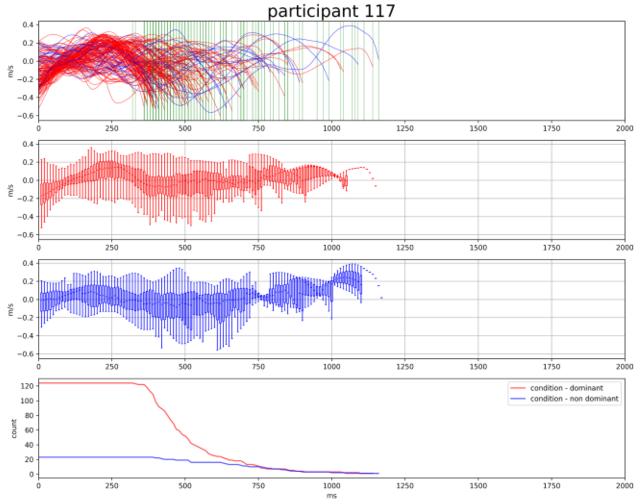
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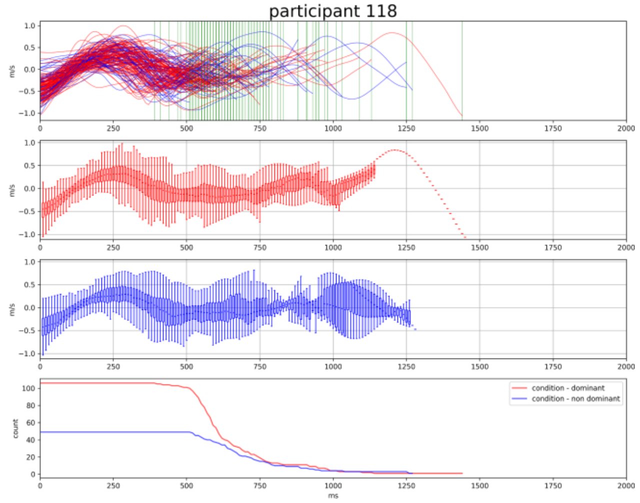
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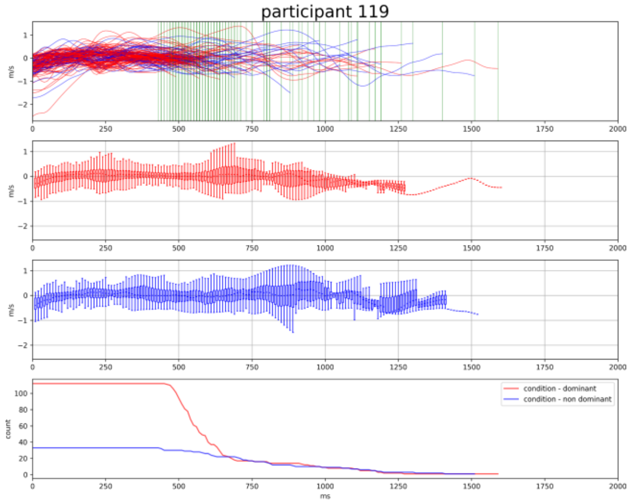
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