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Perception and Execution of Biological Motion Adhering to the Two-thirds Power Law: A Comparison Between Autism Spectrum and Typical Development

By

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Abstract

Individuals with autism spectrum development (ASD) often demonstrate atypical perception and production of biological motion (BM), a term for the movement patterns of animate beings. Given the importance of visual perceptual and motor skills for social interaction and communication, a fundamental concern for those with ASD, further investigation into these domains, their potential association and their underlying role in ASD is critical. This project aimed to examine performance in both domains using a common metric, the two-thirds power law (2/3 PL), a law of motion that characterizes many forms of human movement. Using a preferential looking paradigm, this study examined attentional patterns toward motion adhering to this law, as well as more traditional BM stimuli with temporal or spatial manipulations. The study also employed a novel task to assess adherence to the law and other kinematics during drawing movements on an iPad tablet. Measures of cognitive, motor and social functioning were collected to explore whether task-specific performance related to atypical functioning in these areas. While the study did not detect a significant relationship between domains with respect to the law, the tasks did reveal a number of atypicalities in perceptual and motor performance in autism, as well as some associations with broader social functioning. Limitations and future directions of this research are also discussed.

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Background and Significance

Impairments in nonverbal communication are among the core features of autism spectrum development (ASD; American Psychiatric Association, 2013). These impairments span several domains, including both recognition and use of various forms of communication, such as whole-body movements, hand and arm gestures, facial expressions and shifts in eye gaze. Many of these nonverbal forms of movement are known as biological motion (BM), a term for movement patterns of animate beings, both humans and animals (Johansson, 1973). BM is rich in social cues and carries complex information necessary for understanding and predicting responses, emotions and intentions of others in social contexts (Zilbovicius et al., 2006).

Perception of Biological Motion

Attention to BM is thought to be a well-conserved, early-emerging and “fundamental mechanism facilitating adaptive social engagement and interaction” (Klin et al., 2009). Indeed, research shows that newborns as young as two days old demonstrate a preference for point-light displays of BM over random dot motion (Simion et al., 2008). An early preference for BM has been substantiated in studies which compare BM to both inverted and rigid, non-BM motion displays (Bardi et al., 2011, 2014; Bidet-Ildei et al., 2014). It has been argued that these findings support an innate predisposition to orient to and preferentially process motion information that is biological in nature (Simion et al., 2011; Troje & Westhoff, 2006).

There is also support for the evolutionary conservation of this mechanism, which comes from work with newly hatched visually naive chicks that exhibit a preference for BM over non-BM point-light stimuli even when the display depicted an animal of a different species (Vallortigara et al., 2005). This evidence indicates a predisposition, shared across species, of the visual system for orienting toward objects that move in accordance with biomechanical constraints of living beings. This intrinsic capacity does not appear to be specific to one's own species, and thus would be advantageous to survival and learning (Johansson, 1973; Simion et al., 2011; Vallortigara et al., 2005). Work in those with congenital visual deprivation due to cataracts (CC) provides compelling evidence of the fundamental nature of this mechanism. One study found no behavioral or neural differences in BM perception between controls and those with CC whose vision had later been restored, in contrast to observed impairments in global motion and face processing abilities (Bottari et al., 2015). The selective sparing of BM processing lead the authors to conclude that a dedicated system tuned to BM is in place at birth and can specialize independently of visual input (Bottari et al., 2015).

Other researchers have compared this BM detection mechanism to one for detecting human faces, suggesting that while it appears initially to be experience-independent, the system may continue to tune and specialize across development with increasing perceptual experience (Simion et al., 2011). Support for this theory comes from longitudinal work showing an increasingly robust visual preference for BM emerging over the first 2 years of life (Sifre et al., 2018). Growing experience with and visual input of others across this period of development is likely to contribute to the trend of increasingly pronounced preference for BM. While the role of experience in BM processing has not been fully determined, both perspectives do agree that there exists at least some inherent mechanism directing our proclivity toward BM.

Autistic individuals appear, however, to show atypical perception, sensitivity and recognition of BM (Atkinson, 2009; Koldewyn et al., 2010). Those with ASD lack a typical preference for attending BM stimuli, instead showing greater fixation to scrambled or object motion (Annaz et al., 2012). These differences exist from an early age, as research has shown that autistic 2-year-olds fail to orient towards upright compared to inverted point-light displays of BM (Klin et al., 2009). These perceptual anomalies appear to be specific to BM, as perception of coherent motion and other non-biological motion remains typical and intact (Koldewyn et al., 2010; Price et al., 2012). Furthermore, neuroimaging studies have demonstrated that autistic individuals show atypical patterns of activity (often diminished) in response to BM stimuli that appears to vary with autistic traits, even amongst non-clinical samples (Alaerts et al., 2017; Kaiser et al., 2010; Knight et al., 2022; Koldewyn et al., 2011; Naples et al., 2022; Pelphrey & Carter, 2008; Puglia & Morris, 2017; Thurman et al., 2016).

Yet, the literature is mixed, with some studies finding no evidence for a BM deficit in ASD (Cusack et al., 2015; Jones et al., 2011; Li et al., 2021). Two recent meta-analyses sought to clarify the disparate findings on BM perception across autistic and typically developing populations within this growing body of research and revealed an overall moderate effect size for a BM processing impairment in ASD (Federici et al., 2020; Todorova et al., 2019). Both meta-analyses note high levels of heterogeneity across the studies included, which they subsequently explore and attribute to the variability in task complexity, stimuli used and participant age.

Importantly, Federici et al. (2020) point to a specific feature manipulation of the stimuli, the temporal scrambling in contrast to spatial scrambling, which elicited a pronounced effect on impaired BM processing in ASD. This finding suggests that it may be the temporal properties of the moving dots which constitute a core mechanism playing a role in BM processing anomalies in ASD. This interpretation also aligns with computational work, which points to local motion or optic flow (i.e., the temporal sequence of movement) as the feature critical to processing and recognition of BM, even within a coarse spatial arrangement (Casile & Giese, 2005). Further, such an interpretation fits well with the finding of slowed and/or noisy temporal processing observed across multiple sensory modalities in ASD, especially in dynamic perception (Robertson & Baron-Cohen, 2017).

In line with this theory, a few studies have sought to isolate the temporal properties of BM to further explore this mechanism. Cook and colleagues (2009; 2013) used a paradigm that included two conditions involving movement of a single stimulus following either minimum-jerk BM or gravitational non-BM profiles. Reduced sensitivity and atypical perceptual thresholds were found in the ASD group only in the BM condition. Yet, other studies using single-point stimuli have demonstrated unaffected motion perception thresholds in those with ASD (Edey et al., 2019; Saygin et al., 2010). These contradictory findings warrant further investigation into the sensitivity and attention toward BM. In addition, these studies were conducted in adults, and mixed results may stem from compensatory mechanisms that have emerged to differing degrees across the lifespan. Examining perceptual sensitivity for temporally manipulated, single-point stimuli in children may illuminate how early these perceptual preferences emerge, to what extent they may be tuned across development and whether autistic individuals show atypical developmental trajectories.

An understanding of atypical BM processing in ASD is crucial given that there appears to be a relationship between BM processing abilities and social functioning. Performance on BM perception tasks has been shown to correlate negatively with severity of autism traits (Blain et al., 2017; Blake et al., 2003; Koldewyn et al., 2010; van Boxtel et al., 2016); social network size has been linked to neural sensitivity to BM (Kirby et al., 2018); and sensitivity to BM is associated with measures of empathy (Miller & Saygin, 2013). This evidence suggests that abnormalities in attention to and processing of BM have implications for development of social cognition in both typical and atypical populations. Some researchers have even posited that BM processing is a “hallmark” of social cognition, and that neurocognitive and behavioral evidence point to a tight link between BM processing and broader social development (Pavlova, 2012).

Production of Biological Motion

In parallel with these anomalies in BM perception, motion production is also compromised. Motor deficits in ASD have been well characterized. In a recent study of nearly 12,000 children with ASD, 87% of children were at risk for motor impairment (Bhat & Narayan Bhat, 2020). Other recent work has employed quantitative approaches in order to characterize movement atypicalities early in development. Studies using wearable sensors have detected decreased acceleration in spontaneous and directed limb movements of high-risk infants (Wilson et al., 2021) and toddlers (Focaroli et al., 2016), compared to low-risk and non-autistic counterparts. Other studies employing motion capture/tracking systems have observed that toddlers with ASD show decreased prospective motor control during a ball catching task (Ekberg et al., 2016), as well as differential movement kinematics during free play (Y. C. Yang et al., 2019). The growing use of technology-based assessment has revealed that atypical motor movement is present within the first 3 years of life, even before normative age of diagnosis.

These trends in motor impairment continue throughout development, especially as fine motor skills become increasingly important in daily activities. Studies assessing handwriting and drawing have revealed larger peak velocity, less smooth movements, more variable size trajectories as well as greater path length error (Beversdorf et al., 2001; Grace et al., 2017), and a correlation between writing performance and ASD severity. In executing upper limb reach-to-grasp movements, those with ASD have been shown to take longer to prepare and execute movements, show greater levels of jerk (rate of acceleration), and more movement units than controls (Cook et al., 2013). Precision gripping experiments have revealed that children with

ASD show increased variability, implicating deficient feedback control and motor planning (Mosconi et al., 2015; Wang et al., 2015). Distinctive kinematic profiles in individuals with ASD have emerged in several other motor movements, such as throwing a ball (Staples & Reid, 2010), gait (Calhoun et al., 2011; Cho et al., 2022; Nobile et al., 2011) and gameplay with blocks (Ferrara et al., 2016a).

This dysfunction in both fine and gross motor skills may contribute to disruption of more complex forms of socially-embedded movement. In studies designed to elicit gestures both through command or imitation, children with ASD make more orientation and distortion errors (Dewey et al., 2007; Gordon & Watson, 2015), and demonstrate poorer overall gesture performance, marked by abnormal hand posture (Fourie et al., 2020). Additionally, individuals with ASD show impairments in their ability to imitate others' actions (Dewey et al., 2007; Williams et al., 2004), suggesting a deficit in both the encoding and production of these actions. Research also shows differences in motor movement during social interactions: those with ASD demonstrate lower social motor synchronization with a counterpart (Fitzpatrick et al., 2017), as well as excessive and less complex movement in face-to-face conversation (Zhao et al., 2021). Given how critical execution of gesture and action is for interpersonal communication, these studies make clear the larger role that motor atypicality may play in social interaction, one of the core areas of concern in ASD. Some have even theorized that motor anomalies, especially in the area of prospective motor control, represent a primary manifestation or "intermediate phenotype" of ASD, which subsequently leads to difficulties in the social domain (Casartelli et al., 2016; Trevarthen & Delafield-Butt, 2013).

Despite the growing body of evidence demonstrating that motor impairments are prevalent and pervasive in ASD, motor features are not a part of the autism diagnostic criteria.

The DSM-5 (American Psychiatric Association, 2013), currently used to diagnose autism, includes repetitive and stereotyped motor movements (RRBs), but not overall coordination difficulties in general motor movement. As such, motor impairments are largely underdiagnosed and undertreated in ASD (Bhat & Narayan Bhat, 2020). Recently, however, more researchers have made a case for including motor impairment in the diagnostic process (Bondioli et al., 2021; Iverson et al., 2019; Licari et al., 2021; Mosconi & Sweeney, 2015), with some work providing support that adding motor domains may better capture heterogeneity (Harrison et al., 2021). Motor impairment is often the first observable sign and thus could serve as a marker for early identification and referral for diagnosis.

Further, motor development is crucial in driving other cognitive processes. Previous studies have highlighted the broad impact that motor impairments can have on development of social and communicative abilities, including both expressive and receptive language development (LeBarton & Landa, 2019; Patterson et al., 2021), as well as empathy and face processing abilities (Casartelli et al., 2016; Cummins et al., 2007; Gallese et al., 2013; Iverson, 2010). Furthermore, difficulties with motor skills can result in challenges with activities of daily living, overall health and independence. As such, early intervention in motor delays could alter the trajectory of impairments, improving outcomes in other social cognitive domains.

The Link between Perception and Execution of Biological Motion

Research has explored the relationship between motor execution and BM perception, finding them to have bidirectional influences on one another. Several behavioral studies have demonstrated that observation of BM, but not non-BM, influences motor execution, resulting in an interference effect (Bouquet et al., 2007; Kilner et al., 2003). Conversely, motor execution appears to facilitate perception of BM, especially when movement performed is temporally and spatially congruent with that being observed (Bidet-Ildei et al., 2010; Christensen et al., 2011). Both examples suggest that there is a close coupling between these execution and perception systems.

Additionally, given the concurrent presentation of their delays in ASD and their respective roles in social cognition, it has been posited that impairments in these domains are associated. Indeed, Freitag et al. (2008) found that neural activity during perception of BM, compared to scrambled motion, was strongly associated with hand-finger imitation abilities in both autism and control groups. Similarly, Price et al. (2012) showed that reduced visual sensitivity to human movement was correlated with impaired motor skills in individuals with Asperger syndrome. Another study revealed a relationship between discrimination thresholds for BM and movement kinematics during execution of sinusoidal arm movements in autistic adults (Cook et al., 2013). More recently, a pilot study demonstrated that autistic participants with motor difficulties showed poorer perceptual accuracy and differential gaze preferences when viewing communicative interactions between point-light actors compared to autistic participants without motor difficulties and TD controls (Lindor et al., 2019). This collection of evidence suggests that action perception, particularly with respect to BM, and action execution are closely linked in autism.

While the exact nature of this relationship remains unclear, there are likely to be bidirectional pathways between these domains. Execution of movement may be influenced by perceptual abilities. A visual system tuned to processing BM (in the form of action, hand gestures, body movement) may shape the performance of movement that more closely follows this profile through attention and imitation (Bek et al., 2016; Köster et al., 2020; Ray & Heyes, 2011). In a dysfunctional perceptual system, reduced sensitivity to BM may inhibit adequate processing and perception of dynamic human action, like gestures or other forms of communicative movement. In turn, this altered perception, along with impaired visuo-motor integration (Lidstone & Mostofsky, 2021) may impede learning and subsequent performance of these actions, resulting in motor movements that diverge from the normative BM profile.

The pathway linking these two domains may also proceed in the opposite direction, wherein motor execution has an influence on action perception. For instance, Casile and Giese (2006) tested the visual recognition of gait patterns in subjects before and after non-visual motor training during which they learned a novel upper-body movement. Following training, there was significant improvement in the recognition of only the learned movement, suggesting a direct and selective influence of motor representations on the ability to recognize movement, in the absence of visual learning. In a similar way, one's ability to perceive human movement may be shaped by one's own movement patterns. During development, infants spend much of their time observing their own limb movement (Rochat, 1998; van der Meer et al., 1995) and that of other people around them. Given that this observed movement is "biological" in nature, the visual system will be tuned by these inputs, making it most sensitive and attentive to motion that follows this same profile. This is consistent with an increasing preference for BM over the first couple years of life (Sifre et al., 2018), as the system specializes for this kind of movement. However, autistic individual's experience with their own atypical movement kinematics present early in development may minimize this exposure, tune visual systems toward atypical representations of BM, and contribute to disrupted visual sensitivity toward BM and perception of others' actions.

With bidirectional associations in play, the processes of action perception and execution are closely related and may even co-develop with one another. As such, impairments in either area may further exacerbate one another, leading to a cascade of developmental delays in social communication and interaction. In addition to the ways in which these domains are related behaviorally, as evidenced in the studies presented above, it is also likely that the perceptual and motor domains may be linked by a common underlying brain network.

Neural Mechanisms Underlying Perception–Action Coupling

Research has investigated whether perceptual and motor functioning may share similar underlying neural mechanisms. Indeed, there is neural evidence supporting perception-action coupling. Initially coined “mirror neurons”, a group of premotor and parietal cells in primate brains were discovered to fire when the animal both observed and performed the same action (Rizzolatti & Craighero, 2004). Referred to as the mirror neuron system (MNS), or the action-observation network (AON) in the human brain, this system is active both during observation and execution of an action (Rizzolatti & Sinigaglia, 2010). Several neuroimaging meta-analyses provide corroborating evidence of the “mirroring” properties of these regions (Caspers et al., 2010; Fox et al., 2015; Molenberghs et al., 2012; Van Overwalle & Baetens, 2009). This functional overlap could allow the observer to encode the goals of motor actions by mapping them onto one’s own internally-stored behavioral repertoire and simulating a similar motor representation (Van Overwalle & Baetens, 2009). In this way, implicit motor representations of BM could be used to process visual displays of dynamic, biological stimuli. It has been proposed that this system plays an important role in gaining skills critical for social interaction, such as intention understanding, imitation and empathy, and thus contributes to social-communicative development (Hasson & Frith, 2016; Pfeifer et al., 2008; Rizzolatti & Sinigaglia, 2010), although these complex functions of the MNS/AON have also been challenged (Hickok, 2009).

There is a large body of literature that has examined dysfunction in this system as a potential causal factor in ASD, termed the “broken mirror theory” (BMT) of autism (Gallese et al., 2013; Hamilton, 2013; Williams, 2008). The theory suggests that disruption in perception–action neural coupling precludes those with ASD from developing appropriate imitative and social-communicative skills. Neuroscience research in children and adolescents with ASD has revealed regions of the MNS/AON with abnormal patterns of neural activity during action observation and execution, which is correlated with severity of social impairment or autism traits (Biagi et al., 2016; Dapretto et al., 2006; Iacoboni & Dapretto, 2006; Oberman et al., 2005; Wadsworth et al., 2017; J. Yang & Hofmann, 2016). However, mixed and contradictory findings contribute to the ongoing debate surrounding the ability of this model to account for deficits in ASD (Hamilton, 2013; Southgate & Hamilton, 2008).

The exact role of MNS/AON dysfunction in ASD is still under dispute (as are the functions of the MNS/AON more broadly; Hickok, 2009), and there is much that remains to be discovered about this system in a typical brain. Nevertheless, there is compelling evidence to support the notion that visual perception and execution of biological action are supported by and interact through shared neural mechanisms. Moreover, behavioral studies pointing to a strong bidirectional relationship between perceptual and motor performance in both typical and atypical development provide further indication of this connection.

In recent work from our lab (Fourie et al., 2020), we examined neural processing and production of gesture, with the goal of identifying brain-behavior relationships between visual processing and motor performance. This study built on previous BM literature by using stimuli that more closely mimicked real-world social interaction, in the form of human-like avatars, which were parametrically manipulated to produce identical movements with varying degrees of movement intensity. Autistic participants showed reduced sensitivity to movement intensity in right posterior superior temporal sulcus (pSTS), with levels of movement eliciting differential activity only in the TD group. This finding pointed to aberrant, but not entirely dysfunctional, processing of BM in ASD, especially with respect to the dynamic properties of movement.

These findings and others (Atkinson, 2009; Koldewyn et al., 2010) provide evidence of atypical sensitivity, namely higher thresholds, during biological motion perception as well as sensory perception in other modalities (Yaguchi & Hidaka, 2020). This research, coupled with studies pointing to the local, temporal components of BM as being the most important feature for BM processing (Casile & Giese, 2005; Federici et al., 2020), indicate that the degree of local dynamic properties may be a critical component driving behavioral and neural differences during action observation in autism. We sought to explore this kinematic quality of human movement that makes it "biological" in nature.

In addition to perception of BM, we were also interested in its production, as both areas are implicated in ASD. Similar to the research by Fourie et al. (2020), the goal of the present study was to assess participants in both perceptual and motor domains, in order to identify whether an association between them could be observed. However, methods for evaluating the association between these domains have not used a common metric suited to identify an association. An approach that represents motion similarly in both the perceptual and motoric domains may be essential to examining the relationship between them.

The Two-Thirds Power Law

One way to characterize BM comparably in both perceptual and motoric domains is to use the two-thirds power law (2/3 PL), a kinematic profile which describes a covariation between velocity and curvature of movement, in which the exponent represents the amount with which velocity is modulated by curvature. The name of the law derives from the exponent (two-thirds) in the equation by which it was originally defined:

(1) Angular velocity = K * Curvature $^{2/3}$

More commonly and as will be used in this study, the relationship is expressed using an alternative, mathematically equivalent equation, based on different variables (and thus resulting in a different exponent):

(2) Tangential velocity = K * Radius of curvature $^{1/3}$

In both equations, K represents a velocity gain factor that remains constant across the movement.

The law defines an inverse relationship between tangential velocity and curvature (‘radius of the curvature’ is the inverse of ‘curvature’), such that the velocity is lower in more curved parts than in less curved parts of the movement. This model captures the tendency of the motor system to optimize movement by maximizing its smoothness, and is believed to reflect motor control. Thus, movement adhering to the law is perceived as being constant and uniform despite having variable velocity (Levit-Binnun et al., 2006; Salomon et al., 2016; Viviani & Stucchi, 1992). Single-point motion adhering to this law is also judged to be natural compared to control stimuli violating the law, on the basis of this kinematic feature alone, even when presented without the context of a human form (Bidet-Ildeil et al., 2006; Salomon et al., 2016). Well before overt judgments can be made, infants as young as 4 days old appear to discriminate between 2/3 PL and constant motion profiles, as evidenced through their looking behavior (Méary et al., 2007). This data suggests an early and continuing sensitivity to motion following this law even in presentations of the sparsest stimuli.

This kinematic property of motion extends to several types of motor movements, including arm and foot trajectories (Ivanenko et al., 2002; Richardson & Flash, 2002), eye movements (De’Sperati & Viviani, 1997), drawing (Viviani & Schneider, 1991), and movement planning (Viviani & Flash, 1995). Adherence to the law exists independent of the rate of movement, size of the shape, and type of curvilinear path (ellipse, Lissajous curve, cloverleaf; Hicheur et al., 2005; Levit-Binnun et al., 2006; Viviani & Flash, 1995). This attribute is believed to be a key feature which sets biological motion apart from most artificially-generated motions (Kandel et al., 2000).

Production of motion compliant with this law is present early in development. Research examining the organization and structuring of spontaneous arm movement in 3- to 5-day-old neonates demonstrated a precise coupling of velocity and curvature (Hofsten & Rönnqvist, 1993). This property of motor behavior has also been demonstrated in reaching movements of 5–9-month old infants, despite the apparent lack of coordination of these movements, and independent of whether a reaching movement resulted in a successful grasp (Fetters & Todd, 1987). These studies provide evidence of an innate tendency to execute movement in line with this law, highlighting the fundamental nature of this property of the motor control system.
It appears to be an invariant characteristic which requires no skill or practice, and is present across a range of both functional and spontaneous movements.

As children begin to develop greater motor control, this velocity-curvature association is also present in their drawing movements, such as the smooth-inertial sections of circular scribbles made by 2-year-olds (Adi-Japha et al., 1998). Two additional studies examined the law developmentally in large samples of children ages 5 to 12 and found a close coupling of velocity and curvature in both free-hand drawn (Sciaky et al., 1987) and template-traced ellipses (Viviani & Schneider, 1991). Interestingly, both studies demonstrated that adherence to this law of motor movement progresses developmentally: with increasing age, there was an increase in the strength of the association (measured by correlation coefficient) between curvature (to the power of 1/3) and velocity (Sciaky et al., 1987) as well an increase in beta, the exponent in equation (2) toward the adult value of 1/3 (Viviani & Schneider, 1991). In sum, these studies point to the presence of this fundamental property of human motor behavior early in development, with progressive strengthening and tuning through experience over a period of several years.

Mechanisms Underlying the Power Law in Perception and Production

Given the links between motion perception and execution, it follows that this characteristic of the motor system may also influence how we perceive motion. Research has investigated the ability of the perceptual system to predict the course of dynamic movements based on compatibility with the 2/3 PL. Two studies, one using dots moving along curvilinear paths with varying degrees of predictability (Flach et al., 2004) and the other using more ecologically relevant displays of cursive handwriting (Kandel et al., 2000) found that motion compatible with the 2/3 PL (exponent = 1/3) was more accurately anticipated than motion incompatible with the law (exponent < or > 1/3). Given that the paths in the first study were not specific to human movements, it seems that *this* isolated kinematic-geometric property of motion, *not* the context of the stimuli, emphasizes the motion's relevance to our processing systems. The results are consistent with the notion that our perceptual system is more closely tuned to and thus more effectively able to track movement that adheres to this law. Another study assessed a direct action-to-perception transfer, showing that visual discrimination for the learned movement (which violated the 2/3 PL and thus was not present in typical human movement) can be improved after blindfolded motor training (Beets et al., 2010). These behavioral findings suggest a link between perception and production of motion, as it relates to the biological profile of the 2/3 PL.

Furthermore, perception of motion adhering to this law appears to be supported by biological and neural mechanisms. Simple dot motion following the 2/3 PL appears to elicit fMRI activity that is both stronger and more widespread than other types of motion (Casile et al., 2010; Dayan et al., 2007). This work has been replicated using EEG methodology, in which event-related desynchronization (ERD), considered to reflect cortical motor activity, was stronger and arose faster during observation of motion following the 2/3 PL compared to other motion profiles (Meirovitch et al., 2015). This selectivity and heightened sensitivity indicate a tuning of the brain's perceptual system to kinematics adhering to this law. The observed pattern of neural activity involves networks that are associated with motor planning and production as well as action observation, suggesting that our brains evaluate dynamic visual input in relation to our internal motor representations of movement.

Other research has suggested that the similarity between motor and perceptual processes may stem from similarities in neural coding principles, which affect both systems with respect to this kinematic property (Levit-Binnun et al., 2006). For example, several neurophysiological studies recorded activity from single cells in motor cortex as monkeys performed reaching and drawing movements (Schwartz & Moran, 1999, 2000). The 2/3 PL was evident in the neural correlates of monkey hand movement, and the kinematic components of velocity and directionality could be predicted by firing properties of the system. The authors concluded that execution of motor movement is constrained by neural processing: the capacity of the system to transmit directional information is limited such that as direction of movement changes around a curved trajectory, the arm slows to reflect these neural processing constraints. Additionally, behavioral research using this law of motion has provided support for the common coding hypothesis, which states that action execution and perception rely on a common neural code, which is activated when either process is carried out (Wong et al., 2013; Prinz & Hommel, 2002). While the precise nature of the underlying mechanism is not yet clear, these studies point to some shared coding between perceptual and motor systems that is specialized for motion adhering to the 2/3 PL.