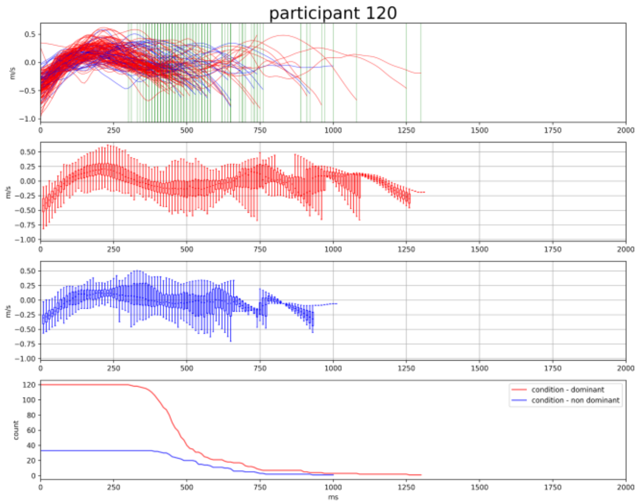
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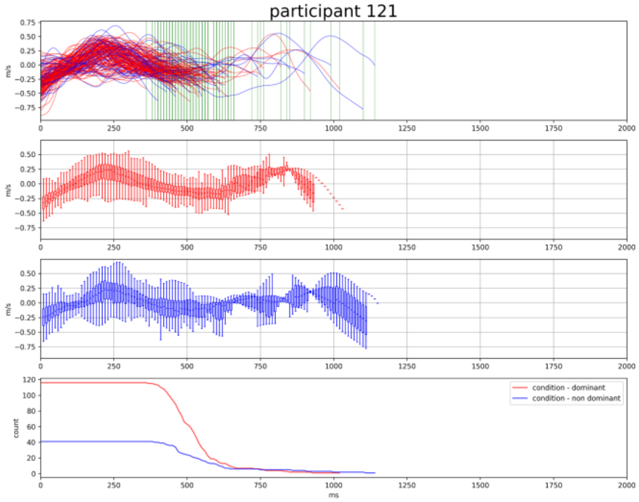
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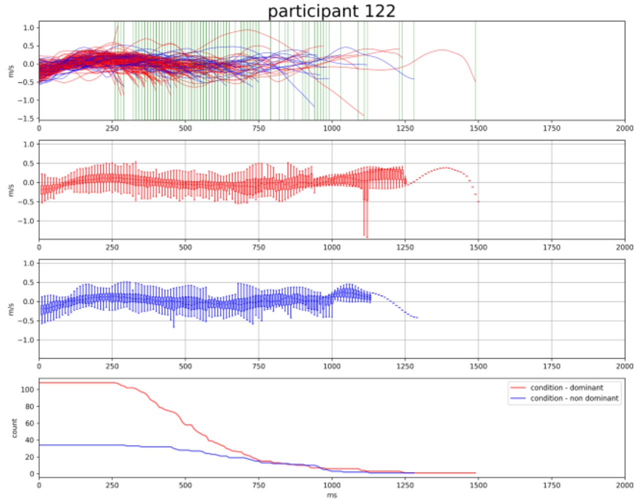
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