Taken together, this work suggests that the 2/3 PL of motion is subserved by biological, evolutionary and neural mechanisms. It appears to be fundamentally embedded in both motion perception and motor execution systems (with some likely overlap between them), and evident early in development. Thus, this law provides a useful tool for studying the association between these two domains, especially in better understanding a developmental condition like ASD with early emerging deficits. Given its age-related developmental trajectory, the law provides a systematic way to assess developing motor control, across an age when more advanced fine motor skills, like handwriting and picture drawing, emerge. It offers a mathematically defined model which captures a fundamental feature of BM, the “biological” quality of human movement. Importantly, the law can be similarly applied in both perceptual and motor domains, providing a way to more directly compare across them. The proposed study seeks to capitalize on the nature of this law to investigate motion perception and execution in ASD as well as explore the association between them.

The Current Study

Aim 1: The first aim was to determine whether autistic individuals exhibit differential preference and sensitivity for movement that varies in its adherence to the 2/3 PL. Most existing paradigms investigate BM using point-light displays (PLDs) that consist of an array of illuminated dots moving like the joints of a human. While these types of stimuli provide a more impoverished depiction of human movement, they are still likely to require some global motion integration and recruit higher order association areas in order to successfully extract and process the human form. It is possible that reports of impaired performance in ASD have been inflated due to greater processing loads beyond basic perceptual abilities.

Furthermore, research has pointed to temporal features as being integral to revealing BM perceptual anomalies in ASD (Casile & Giese, 2005; Federici et al., 2019). Existing research demonstrating diminished sensitivity to BM in the form of a single stimulus with a biological kinematic profile has been conducted with adults and required an overt motor response to determine discrimination thresholds (Cook et al., 2009; 2013; Edey et al., 2019). However, little is known about the emergence of sensitivity to this kinematic feature of BM earlier in development, which is critical to understanding an early-emerging condition like ASD. Our study will employ a passive viewing task in which attentional preferences will be detected without the need for explicit instruction or overt responding, allowing us to measure these behaviors in young children.

Our study extends the adult literature by similarly isolating the temporal features of BM from the global, configural human form. The 2/3 PL provides a kinematic profile capturing the “biological” quality of human movement and can be applied to a single point. By using the most simple, low-level stimuli, a single dot in motion, we attempted to minimize any additional computational demands associated with processing PLD stimuli and evaluate perception of the local, temporal, “biological” property of human motion. In addition to single-point motion, we also presented participants with more complex stimuli (i.e., PLDs) that are traditionally used in the literature on BM processing. The authors of a recent meta-analysis, which showed a pronounced effect for temporal over spatial scrambling in autism, called for using multiple forms of non-BM stimuli within the same sample (Federici et al., 2020). As such, we included both a spatially and temporally scrambled condition as comparisons. In this way, we were able to examine whether sensitivity for single-point BM is related to, and potentially underlying, BM perception and attention abnormalities in ASD more broadly.

Hypotheses for Aim 1: (a) We hypothesized that autistic participants would show diminished preference and sensitivity for single-point stimuli that adhere to the 2/3 PL compared to TD participants. (b) We expected that autistic individuals would show atypical visual attention in the temporally scrambled condition, compared to the spatially scrambled condition. (c) Further, we expected that individuals, across both groups, with atypical attention for single-point motion would similarly show atypical attention for point-light displays of BM, particularly in the temporally scrambled condition.

Aim 2*:* The second aim will address the question of whether autistic individuals differ from controls in their execution of movement. By measuring adherence to the 2/3 PL, we aimed to systemically assess the "biological" quality of movement execution that can be quantified according to this model. Research on motor kinematics in ASD has typically examined standard measures of velocity and acceleration and has revealed discrepant findings. For example, some studies report slower peak velocity (Glazebrook et al., 2016) while others show faster velocity (Forti et al., 2011; Grace et al., 2017; Lu et al., 2022) of autistic movement compared to controls, depending on the paradigm and task objectives. No studies have investigated adherence of movement to the 2/3 PL in ASD, which may be a better metric given that this law reflects motor control and governs execution of many forms of BM. Studies which do examine a closely-related metric, jerk, appear to show consistent findings of increased jerk in individuals with ASD compared to typically developing controls (Cook et al., 2013; Ferrara et al., 2016b; Nobile et al., 2011; H. C. Yang et al., 2014). This study will add to this literature on motor abnormalities in ASD to determine whether group differences exist with respect to the 2/3 PL, specifically.

Additionally, this study employed novel methodology to assess kinematics. Most research examining limb kinematics requires motion capture technology that is expensive, challenging and time-consuming to administer. In order to capture atypical motor execution in a more cost-effective yet systematic way, there is a need for precise, digitally-based and sensitive measures which yield richer and more objective data. The autism community more broadly has called for the use of digital measurement tools, to counteract challenges associated with autism diagnosis such as the lack of measurement precision and the reliance on clinical observation by trained professionals (Dawson & Sapiro, 2019).

Given the relevance of development to our research question, identifying a method with which to collect data in children was imperative. This research used an innovative approach by capturing movement kinematics through an iPad activity that was accessible and appealing to children. Smart tablet technology has been used successfully to identify kinematic motor differences in ASD, with high levels of engagement amongst a group of 37 autistic and 45 typically developing children ages 3 to 6 (Anzulewicz et al., 2016; Lu et al., 2022; Wei Chua et al., 2021). This use of novel technology holds promise as an objective and appealing method of assessing adherence to the 2/3 PL and kinematic features in young children.

In addition to examining adherence to the 2/3 PL specifically, we also collected more traditional measures of acceleration and jerk as well as a global measure of motor functioning. Having multiple assessments of motor performance allowed us to investigate whether individuals who showed greater divergence from the 2/3 PL in their execution of movement also showed more divergent kinematics and general motor impairment.

Hypotheses for Aim 2: (a) Given the literature on motor abnormalities in ASD and the findings of increased jerk in execution of arm movements, we predicted that autistic individuals would show less adherence to the 2/3 PL compared to their TD counterparts, reflecting poorer motor control in accordance with this law. (b) We also predicted that the autistic group would demonstrate greater levels of jerk, compared to the TD group. (c) Further, we hypothesized that more aberrant performance on the iPad activity would be associated with lower fine motor skills.

Aim 3: To elucidate the association between perception and execution of BM, we compared performance on each task. By including assessments of motion perception and execution, with comparable outcome measures related to a common kinematic profile, the project examined whether preference and sensitivity for BM (adhering to the 2/3 PL) is related to execution of BM (in how closely it adheres to the 2/3 PL). This aim employed an individual differences approach, in which each participants' visual sensitivity to the law was correlated with their adherence to the law when executing movement. This approach allowed us to explore whether the heterogeneity of performance in perceptual and motor domains was associated, and further, whether this association varied between TD and autistic children.

***Hypothesis for Aim 3*:** Research presented earlier suggests a close association between perception and execution of movement across a variety of behavioral paradigms, and specifically in relation to the 2/3 PL. Furthermore, neuroscientific research has identified an overlap in the neural mechanisms subserving motion perception and production. This evidence points to the notion that our perceptual sensitivity may influence our execution of movement, and conversely, that perception of BM may be constrained by the way we produce movement, by way of these shared neural representations. Thus, we predicted an association between an individual's perceptual sensitivity to motion adhering to the 2/3 PL and their adherence to the law in their execution of movement, across both groups. By manipulating and measuring this law of motion in both domains, we can evaluate whether this “biological” characteristic of movement may be an integral link between perception and action.

Methods

Participants

Participants with ASD were recruited through the UC Davis MIND Institute research registry database. Participants had an existing autism diagnosis, which was obtained via clinical assessment (confirmed through clinical, medical and/or school records; in most cases, the Autism Diagnostic Observation Schedule was administered, but scores were only available for a limited number of participants, and thus this assessment was not included in analyses). We also recruited typically developing (TD) controls through a local birth registry database (letters sent to families in areas around Davis, California, who had then agreed to participate in research). Participants were excluded from both groups if they had an acute medical condition, history of encephalopathy, encephalitis, seizures or traumatic brain injury, or were born more than 2 weeks prior to their due date. Additionally, autistic participants were excluded if they had another developmental or genetic condition related to ASD (e.g., fragile X syndrome, tuberous sclerosis, cerebral palsy, etc.). Participants were between the ages 4 through 8. See Table 1 for demographic details.

Participants visited the Neurocognitive Development Lab at the Center for Mind and Brain for a 1–1.5-hour visit. An IRB approved research team member collected informed consent from the children’s legal guardian. Verbal assent from the child was obtained, when possible. Eye-tracking was completed first, followed by the iPad task, and the cognitive assessment.

Eye-Tracking Task

The experimental task was a forced choice preferential looking paradigm, in which two different movement profiles were displayed on each half of the presentation screen simultaneously. To measure preference for and sensitivity to motion adhering to the 2/3 PL, we used pairs of identical visual stimuli that differ *only* in their adherence to the law. Target stimuli consisted of a white dot moving counter-clockwise along an elliptic path on a black background. Ellipses have been used in previous studies investigating the 2/3 PL as the variability in curvature throughout the path necessitates a change in velocity (Levit-Binnun et al., 2006; Méary et al., 2007; Salomon et al., 2016). The two motion profiles varied only in their adherence to the 2/3 PL, as determined by the exponent β (beta) in the following equation:

(1) Tangential velocity = K * Radius of curvature $^{\beta}$

The β exponent was a value of either 0 (constant tangential velocity for the entire trajectory) or 0.33 (motion adhering to 2/3 PL; velocity faster on straight compared to curved portions; representing smooth, biological motion). See Figure 1 below. All other variables (size of ellipse, average velocity, time per revolution, etc.) were held constant and the velocity gain factor, K, was set at 0.5. Each stimuli pairing was presented for 15 seconds.

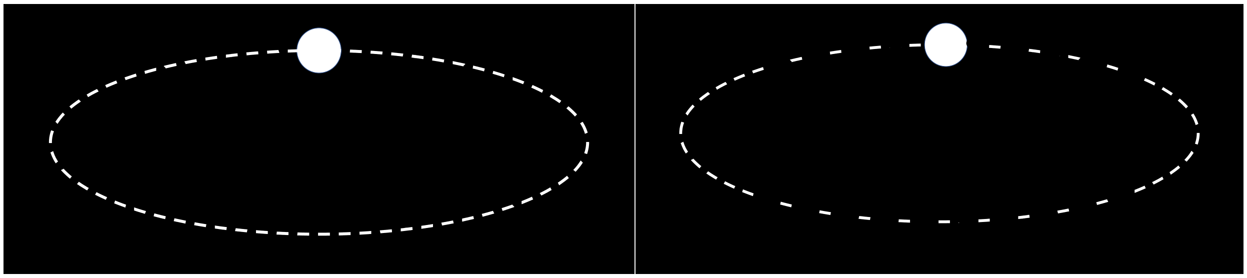


Figure 1. A depiction of the single-point condition: two dots displayed simultaneously moving along elliptical trajectories (represented by dashed lined), one with constant velocity (left), the other in adherence to the 2/3 PL (right).

The stimuli were adapted from a study by Salomon et al. (2016), which tested discrimination for the 2/3 PL in adults. Previous research has examined the effect of various elliptical parameters on how uniform a movement adhering to the law appears, including the shape and size of the ellipse, as well as the duration of movement (Levit-Binnun et al., 2006). This work demonstrated that the eccentricity (how elongated the ellipse is) had the greatest effect on the perception of movement uniformity, with higher eccentricity values eliciting greater uniformity judgements (Levit-Binnun et al., 2006). The eccentricity value of 0.97 was found to be optimal for rating motion as uniform and has been used in other research on kinematic laws of motion (Dayan et al., 2007). Our ellipses had an eccentricity of 0.94.

To assess preferences for BM as it is traditionally depicted in the literature, we also presented point-light stimuli of human walkers (PLWs), consisting of 13 light points corresponding to the major joints of the body. These PLW stimuli were generated using PLAViMoP software (Decatoire et al., 2018). There were two conditions in which a typical, upright PLW was paired with a different scrambled stimulus: (a) a spatially scrambled condition, in which each light point took a random place but conserved its initial trajectory and dynamic (Figure 2), and (b) a temporally scrambled condition, in which each light point moved with an inverted velocity profile but maintained its original spatial position (path and movement duration), resulting in local, dynamic features that appeared somewhat atypical (Figure 3). In the first condition, the spatial scrambling ensured that the configural cues in the original biological motion displays were completely eliminated but the local motion information remained unchanged, while in the temporal scramble, the configural features were kept constant while the local kinematics of human movement were altered. Each stimuli pairing was presented for 5.15 seconds and the side of the screen was counterbalanced across trials. These conditions mimic the spatial and temporal conditions of the Federici et al. (2020) meta-analysis, in which studies using a temporally scrambled stimulus resulted in more pronounced impairment autistic performance.

Figure 2. Example of the spatially scrambled condition, a typical PLW (left) paired with a spatially scrambled PLW (right).