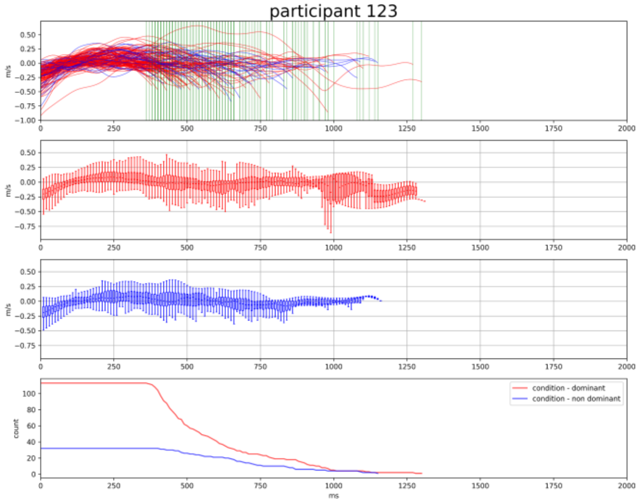
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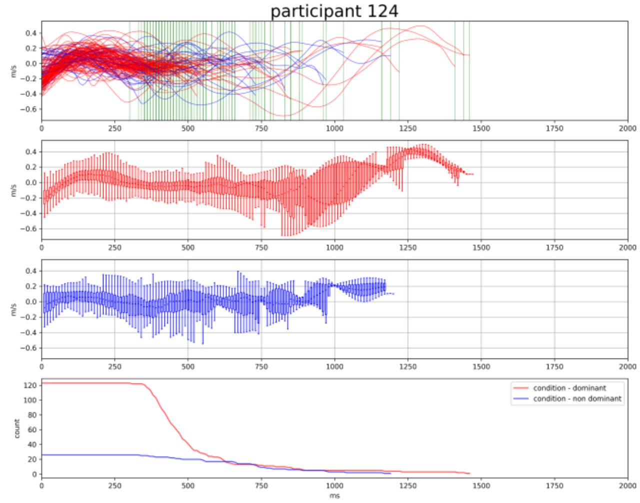
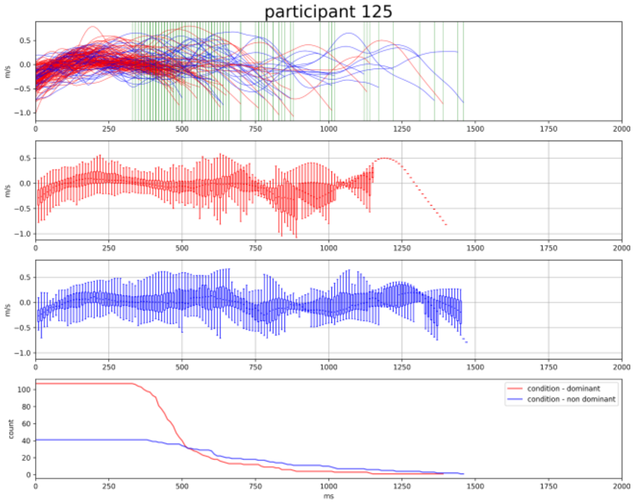
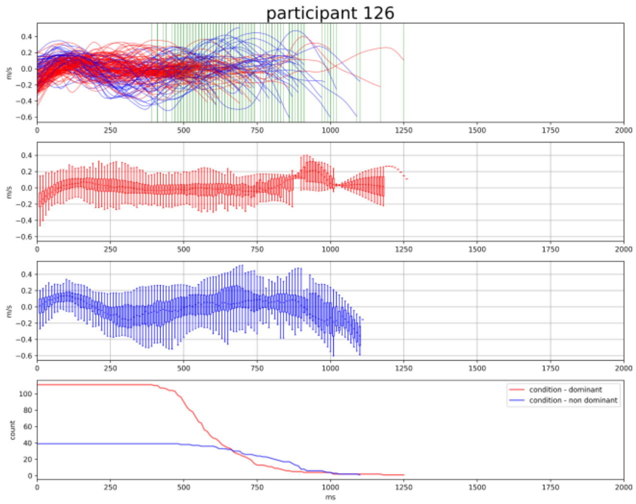
ms
condition - dominant
condition - non dominant


participant 124
m/s
count
ms
condition - dominant
condition - non dominant

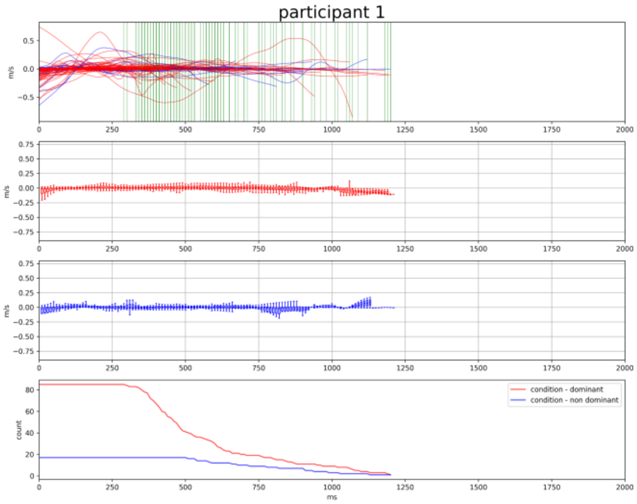


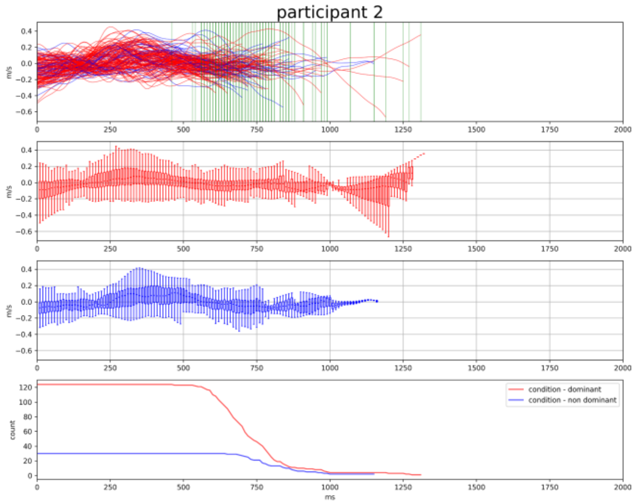


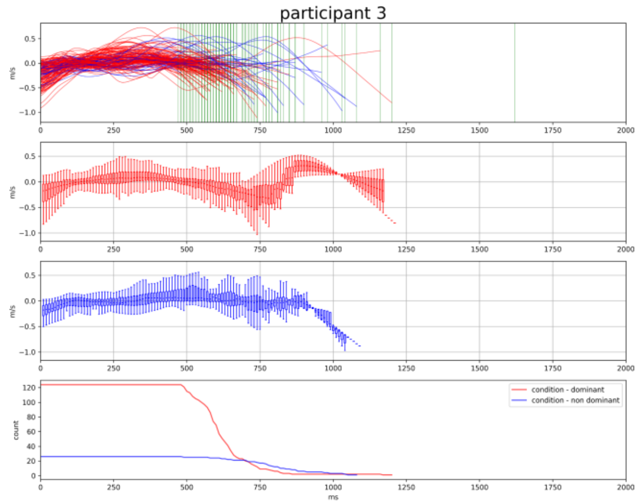
From these graphs we note that, although all participants showed a bell-shaped velocity profile at the beginning of movements, there is a wide intra-group variability. The significance of this motor variability, in relation to the individual characteristics of typically developing children, is largely under-studied in the scientific literature and deserves further investigation to explore the possibility of capturing predictive cues about the children's motor development.

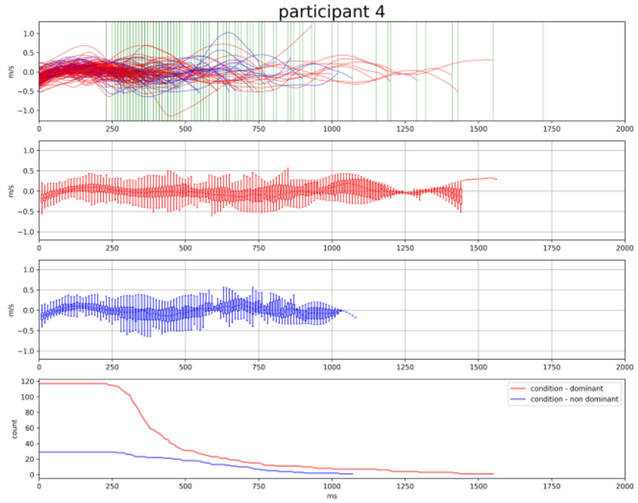
3. ADHD children

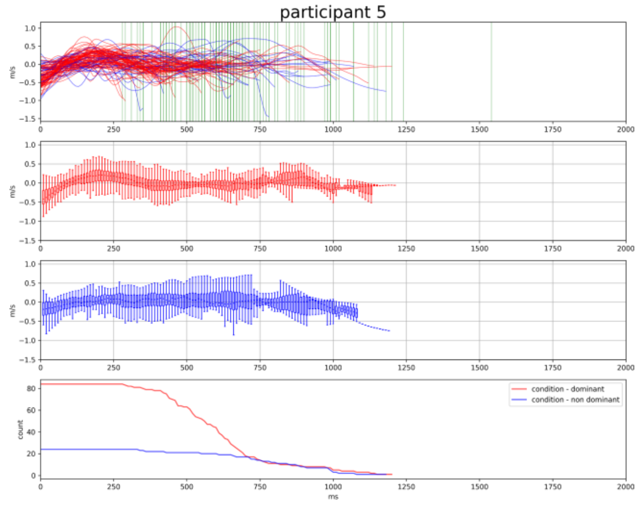
Here we report graphical visualisations of individual data from the **ADHD group**. For this cohort of 17 participants, numbers ranging from 1 to 17 are reported in the Figure title as participants' identification code.