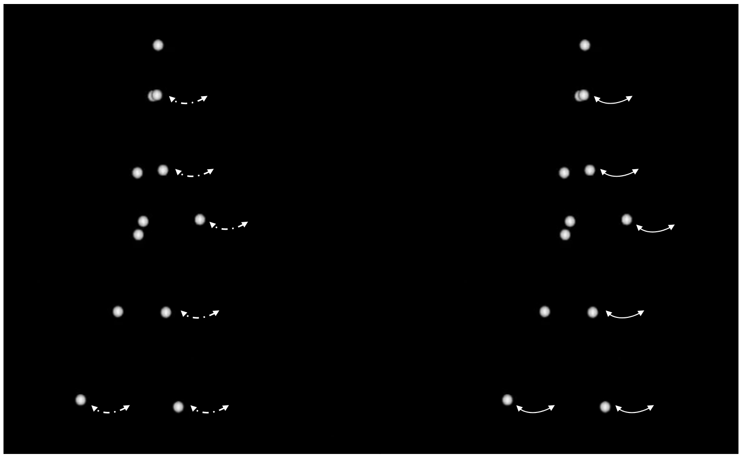


Figure 3. Example of temporally scrambled condition, a typical PLW (right; lines represent smooth, biological movement) paired with a temporally scrambled PLW (left; lines represent "jerky", inverted velocity profile).

The last condition was a single stimuli presentation, consisting of the same single-point elliptical movement described above, moving with either constant or 2/3 PL motion. This exploratory condition was included to examine whether the ability to track a dot moving with either a biological (2/3 PL) or non-biological (constant velocity) profile differed.

Stimuli was presented on a 17-inch monitor (1280 x 1024 pixels resolution), while eye gaze was recorded by an infrared binocular eye tracker (Tobii X60 Monitor Mount). Eye tracking data was collected at a sample rate of 60 Hz. The average accuracy of the recorded eye coordinates was about 0.5°, which is approximately 0.5 cm at a viewing distance of 65 cm. A standard five-point calibration was completed for all participants prior to beginning each run. Each trial began with a 1000-ms central fixation cross, followed by a motion pairing. There were three types of blocks: single-point condition (with 2 pairings); PLW conditions (with 6 stimuli pairings), and single-point tracking condition (with 1 single presentation). Each run lasted approximately 3.5 minutes. Participants were able to rest in between runs. Trial order was counterbalanced between participants.

Assessment of Motor Execution

To measure adherence with the 2/3 PL in the movement execution, we assessed the kinematics of finger movements on an iPad tablet. Participants were instructed to first draw and then trace ellipses in a bespoke application, created in collaboration with researchers at the University of Strathclyde. Ellipses were chosen to maximize the similarity between the perceptual and motor assessments, and to build on existing literature examining the 2/3 PL developmentally. The template ellipse for tracing trials had the same eccentricity as those shown in the eye-tracking assessment (E = .94, with a perimeter of 33.41cm, to note: adherence to the 2/3 PL in motion production appears unaffected by eccentricity and size), and was rotated from horizontal by 45° for ease of finger movement (counter-clockwise for right-handed subjects; clockwise for left-handed subjects). Participants were free to choose the rhythm of movement but were instructed to try to maintain a constant rhythm throughout all cycles for a given trial. We included both drawing and tracing activities to examine kinematic differences resulting from varying level of task constraints. The drawing activity took approximately 20 minutes to administer.

Behavioral Measures

We also collected a neuropsychological measure of cognitive functioning and parent-report measures of social impairment and motor ability. Overall cognitive ability was assessed using either the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 2011) for the first 10 subjects or the Stanford-Binet Intelligence Scales, Fifth Edition (SB; Roid & Pomplun, 2012) for all others. Both verbal and nonverbal IQ scores were obtained as well as a full-scale score. The Social Communication Questionnaire (SCQ; Rutter, Bailey & Lord, 2003) was used to provide a measure of communicative and social functioning. The Vineland Adaptive Behavior Scales, 2nd Edition (Sparrow, Cicchetti & Saulnier, 2010) was used to assess both gross and fine motor ability. We also collected demographics information including age, race/ethnicity, gender, handedness, as well as frequency of iPad or tablet use (daily, few times/week, few times/month, very rarely or never).

Data Processing

Eye-Tracking Task

Fixations were defined using the Tobii fixation filter, such that maximum angle between fixations was 0.5° and fixations had to be longer than 60ms. For preferential looking trials, areas of interest (AOIs) of identical size for paired stimuli were drawn using Tobii ProLab software. For PLW trials, all AOIs were defined as 14.5 x 18.5° rectangles; for single-point elliptical stimuli, all AOIs were 20.5 x 14° in size (estimated using a distance from the screen of approximately 65cm). The participant was considered to have looked at either stimulus if their gaze coordinates fell within the borders of either AOI. Total fixation duration in each AOI was extracted and a preference index for each stimulus type was calculated as the proportion of time spent looking within the AOI surrounding that stimulus, compared to the overall looking time to both stimuli (score of 0 to 1, with 0.5 representing chance looking). Location of first fixation was determined as the AOI on which the participant first fixated their gaze at the start of a trial; a proportion was calculated for each stimulus to indicate how frequently the participant looked first at that stimulus across all trials in the condition. Latency of first fixation was computed as the amount of time before a participant first fixated on a stimulus, following stimuli onset. This metric was determined separately for each stimulus, providing an average latency for each stimulus within the condition. Lastly, number of gaze shifts was calculated as the number of times the participant's gaze switched from one AOI to the other during a single trial, used as a measure of ongoing visual scanning and active comparison between stimuli. For each condition, looking metrics for all trials were averaged to create an average score for each motion profile within the condition. For the single stimuli presentation trials, a dynamic AOI following the dot along the elliptical path was created. Total AOI fixation was extracted and divided by the total looking time to the screen during that trial to determine an overall "tracking score," indicating how closely the participant tracked the dot in constant and 2/3 PL motion conditions.

Runs were excluded due to quality issues when there was difficulty with task compliance (excessive movement, constant attention redirection required, parental interference), when Tobii recorded less than 50% gaze samples (i.e., the number of gaze samples collected by eye tracker compared to the theoretical maximum), or when there were technical issues with the eye tracker and/or calibration. As a result, 5 TD and no ASD participants had no usable runs. All metrics were calculated separately for each run, and then averaged between runs when there were two valid runs. To check for differences in data collection quality between the final samples, we compared the percentage of gaze samples in each group. The TD group did show a greater percentage of samples (82.5%) compared to the ASD group (73.7%), $p = .045$, suggesting an overall diminished level of attention on the task in the ASD group.

iPad Task

The application recorded participants' swiping movements on the screen, collected at a sampling rate of approximately 120 Hz, in the form of x and y coordinates of finger location over time. Because the data was sampled at variable rates (due to the collection instrument and iPad ProMotion technology), x, y and time vectors were first resampled. Then, x and y position vectors were filtered using a fourth-order, zero-phase shift, 10Hz low-pass Butterworth filter (Bartlett, 2007). We defined continuous segments of movement as those for which a participant's finger made constant contact with the screen; any invalid movements (without end points) were excluded from analysis. We then excluded data from the first revolution of each segment when participants were accelerating to reach a stable pace, as well as the final portion of movement following the last full revolution (as sampling rate often dropped off, a feature of the ProMotion technology). Resulting portions of the segments needed to include at least two full revolutions (sufficient data for linear regression) to be included in the analyses.

To determine adherence to the 2/3 PL for each continuous segment, path curvature (measured as radius of the curvature, calculated based on three consecutive data points) and tangential velocity were computed for each data point. The common log values of these variables were linearly regressed to determine the exponent (β; beta) representing the power relation between them, according to the equation: Tangential velocity = K * Radius of curvature$^{\beta}$ (see Figure 4). Given that the 2/3 PL is demonstrated only for curvilinear trajectories, data from curvature values representing nearly flat segments (high radius of the curvature values) of movement were excluded from further analyses, a procedure employed in another study calculating the beta value from elliptical movement in this way (Wann et al., 1988). This upper curvature threshold was determined by calculating the maximum radius of the curvature value on the template ellipse (the flattest portion): a log value of 2.35. At this point, curvature is minimal; beyond this level of flatness, we do not expect the velocity to be modulated according to the 2/3 PL. The beta exponent was calculated for data points below this curvature value cutoff.

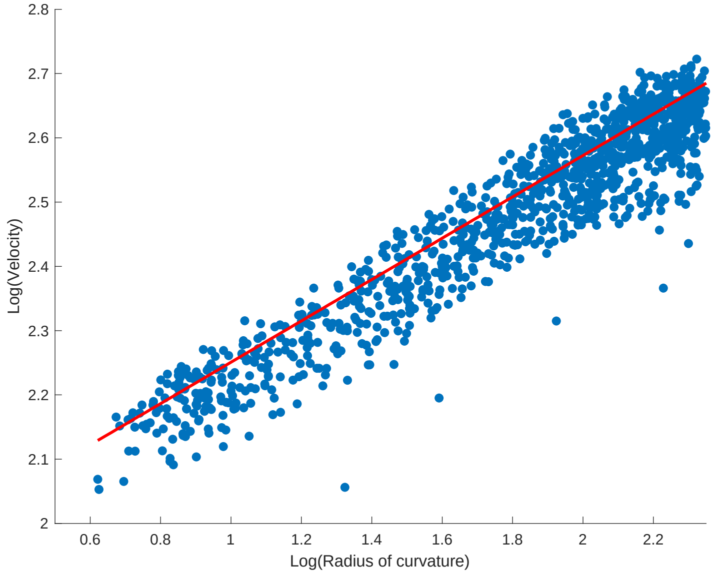


Figure 4. Plot of the logarithms of radius of curvature and tangential velocity for a tracing trial of a TD participant. The red line represents the slope of the relationship between the variables (shown here at β = .32).

For any continuous segment of movement, K, the velocity gain factor, is held constant and as such, irrelevant to our calculations. The exponent beta quantifies the segment's adherence to the 2/3 PL: exponents with a value of 0.33 represent perfect adherence with the law; exponents less than 0.33 suggest that participants performed movement at more constant velocity regardless of the degree of curvature (the change in velocity across levels of curvature is less than ideal); exponents greater than 0.33 characterize movements that modulate velocity at points of curvature to a greater-than-ideal degree (the change in velocity across levels of curvature is more pronounced). Additionally, acceleration and jerk for each continuous segment (including the whole range of curvature values, even above the 2.35 curvature cutoff) were calculated as the absolute value of the derivatives of velocity and acceleration, respectively. For each participant, the average and standard deviation of the beta exponent, acceleration and jerk across all segments was used as a measure of their adherence to the 2/3 PL and intra-individual variability, calculated separately for drawing and tracing trials.

As a further investigation to explore the difference in kinematic metrics across varying levels of curvature, we split the curvature at a level of 1.5 in logarithmic scale (based on calculations of curvature across the template ellipse; this value corresponds to a radius of curvature of 3.2 cm). Next, we determined beta values separately for data points below (curved portions) and above (flat portions) this cutoff point, as well as calculated velocity, acceleration and jerk values for each of these curvature ranges to explore the variability in these metrics across the varying levels of curvature.

Analyses

All analyses were conducted in R. To determine whether groups differed on any of the eye-tracking metrics, we used independent samples t-tests or Mann Whitney U-tests (when assumptions were violated). For some metrics, the two PLW conditions (spatial and temporal scramble) were compared directly using a 2x2 ANOVA with group and condition, given that these conditions were identical (presented for equal durations, paired with the same typical PLW, and with equally sized AOIs). We also examined relationships between preferences across conditions by comparing metrics on single-point trials to those on more traditional PLW conditions, using linear regression. Furthermore, we examined whether eye-tracking metrics (in single-point and PLW conditions) were related to measures of social functioning, as assessed by the SCQ, to determine whether attention to BM may be associated with global social functioning.

To compare group performance on the iPad task, we used a series of t-tests or Mann-Whitney tests with each of our metrics of interest, always separately for drawing and tracing trials. Further, the relationship between these task-specific kinematic metrics and fine motor functioning assessed by the Vineland was examined using linear regression, to determine whether adherence to the 2/3 PL in drawing movements relates to motor functioning, more broadly. We also performed linear regression of iPad variables on age to assess the age-related trends in task-specific motor metrics.

In order to determine whether we could detect an association between patterns of visual attention on the eye-tracking task and kinematic features of motor performance on the iPad with respect to the 2/3 PL, we correlated outcome measures of fixation toward single-point motion adhering to the law and the beta values (a measure of adherence to the law), using linear regression. We included IQ as a covariate to all group comparisons that were significant.

Results

Sample Characteristics

The final sample included 33 typically developing and 24 autistic participants, ranging in age from 55 (4 years) to 107 months (8 years). Groups were matched on age (*p* = .29) and performance IQ (*p* = .06). The TD group had significantly greater verbal IQ, full scale IQ, SCQ and Vineland motor score compared to the ASD group. The TD group included 16 male and 17 female participants; the ASD group included 18 male and 6 female participants. In the full sample, 38 (66%) of the participants were Caucasian, 1 was Asian, 1 was American Indian and 17 (30%) identified with multiple races. Across these racial groups, 12 participants (21%) of identified with a Hispanic/ Latinx ethnicity. See Table 1 for demographic information. Numbers in each sample for each task will be outlined in the sections below.