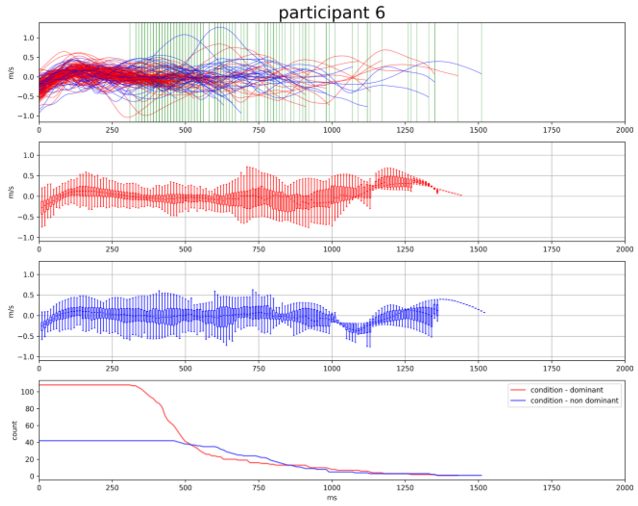


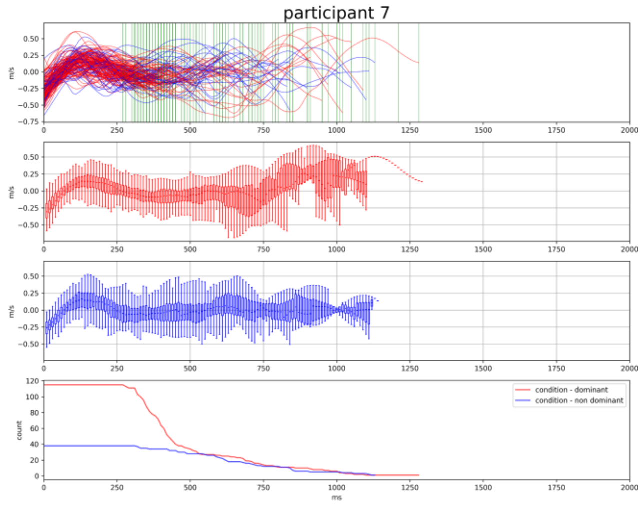


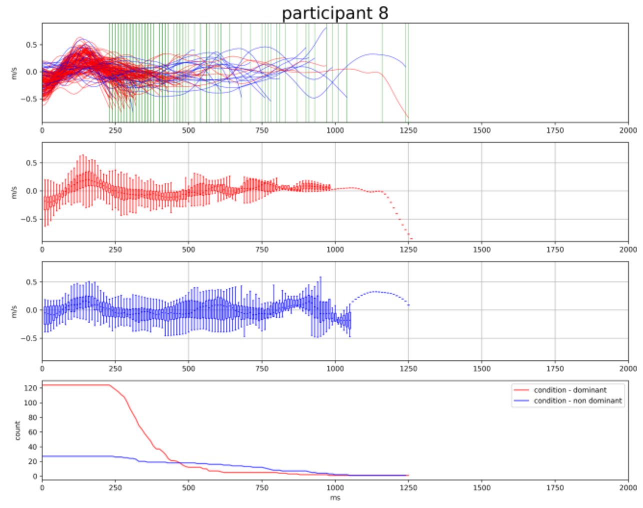

participant 3

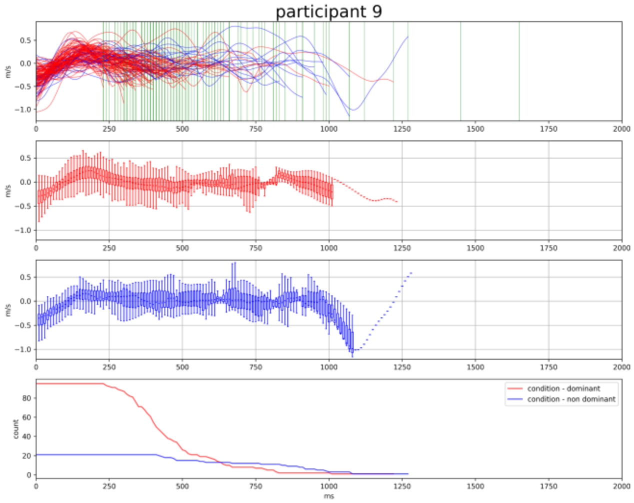

participant 4

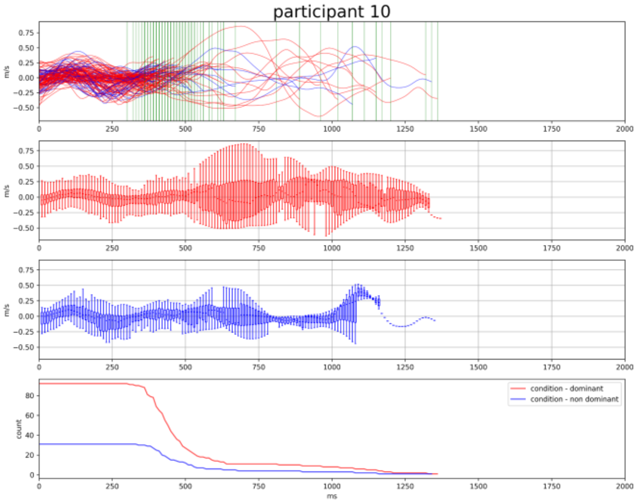

participant 5

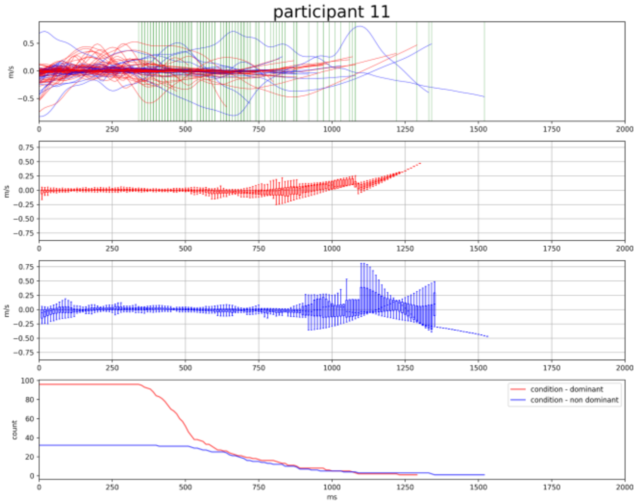

participant 6

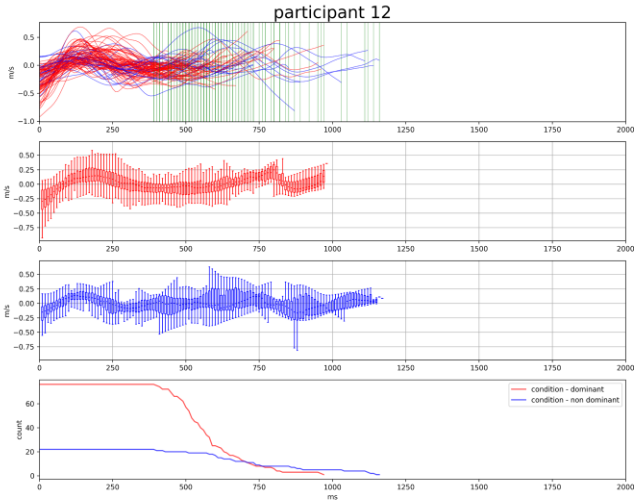

participant 7

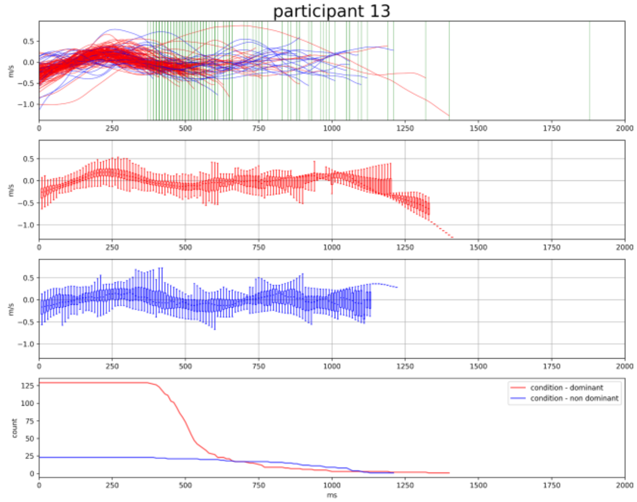

participant 8

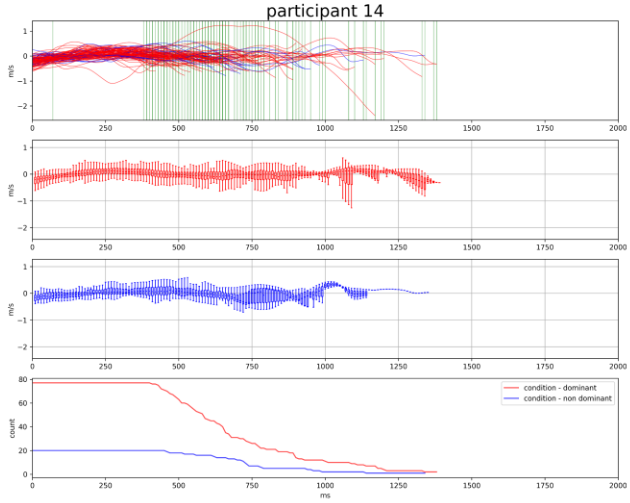

participant 9
m/s
count
ms
condition - dominant
condition - non dominant
0
250
500
750
1000
1250
1500
1750
2000