	TD group	**ASD group**	**Significance**
Age (months)	80.12 (15.12)	84.46 (15.49)	*p* = .297
FSIQ	117.03 (13.17)	101.04 (17.76)	*p* <.001
Performance IQ	110.52 (12.28)	101.67 (19.21)	*p* =.06
Verbal IQ	118.33 (14.16)	98.70 (16.87)	*p* <.0001
SCQ	3.55 (3.35)	19.52 (6.60)	*p* < .00001
Vineland (motor score)	104.45 (10.44)	80.26 (15.01)	*p* <.00001

Table 1. Demographics for both groups in the entire sample, including age in months, full-scale IQ (FSIQ), performance and verbal IQ, Social Communication Questionnaire (SCQ) and Vineland motor subscale.

Eye-Tracking Task

The final sample with usable data from this task included 28 (2 with a single run) TD and 24 (4 with a single run) autistic participants. Performance on the preferential looking task was assessed for each of the three conditions. As a measure of overall attention, we compared groups on total gaze duration within either AOI for each condition. In all conditions, the TD group showed greater overall looking to the stimuli (single-point *M* = 78s; spatial scramble *M* = 67s, temporal scramble *M* = 65.5s) compared to the ASD group (single-point *M* = 54s; spatial scramble *M* = 51s, temporal scramble *M* = 52s), *p* = .001, .011, .014 respectively. There was a positive association between IQ and overall fixation duration on all conditions ($p < .05$); however, the group differences were still significant after controlling for IQ. Further analyses for looking time measures employed the use of proportions (by dividing by overall looking to both stimuli on a trial) as the variable of interest, therefore controlling for the group difference in fixation duration.

During the single-point condition, participants were presented with pairs of stimuli consisting of a single dot moving with either constant or 2/3 PL motion, a dominant law of motion governing BM. Neither group showed an attentional preference toward one stimulus over the other: both fixation duration across the entire trial (2/3 PL: TD *M* = 51.9%, ASD *M* = 50.7%) and frequency of first fixation (TD *M* = 51.0%, ASD *M* = 49.0% to 2/3 PL) were not statistically different from chance or by group (*p* = .5 and *p* = .6, respectively). Both groups did fixate more quickly toward the constant motion (TD *M* = .35, ASD *M* = .66) compared to the power law motion (TD *M* = .57, ASD *M* = .78), but not significantly so, and groups did not differ from one another in this regard. However, groups did differ on the number of times they switched between AOIs during these trials, with the TD group switching their attention significantly more often (*M* = 7.22) compared to the ASD group (*M* = 5.02; *p* = .03). A one-way ANCOVA was conducted to compare the groups while controlling for IQ: the group effect was still significant [F(1,46) = 6.12, *p* = 0.017], with the effect of IQ marginally significant (*p* = .059). See Figure 5.

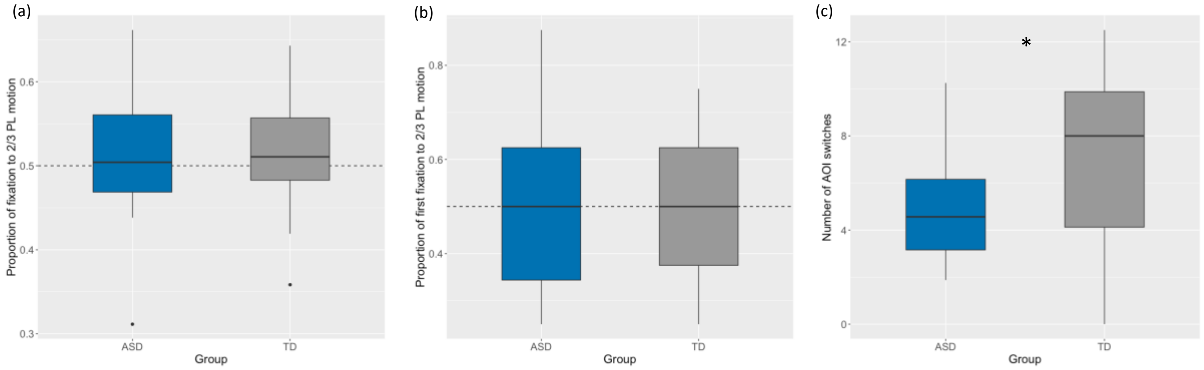


Figure 5. Eye tracking metrics for the single-point condition, including a) proportion of total and b) first fixation to the 2/3 PL stimulus and c) number of AOI switches by group (ASD = blue; TD = grey). The dashed line on the left two plots represents chance looking to the 2/3 PL stimulus. The asterisk represents a significant group difference.

On the temporally scrambled condition, the TD group showed increased overall attention toward the temporally atypical PLWs at trend level (*M* = 53.3%, *p* = .07), while the ASD group demonstrated chance looking to both stimuli (*M* = 51.9%, *p* = .22); however, this group difference did not reach significance (*p* = .60). Both groups showed similar initial orienting behavior in their first fixation, looking more frequently toward the typical (TD *M* = 53.6%, ASD

M = 53.4%) compared to the scrambled PLW, and groups did not differ in their latency to fixate toward the typical PLW (TD *M* = .47s, ASD *M* = .62s, *p* = .16), pointing to similar looking behavior toward the typical PLW across both groups. However, the TD group was faster to fixate towards the temporally scrambled PLW (*M* = .16s) compared to the ASD group (*M* = .38s, *p* = .03). Furthermore, the TD group made significantly more attentional switches between stimuli in this condition (*M* = 1.47) compared to the ASD group (*M* = 1.04, *p* = .03). See Figure 6. This effect of group was still significant, after controlling for IQ (*p* = .02).

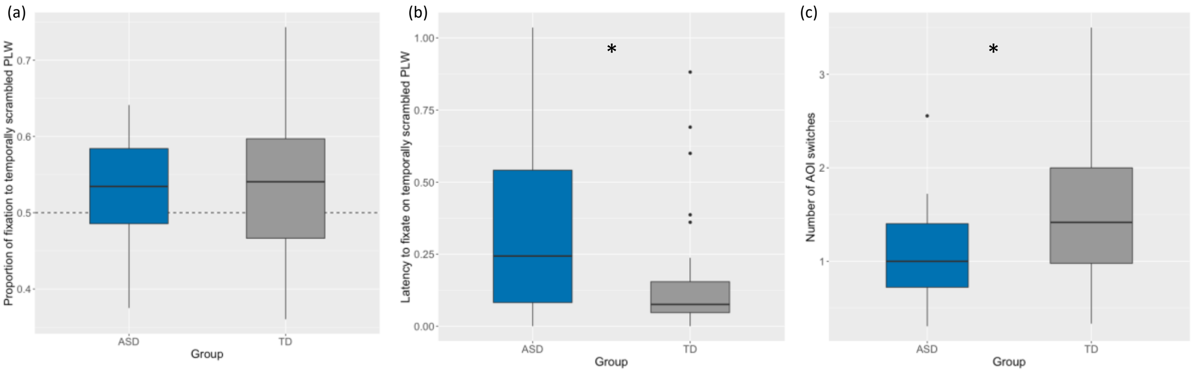


Figure 6. Eye tracking metrics for the temporally scrambled condition, including a) proportion of total fixation to and b) latency to fixate on the scrambled stimulus and c) number of AOI switches by group (ASD = blue; TD = grey). The dashed line on the left plot represents chance looking to the stimuli. An asterisk represents a significant group difference.

On the spatial scrambled condition, both groups fixated for longer durations on the scrambled PLWs, with the TD group showing a stronger preference (*M* = 68.9%) compared to the ASD group (*M* = 60.7%) at a trend level (*p* = .07). Similarly, both groups looked first more frequently toward the scrambled stimulus (TD *M* = 67.1%, ASD *M* = 63.9%), but did not differ from one another (*p* = .4). There were no group differences with respect to latency to fixate on either scrambled or typical PLW. Both groups were faster to fixate on spatially scrambled motion (TD *M* = .13s, ASD *M* = .19s) compared to typical PLW (TD *M* = .46s, ASD *M* = .60s, *p* < .01 for both groups). Lastly, groups did not differ in the number of switches they made between stimuli (TD *M* = 1.34, ASD *M* = 1.26, *p* = .96). See Figure 7.

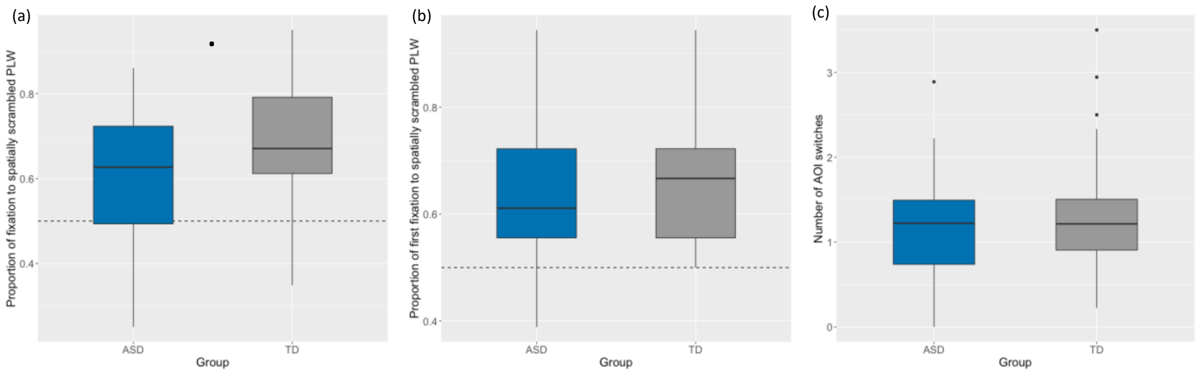


Figure 7. Eye tracking metrics for the spatially scrambled condition, including a) proportion of total fixation, b) proportion of first fixation on the scrambled stimulus and c) number of AOI switches by group (ASD = blue; TD = grey). The dashed line on the left two plot represents chance looking. A dot represents a trend toward a significant group difference.

Given the differential findings across PLW conditions, we directly compared across these conditions on both the latency to first fixation and the number of attention shifts, using 2x2 ANOVAs with group as the between-subjects factor and condition (temporally or spatially scrambled) as the within-subjects factor. For latency to first fixate on the atypical, scrambled stimulus, there were significant main effects of both group (p = .02) and condition (p = .014), as well as a marginally significant interaction (p = .052). Follow-up comparisons show that the TD group's latency to fixate on the scrambled stimulus did not differ by condition (p = .57), however the ASD group was faster to fixate toward the spatially scrambled compared to the temporally scrambled stimulus (p = .046); see Figure 8. This effect was still significant after adding IQ into the model as a covariate.

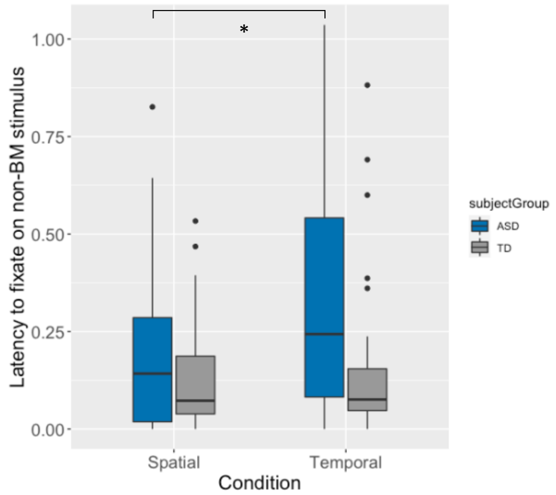


Figure 8. Latency to first fixate on the scrambled PLW by condition and group (ASD = blue, TD = grey). The asterisk represents a significant difference between conditions in the ASD group.

In comparing the number of AOI switches made across conditions, there was a significant interaction between condition and group (*p* = .023). Follow-up comparisons revealed that the TD group did not differ in the frequency with which they shifted their attention on spatially (M = 1.34) compared to temporally scrambled PLW (*M* = 1.47) trials (*p* = .28); the ASD group, on the other hand, shifted attention between stimuli more frequently in the spatially scrambled (*M* = 1.26) compared to temporally scrambled (*M* = 1.04) condition (*p* = .022; see Figure 9). This effect remained significant when controlling for IQ.

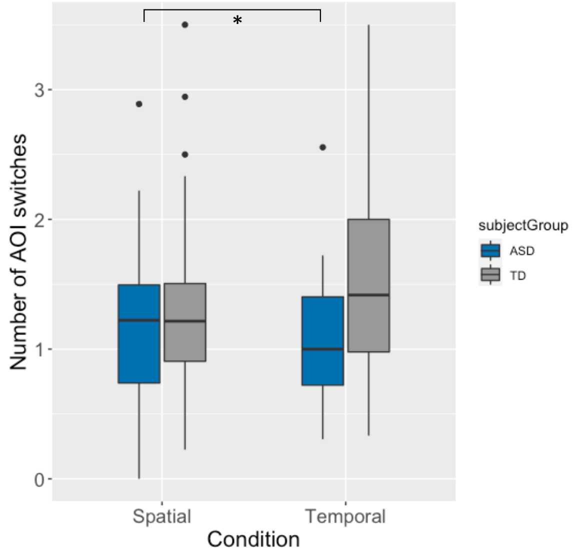


Figure 9. Number of AOI switches by condition and group (ASD = blue, TD = grey). The asterisk represents a significant difference between conditions in the ASD group.