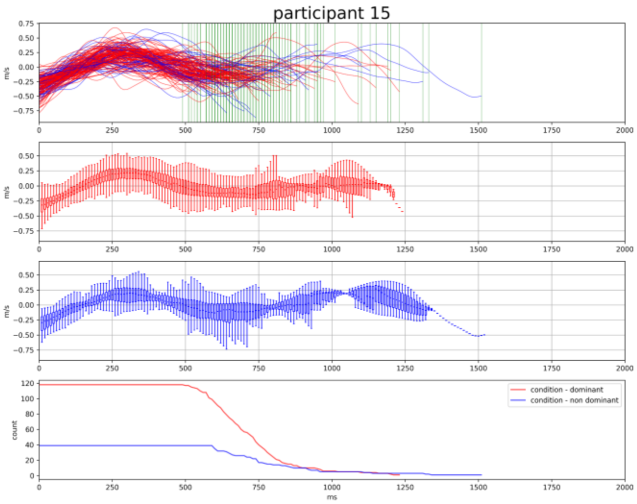

participant 10
m/s
count
ms
condition - dominant
condition - non dominant
0
250
500
750
1000
1250
1500
1750
2000

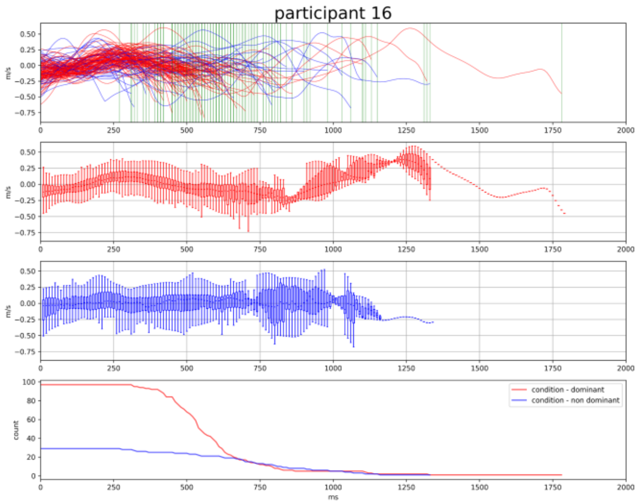

participant 11
m/s
count
ms
condition - dominant
condition - non dominant
0
250
500
750
1000
1250
1500
1750
2000

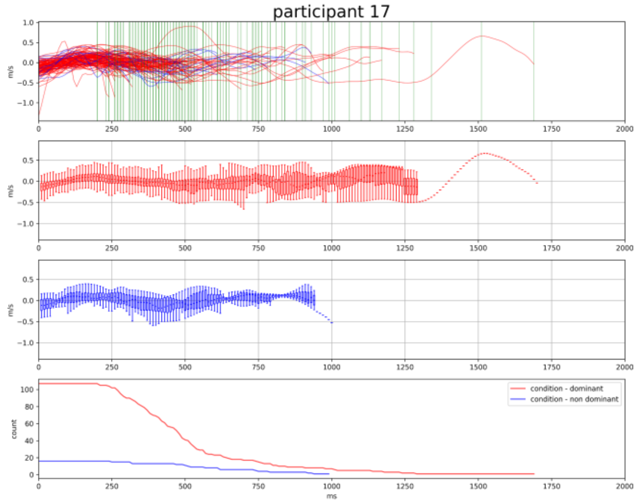

participant 12
m/s
count
ms
condition - dominant
condition - non dominant
0
250
500
750
1000
1250
1500
1750
2000


participant 13
m/s
count
ms
condition - dominant
condition - non dominant
0
250
500
750
1000
1250
1500
1750
2000


participant 14
m/s
count
ms
condition - dominant
condition - non dominant
0
250
500
750
1000
1250
1500
1750
2000







From these graphs we observe that some children from the **ADHD group** did not show an initial bell-shaped velocity pattern (see *participants 1, 2, 3, 11, 14*). As for the TD group, profound intra-group variability is visible and would be worth further investigation. We can speculate that, beyond diagnosis, individual differences in children's motor developmental trajectory interact with other neuropsychological domains to delineate risk profiles that merit clinical attention.

S4 References

[1] Angeli, A., Valori, I., Farroni, T. & Marfia, G. Reaching to inhibit a prepotent response: A wearable 3-axis accelerometer kinematic analysis. *PLOS ONE* **16**, e0254514 (2021).

[2] Dahan, A. & Reiner, M. Evidence for deficient motor planning in ADHD. *Sci Rep* **7**, 9631 (2017).