We also examined whether individuals with atypical sensitivity for single-point motion would similarly show atypical attention and preference for point-light walker displays of BM, particular in the temporally scrambled condition. However, no relationships between metrics on single-point and PLW conditions were observed.

In the tracking condition, stimuli of elliptically moving dots were presented separately to assess whether participants' ability to follow the dot with their gaze differed as a function of the motion profile. A 2x2 ANOVA with group and motion type (constant vs. 2/3 PL) revealed a significant main effect of group ($p < .0001$), such that the TD group held attention on the moving dot for a greater proportion of time ($M = 26.5\%$) compared to the ASD group ($M = 10.1\%$). Although both groups showed greater fixation toward the dot moving with adherence to the 2/3 PL, there was no significant main effect of motion type or an interaction.

Relationship with Social Functioning

Lastly, we investigated whether any of the patterns of attention during the eye-tracking task were related to social and communicative functioning, as measured by the Social Communication Questionnaire. In the TD group, greater social functioning (lower SCQ score) was associated with *greater* attention toward the spatially scrambled versus traditional PLW ($r = -.50$; $p < .01$); no such association existed in the ASD group ($r = -.005$; $p = .98$). Conversely, better social functioning (lower SCQ score) was associated with *less* attention toward the temporally scrambled compared to the typical PLW in the TD group ($r = .42$; $p = .03$); no association was present in the ASD group ($r = -.18$; $p = .40$). See Figure 10. SCQ scores showed no other associations with any other eye-tracking metrics in either of the groups.

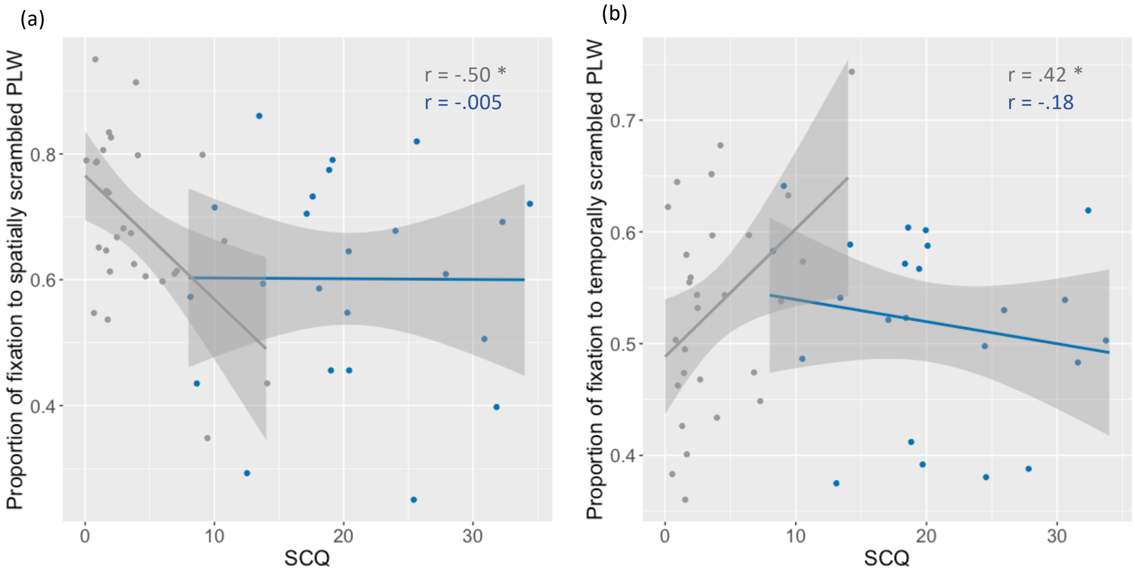


Figure 10. Association between SCQ total scores and proportion of fixation to a) spatially and b) temporally scrambled stimuli. Regression lines depicted separately for each group (ASD = blue; TD = grey). Significant associations are depicted with an asterisk next to the regression coefficient.

iPad Task

Analyses were completed with the full sample of 33 TD and 24 autistic participants. Within the ASD group, 3 participants completed only partial data collection: 2 only completed drawing trials, and 1 only completed tracing trials due to difficulties with task compliance. Based on data collection notes and visual inspection, some trials were excluded due to participants producing non-elliptical shapes.

Kinematic Metrics

On tracing trials, there was a trend toward significance (p = .09), with the ASD group demonstrating greater beta values (M = .36) compared to the TD group (M = .33). On drawing trials, the ASD group had significantly greater beta values (M = .33) than the TD group (M = .29; p < .01). See Figure 11 for group averages and Figure 12 for box plots of each participants' beta values across all segments. For tracing trials, autistic participants demonstrated greater intra-individual variability across segments (M = .099), compared to TD participants (M = .063; p =

.01). Variability on drawing trials did not significantly differ by group (TD *M* = .077, ASD *M* = .093, *p* = .4). Group variances were compared using an F-test: on tracing trials, inter-individual variance was greater in the TD group (*M* = .002) compared to the ASD group (*M* = .003; $F_{21, 32}$ = 2.18, *p* = .045). On drawing trials, group variances did not differ ($F_{22, 32}$ = 1.00, *p* = .96).

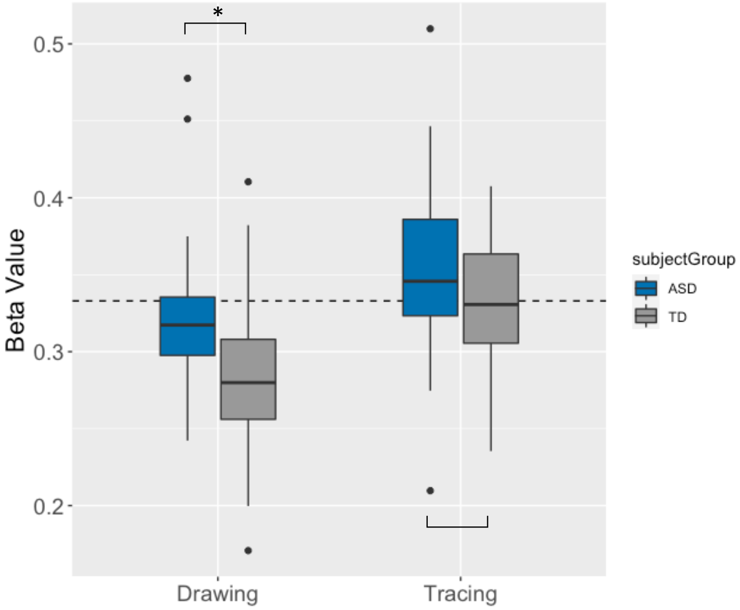


Figure 11. Plot of the average beta value for each trial type (drawing and tracing), by group (ASD = blue, TD = grey). The dashed line represents perfect adherence to the 2/3 PL (beta = .33). Significant group difference is indicated by the asterisk; trending group difference is indicated by the bracket with no marker.

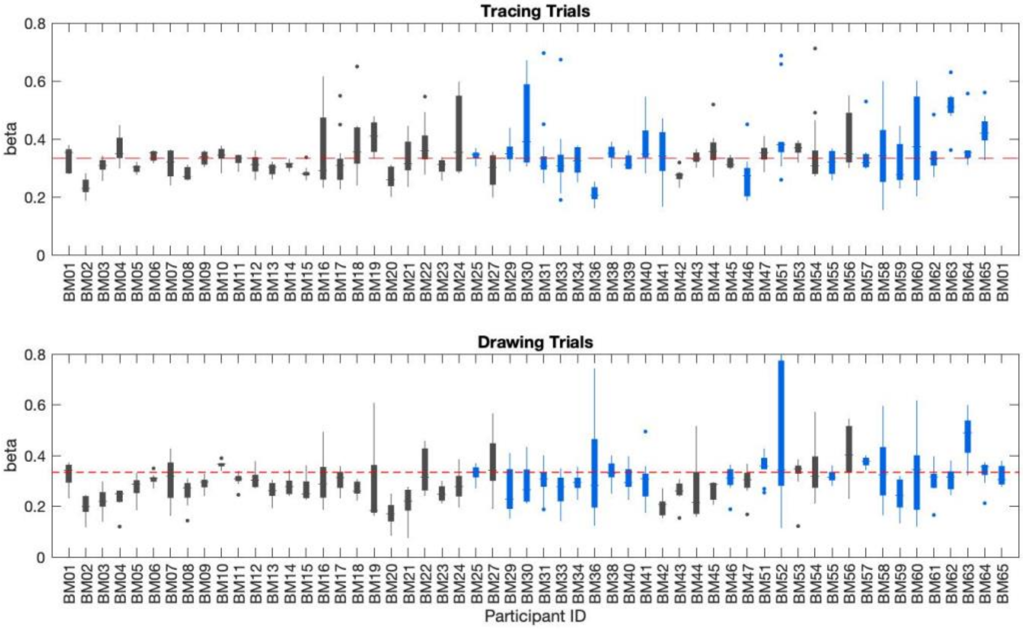
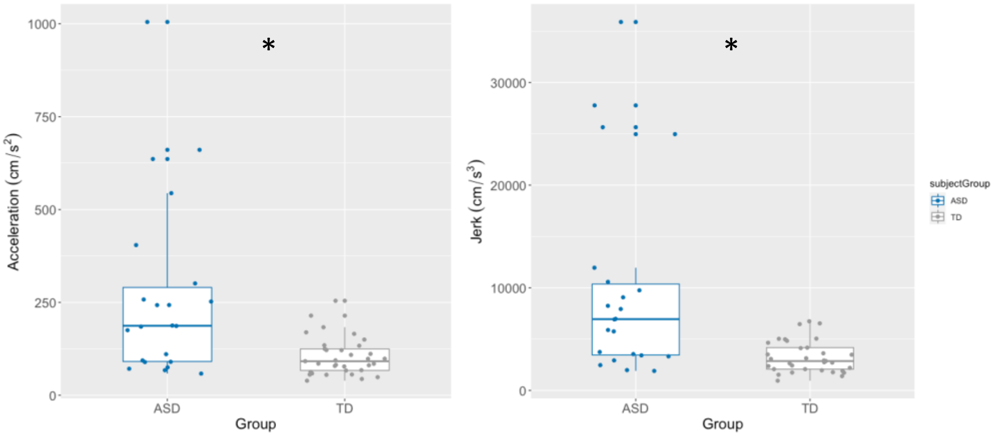


Figure 12. Boxplots of each participants' beta values across all their continuous segments of movement in both tracing (above) and drawing (below) trials (ASD = blue, TD = grey; red dashed line: beta = .33, perfect adherence to 2/3 PL).

Metrics of absolute acceleration and jerk were also examined. Compared to TD participants, autistic participants showed significantly greater acceleration during drawing (ASD *M* = 271.71, TD *M* = 120.43, *p* = .0001) and tracing trials (ASD *M* = 269.81, TD *M* = 103.55, *p* = .0007). They also showed greater levels of jerk on both drawing (ASD *M* = 9663.98, TD *M* = 3996.15, *p* < .0001) and tracing trials (ASD *M* = 9578.42, TD *M* = 1556.27, *p* < .0001). Additionally, the variance in both metrics was significantly greater in the ASD group compared to the TD group on both tracing (both *p* < .00001) and drawing trials (both *p* < .00001). See Figure 13.

(a) Tracing trials



(b) Drawing trials

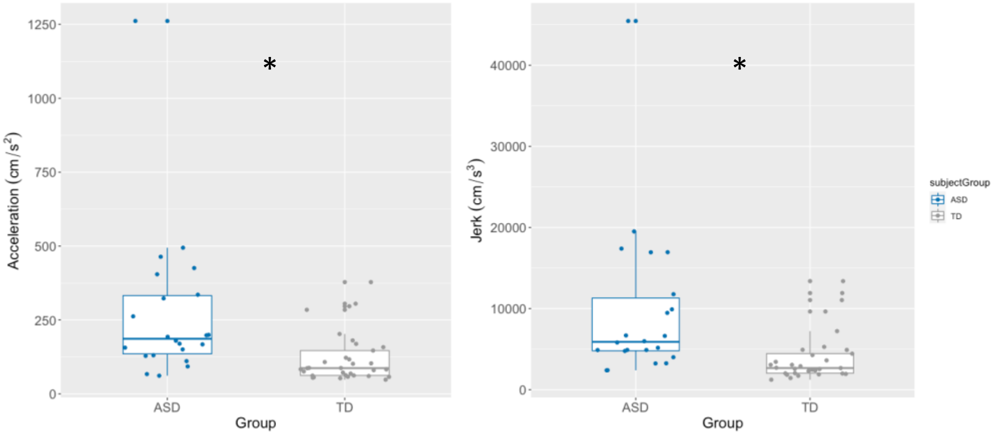


Figure 13. Average acceleration and jerk for both (a) tracing and (b) drawing trials across both groups (ASD = blue; TD = grey). Dots depict individual participant average values. An asterisk represents a significant group difference.

Curvature Split Analysis

To further explore differences in beta values and to examine whether curved (low radius of curvature) or straight (high radius of curvature) portions of movement are driving group differences, we examined whether kinematic metrics (beta value, velocity, acceleration, jerk) varied as a function of curvature to different degrees across groups using a 2x2 ANOVA with group (ASD vs. TD) and level of curvature (high/flat vs. low/curved).

During tracing trials, beta values showed only a significant effect of curvature, no main effect of group or interaction. However, average beta values for groups differed by a larger degree on the curved portions of movement (ASD *M* = .39, TD *M* = .36) compared to the flat portions (ASD *M* = .26, TD *M* = .25), despite not reaching significance. For velocity, there was a main effect of group (*p* = .002), a main effect of curvature (*p* < .000001), and an interaction between group and curvature (*p* = .002). Pairwise comparisons revealed that velocity was faster on the straight compared to the curved sections (as is dictated by the 2/3 PL), and in the ASD compared to the TD group overall. Notably, the interaction effect was driven by a *greater* difference in velocity between straight and curved portions of movement in the ASD group compared to the TD group. The same 2x2 ANOVA for acceleration resulted in only a main effect of group (*p* = .007), such that the ASD group accelerated more quickly than the TD group across both levels of curvature, but neither the effect of curvature (*p* = .08) nor the interaction between group and curvature (*p* = .21) was significant. Jerk values also showed a main effect of group (*p* = .0004), main effect of curvature (*p* < .000001), and an interaction between group and curvature (*p* = .001). Similar to velocity, the significant interaction was a result of the ASD group showing a *greater* difference in jerk between straight and curved portions of movement compared to the TD group. See Figure 14.

On drawing trials, there was a significant effect of curvature (p < .00001) and marginally significant effect of group (*p* = .059), such that average beta values on the straight portions of movement were significantly greater in the ASD (*M* = .23), compared to TD group (*M* = .19; *p* = .028), while the curved portions did not differ by group (ASD *M* = .35, TD *M* = .34, *p* = .81). For velocity, there was main effect of both group (*p* = .002) and curvature (*p* < .00001) as well as an interaction between them (*p* = .002). Pairwise comparisons show that the ASD group had greater differences in velocity between curved and straight portions compared to the TD group. Acceleration showed a main effect of group (*p* = .0007), a main effect of curvature (*p* < .00001), but no interaction. Lastly, jerk values showed a main effect of group (*p* < .00001; ASD > TD), a main effect of curvature (*p* < .00001; curved > straight) and an interaction effect (*p* = .004), in which the differences in jerk on curved versus straight sections was more pronounced in the ASD group.

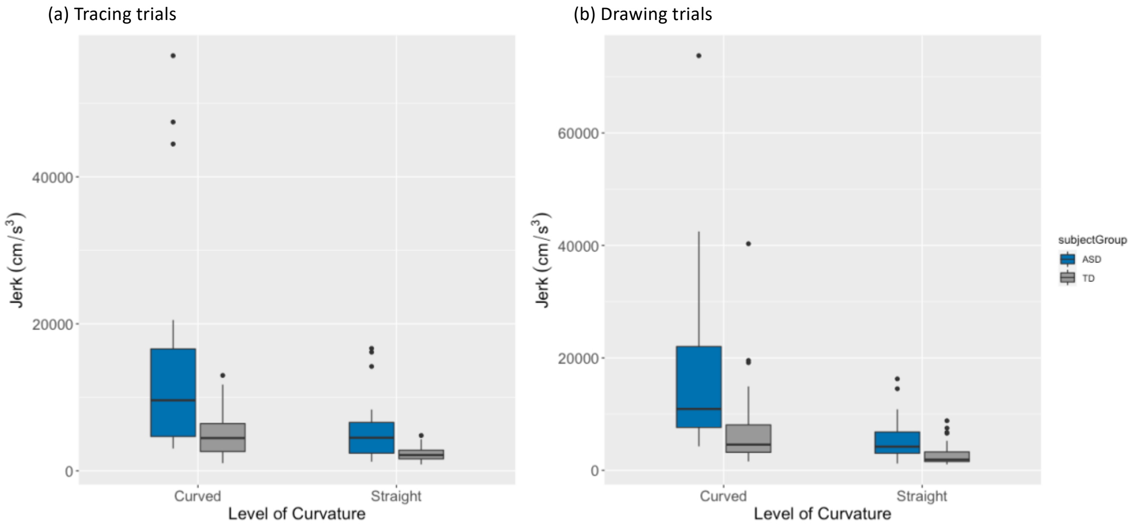


Figure 14. Average jerk by curvature level and group (ASD = blue, TD = grey), on (a) tracing and (b) drawing trials. Critically, on both tracing and drawing trials, there was an interaction effect such that differences in jerk across curvature levels were more different in the ASD compared to the TD group.

Age-Related Trends in Kinematic Features

Age-related trends in motor kinematics during the iPad activity were also explored. On tracing trials, the TD group showed a negative association between age and beta value (*r* = -.002, *p* <.0001), acceleration (*r* = -1.45, *p* =.01) and jerk (*r* = -55.21, *p* = .001). Similarly, on drawing trials, there was a significant negative relationship between age and beta value (*r* = -.001, *p* = .028), acceleration (*r* = -2.29, *p* =.02) and jerk (*r* = -86.50, *p* = .016) in the TD group. There were no significant relationships between age and any kinematic features in the ASD group.

Relationship with Motor Functioning

Finally, we examined the relationship between metrics on the iPad task (beta value, individual variability in beta value and jerk) and parent-reported motor skills as measured by the Vineland Adaptive Behavior Scales. We focused on the fine motor v-scale score, as the iPad task required fine motor skills. The only significant association that emerged was a negative relationship between variability in beta and the fine motor score (r = -.01, p = .01), such that less intra-individual variability across drawing trials was related to greater motor functioning. No other associations reached significance. In addition, no kinematic metrics on the task were related to frequency of iPad/tablet use.

Relationship Between Eye-Tracking and iPad Measures

We also sought to explore the association between perception and execution of BM as characterized by the 2/3 PL, by comparing performance on each of the tasks. This analysis was conducted with 22 autistic and 28 TD participants, who had usable data for both tasks. For the iPad task, we used an individual's overall beta value as well as the value representing deviation from perfect adherence to the 2/3 PL (i.e., a beta value of .33) on the tracing trials, which produced the more constrained and standardized data compared to drawing trials. On the eye-tracking task, we used metrics of fixation duration and first fixation to the 2/3 PL on the single-point condition. Neither group showed a significant relationship between either variable from each task. However, there was a consistent negative association between fixation metrics to the 2/3 PL and the beta variables in both groups. In other words, increased initial orienting and sustained attention toward the 2/3 PL motion profile was related to less deviation from the 2/3 power law in movement execution. In the ASD group, the association between first fixation to the 2/3 PL motion and deviation from the "ideal" beta value reached trend level significance (r =

-.43; *p* = .052); the TD group showed a similar negative association that was not significant (*r* = -.11; *p* = .60). See Figure 15.

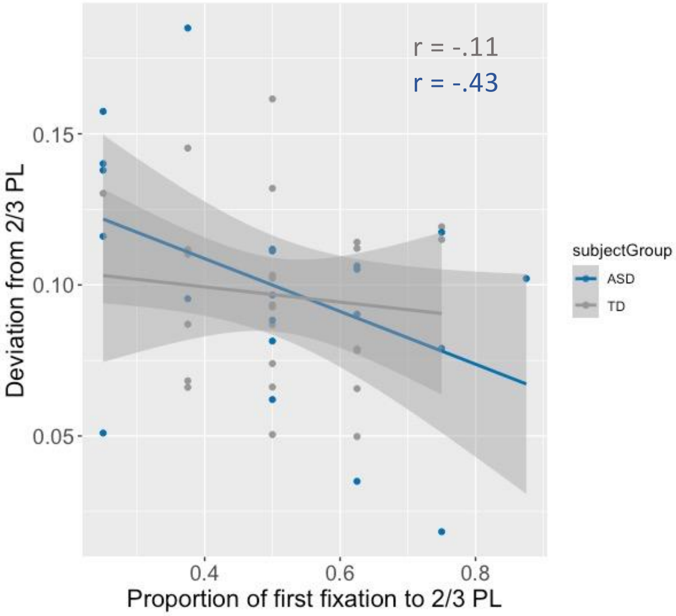


Figure 15. Relationship between proportion of first fixation to the 2/3 PL (eye-tracking task) and deviation from the 2/3 PL (iPad task). Regression lines (with respective coefficients) are depicted separately for each group (ASD = blue; TD = grey). These associations did not reach statistical significance.

Discussion

Perception of Biological Motion

During the eye-tracking task, participants were shown various presentations of BM and non-BM stimuli (both simultaneously and separately) to determine whether there were group differences in how attention was allocated toward these types of stimuli. Across all conditions, the ASD group spent less time looking toward the stimuli in general. This reflects an overall diminished level of attention toward the stimuli, not specific to any one condition, perhaps due to less interest in the stimuli, more gaze wandering or random saccades outside the AOIs. Furthermore, there was an association between overall fixation to stimuli and IQ, suggesting that these differences in attention to stimuli may be driven in part by group differences in IQ.

However, analyses of looking times used proportion scores to correct for overall attention differences, thereby controlling for group differences in fixation. Results from single-point and PLW conditions are discussed below.

Attention to the 2/3 PL

During the single-point condition, participants were presented with pairs of stimuli consisting of a single dot moving with either constant or 2/3 PL motion, a dominant law of motion governing BM. The majority of fixation metrics on this condition did not differ by group or by stimuli type. Neither group fixated for longer duration or fixated first more frequently on either motion type. While both groups were faster to fixate toward the constant compared to 2/3 PL motion, these differences did not reach significance. Given that AOIs in this condition overlapped in area with the central fixation cross, this result may not capture real attention allocation, but rather gaze lingering following the fixation cross. The exploratory assessment of gaze tracking in which each motion profile was presented separately (rather than simultaneously) similarly revealed no difference in visual pursuit of a dot adhering to or violating the 2/3 PL. Overall, these findings suggest that groups did not discriminate between these motion types, or at least that their looking behavior does not reflect any differential visual preference for, or difference in ability to track, one stimulus type over the other.

The only metric on which groups differed was the frequency with which they switched attention from one AOI to the other during a trial, with the TD group switching significantly more times compared to the ASD group even when controlling for IQ (which did also have a marginally significant effect on attention, with greater IQ associated with increased switching between trials). This finding could indicate that the TD group was better able to detect a difference between 2/3 PL and constant motion, and that attention was allocated to visually compare these motion profiles, reflected in the greater switching frequency. Despite this increase in attentional shifts on the part of the TD participants, they did not ultimately prefer to look at one stimulus over the other, so it is difficult to make strong interpretations.

These results within the TD group were unexpected. Previous research has demonstrated discrimination for single-point elliptical motion following the 2/3 PL in both infants and adults. A study with 4-day-old neonates used a very similar preferential looking paradigm in which participants were presented with white points moving with BM (2/3 PL) or non-BM stimuli over two 31-second trials of uninterrupted motion (Méary et al., 2007). The infants looked for longer duration at the non-BM stimulus (56% and 54% of the time for each trial, respectively), demonstrating an ability to detect a difference in the stimuli even at this very early age. However, in addition to being assessed in much younger children, this paradigm had some notable differences from ours: light points were larger (2.9% vs. 1.3% of total screen area), moved significantly faster (1.07s vs. 2.5s per revolution) and were presented for longer trial durations (30s vs. 15s) than those used in our task. In conjunction, these factors may have altered the processing of the stimuli and resulted in the differential looking that our task failed to detect.

Another study with adults presenting single-point elliptically moving stimuli (adhering to or violating the 2/3 PL) found that participants were able to accurately categorize motion profiles as natural or unnatural, demonstrating an ability to discriminate these motion types on the basis of their kinematics (Bidet-Ildeil et al., 2006). However, this task relied on specific judgments (participants were instructed to respond via button press) rather than looking behavior (no explicit instructions provided) to assess discrimination abilities, which may help explain our null finding. The most important difference between our stimuli and that of these two previous studies was the non-biological, control stimuli that was used in comparison to the 2/3 PL motion.

In both studies, control stimuli followed an inverted 2/3 PL profile (beta = -.33), that had greater divergence from the power law than the constant velocity profile (beta = 0) used in our task. While these studies do demonstrate that both infants and adults are sensitive to the kinematics of the 2/3 PL, this discrimination hinges on the what motion profile is being compared. Visually, the inverted 2/3 PL motion profile results in a greater deviation from the 2/3 power law than constant motion, and empirically, this motion profile is discriminated more quickly than the 2/3 PL compared to constant motion (Salomon et al., 2016). Therefore, it is likely that these studies elicited patterns consistent with discrimination in typical populations because the stimuli used as a comparison are more visually distinct.

Our findings also diverge from research using neuroscientific methods to examine differences in brain activity when observing simplified non-human (single dot or cluster of dots) motion adhering to this law. Several studies using EEG and fMRI provide evidence that the brain is selectively tuned to motion following this kinematic regularity, showing greater activity in response to 2/3 PL than both constant and inverted 2/3 PL motion profiles (Casile et al., 2010; Dayan et al., 2007; Meirovitch et al., 2015). Yet, the brain's heightened activity in response to this motion profile may not manifest as preferential visual attention, as observed behavior does not always reflect brain activity. Interestingly, these studies also provide evidence that neural activity depends on the degree of compliance with the 2/3 PL, with more divergent stimuli (inverted 2/3 PL) eliciting weaker responses compared to less divergent stimuli (constant). These findings are consistent with the behavioral data suggesting quicker discrimination of inverted 2/3 PL compared to constant motion profiles. One potential interpretation is that looking behavior may not differ unless deviation from the 2/3 PL is detectable over a certain threshold (e.g., for inverted 2/3 PL motion, but not constant motion). In our preferential looking task, it appears that constant motion as a non-BM comparison may not be sufficient to elicit differences in looking behavior. A more distinct comparison stimulus may have resulted in attention patterns more in line with what is typically observed in the literature.

Similarly, the exploratory tracking condition failed to produce differences in gaze following of motion adhering to or violating the 2/3 PL. However, both groups were slightly better at tracking the 2/3 PL dot than the dot with constant motion, suggesting there may be a trend towards a difference. We expected to see greater gaze following for the dot following the 2/3 PL as it yields movement that is smooth and uniform. In a number of paradigms designed to examine motion tracking, smooth pursuit and anticipation of motion was found to be most accurate for motion adhering to the 2/3 PL compared to other motion profiles violating the 2/3 PL, including constant motion (De'Sperati & Viviani, 1997; Flach et al., 2004; Viviani et al., 1987; Viviani & Mounoud, 1990). These studies concluded that motions that are compatible with the law are more predictable and familiar to our visual systems and therefore easier to follow. Our null findings may be attributed to the quick speed with which the dots moved that may have been too fast for proper smooth pursuit. Flach et al. (2004) demonstrated that smooth pursuit eye movements work best within a slower velocity range, and that at higher ranges, we are more likely to employ catch-up saccades. In addition, the dynamic AOI feature of the eye-tracking software used to extract this tracking metric is not designed for this purpose and a different analytical approach may have produced differences with respect to motion profile. These previous studies were also conducted on adults, who were explicitly instructed to follow the target as accurately as possible, while our study used a passive viewing paradigm in children.

To our knowledge, this is the first study to examine visual attention toward the 2/3 PL compared to constant motion in this age range and with a sample of autistic participants. Our results reveal no behavioral looking patterns in line with an ability to discriminate or differentially track these motion profiles for either group. Additional areas of inquiry are discussed in the final section.

Attention during PLW Conditions

During the PLW conditions, participants were presented with typical PLWs paired with either a spatially (dots moved to random locations) or temporally scrambled (dots' velocity profiles inverted) PLW. Overall, groups differed on more metrics during the temporally scrambled compared to the spatially scrambled condition. On the spatial condition, both groups showed a similar visual preference for the scrambled PLWs both in initial and sustained attention, and did not differ on latency to fixate on either stimulus or the number of switches made between stimuli. Overall, groups looked initially more quickly and more frequently toward, and spent more time overall time looking at spatially scrambled PLWs, suggesting that this spatially scrambled type of stimuli is both catching and holding the attention more than typical PLW stimuli.

Performance in the spatially-scrambled condition was unexpected. As commonly seen in the BM literature, we hypothesized that participants, particularly in the TD group, would demonstrate a preference for PLW over scrambled motion (Bardi et al., 2011; Bidet-Ildei et al., 2014; Klin et al., 2015; Simion et al., 2008). Yet, results on this task show a clear preference in the opposite direction (both in fixation duration and initial orienting behavior). One explanation for these findings is that all participants spent more time looking at scrambled motion because it was more visually interesting, novel and difficult to identify. Anecdotally, many participants reported trying but being unable to discern "what" the scrambled PLW was (e.g., "that looks like an animal… or some kind of creature”, despite the dots being randomly located), as compared to the clearly evident human walker.

Importantly, most existing studies which find an early preference for BM in the form of PLWs employ comparison stimuli that is either inverted (which is known to disrupt the configural processing), rigid/mechanical or random in form (which removes the biological quality of the dots). In contrast, the dots in our spatial scramble retained their local dynamic information (smooth, back-and-forth velocity profiles consistent with animate motion), making it easier for participants’ attention to be captured by this seemingly “biological” stimulus. The fact that the TD group looked comparatively longer at the spatially scrambled stimuli (at trend level, the only group difference in this condition) may be explained by a greater familiarity with the typical PLW in TD group. A typically developing perceptual system which is tuned to biological motion may process this type of motion more automatically, and thus direct greater attention toward the novel non-BM stimulus. The divergence of our findings from previous literature emphasizes how critical the choice of the comparison stimulus is to such investigations.

On the temporally manipulated condition, groups did show some differences in their looking behavior. The TD group showed slightly increased overall attention and were quicker to orient toward the temporally scrambled PLW as well as showed more attention shifts between stimuli on these trials. These group differences provide evidence that attention was more quickly captured and sustained for longer by the temporally scrambled PLW in the TD group in ways that the autistic group’s attention was not. Furthermore, the increased attention shifting indicates that TD participants performed more visual comparisons between typical and atypical stimuli, perhaps suggesting that they were better able to detect (more tuned to) a difference between stimuli. It is possible that the TD participants were better able to discriminate the slight kinematic difference between stimuli, finding the atypical motion profile “odd” in the context of the human form. Conversely, the lack of visual preference for and slower latency to orient to the atypical PLW in the ASD group may point to an inability to discriminate the differences in kinematically atypical motion. The results suggest that those with ASD may be less sensitive than TD children to the local kinematic features of a dynamic human form.

Overall, these findings suggest that groups differed in their attention and looking behavior during the temporally scrambled condition more so than during the spatially scrambled condition. Group differences remained significant after controlling for IQ, suggesting that IQ is not able to explain all of the variance in eye-tracking behavior. Furthermore, direct comparisons between conditions revealed significant group by condition interactions, in which differences in looking behavior (latency to atypical stimuli and attention shifting) emerge only between conditions in the ASD group or in the temporally scrambled condition between groups. For example, the TD group seems to respond with similar visual attention (be equally tuned to) to stimuli that differs in both temporal phase and spatial configuration, while the ASD group shows less attentional shifting on temporal compared to spatial scrambling.

These findings may be an indication of the ASD group’s diminished ability to detect a difference between temporally atypical stimuli. Spatially scrambled stimuli produce an apparent distinction when paired with a typical PLW (clearly altering attention), while the manipulation in the temporally scrambled condition is more subtle. Each of the points of the PLW remain in their original locations, yet they move with reverse velocity, so the overall walker appears to walk only slightly abnormally. Visual motion processing in autism is often thought of as being a deficit of degree, such that those with autism or autistic traits have higher detection thresholds (Koldewyn et al., 2010; Yaguchi & Hidaka, 2020). Thus, in the context of a preferential looking paradigm, they may require more (apparent) signal or a larger input to detect a difference, and demonstrate impaired performance only when stimuli are minimally different. It seems that perhaps the temporal (compared to the spatial) manipulation in our task was insufficient to meet this supposed threshold required by the visual system of autistic participants to detect a difference.

Furthermore, these results are consistent with a recent meta-analysis showing significant impairment in ASD performance (moderate to large effect sizes) on studies using temporally scrambled/out-of-phase stimuli as a comparison, but an absence of group differences when using comparison stimuli that was spatially reconfigured (Federici et al., 2019). Our findings lend support to the author’s claim that the temporal properties of dots contained in PLWs play an integral role in the difficulties faced by autistic individuals in BM processing. Rather than being a monolithic deficit in BM processing, anomalies in ASD seem to depend on what sub-component properties of the target stimulus are manipulated. These results, in conjunction with existing literature, point to the notion that these more subtle, local, temporal features may be more challenging for those with ASD to process efficiently. The atypical nature with which autistic individuals process this form of sensory input could have implications for social cognition, given that these visual dynamics of human movement may carry complex and nuanced social information.

Comparison of Temporal Manipulation Across Conditions

While the eye-tracking task did reveal differences in looking behavior towards our temporally manipulated versus typical PLW (as well as group differences on some metrics), we failed to find the same differences in looking behavior to the kinematically manipulated stimuli in the single-point condition. In this condition, we isolated the temporal component of biological motion, presenting dots which either complied with or violated the 2/3 PL. Unexpectedly, the BM profile applied to a single dot was not sufficient to elicit differential looking behavior between either stimulus in either group, where we predicted a visual preference for the 2/3 PL. While in both conditions the stimuli were manipulated along a temporal dimension (albeit via distinct processes), only the array of dots in the PLW form resulted in differences in looking behavior in both groups (although to a lesser extent in the ASD group). Despite the loss of local motion information, the PLW stimulus maintained global compatibility with a human figure, and thus was processed as a human walking. The single-point condition, on the other hand, yielded stimuli which did not resemble a human-like configuration. In simplifying the stimuli to a single dot, the "biologicalness" of the motion was also removed from its human context, and thus may not have been perceived as traditional BM. In addition, as discussed previously, it is possible that the constant velocity non-BM motion used as a comparison was not sufficiently visually different to be perceived as a contrast to the BM stimulus.

These disparate results suggest that participants in the TD group may be sensitive to kinematic features but only in the context of human form. This tracks with a computational model created by Casile & Giese (2005), who demonstrated the need for coarse form/configuration when recognizing PLW; their model showed that opponent motion (i.e., the back and forth swinging of the PLW dots) was an important factor in leading to detection of a PLW as biological. Because this feature was not present in the single-point "biological" (2/3 PL) elliptical motion, it may not have been processed by the same underlying BM-specific mechanisms. Furthermore, there was no relationship between metrics on the single-point and PLW conditions, which further supports the conclusion that these conditions may have been processed using different mechanisms. While the local, temporal features of BM do play an important role in their recognition, it appears that the global form of the stimuli is also a crucial component.

Links to Social Functioning

Attentional preferences for BM and non-BM motion were also related to social functioning, but only in the TD group. Higher levels of social functioning were related to differential attention patterns toward the BM stimuli in each PLW condition: *increased* attention toward (greater preference for) the spatially scrambled PLW, but *decreased* attention toward the temporally scrambled PLW. This opposing relationship is worth considering further. One potential explanation for the positive relationship between preference for spatially scrambled PLW and social skills could be that those with greater social functioning have a stronger familiarity with the typical PLW and thus a stronger novelty response (increased looking) toward the spatially scrambled PLW in that condition. By contrast, the opposite trend in the temporally scrambled condition, could be due to the greater subtlety of that manipulation, in which those with better social functioning preferred the smoother, more biological velocity profile of the typical PLW. That these relationships were not significant in the ASD group signifies that social functioning does not seem to track with looking behaviors in autistic individuals. It is also possible that the individual variability in the ASD group could be driven by other factors or simply contain more “noise” (e.g., looking outside the AOI, less attention overall) such that their looking behavior was not as meaningful as it was in the TD group. These findings suggest that the way in which attention is allocated toward or captured by BM may play a role in how social skills develop in typically developing individuals.

Execution of Biological Motion

Adherence to the 2/3 PL

Using novel iPad methodology, this study examined whether autistic and TD participants differ in how well their drawing movements adhered to the 2/3 PL. This law of motion models a mathematically prescribed coupling between the curvature and velocity of a movement and governs drawing movements from an early age. This task was successful in producing movement with this characteristic curvature-velocity coupling, with average participant beta values ranging from .2 to .5 (.33 represents perfect adherence to the 2/3 PL). On both drawing and tracing trials, our task revealed group differences in beta value (representing the velocity–curvature relationship), with the ASD group showing greater beta values. Tracing trials presented a more constrained task, where participants moved along a prescribed elliptical trajectory, yielding results that are more comparable across both trials and participants. On tracing trials, the TD group's beta value of .33 suggests close adherence to the ⅔ PL, while the increased beta in the ASD group (*M* = .36) points to an atypical velocity–curvature coupling. Specifically, the elevated beta value in the ASD group suggests that the change in velocity across the range of curvature is steeper than "ideal" (i.e., perfect adherence to 2/3 PL). This would indicate that velocity slows by more than is "ideal" on curved sections, while velocity increases by more than is "ideal" in flat sections. The values observed in our study are actually higher than what has been shown in a previous study using a similar protocol with template ellipses, in the range of .27 to .30 for children ages 5 to 8 (Viviani & Schneider, 1991). The increased values produced by our task could be related to higher data sampling rates (120 Hz in our task vs. 88 Hz in the previous study) or the use of a filtering protocol (no filtering procedure was reported in Viviani & Schneider, 1991).

Drawing trials, on the other hand, presented a much less constrained, free-form assessment of motor performance. During these trials, participants often produced shapes that differed in size and shape and were highly variable across trials, since there was no template to follow. These trials also revealed greater beta values in the ASD (*M* = .33) compared to the TD group (*M* = .29), however the ASD group actually demonstrated closer adherence to the 2/3 PL. While a beta value of .33 is considered to represent the perfect adherence to the 2/3 PL, it may not be appropriate to evaluate against this standard metric on the drawing trials. While the same elliptical shape was presented in both trial types, participants copied it without a template and often had difficulty extending the full length of the ellipse accurately. Thus, the shapes produced on drawing trials tended to be more circular in shape. As such, data collected on these trials did not have as large a range of curvature values, and was especially limited in the most curved portions. As was revealed by the curvature split analysis, beta values are higher in the curved compared to the flat sections of movement, thus with fewer data points in the most curved range of curvature values, a lower beta value would be expected. Indeed, the beta values produced by the drawing task were lower than those in the tracing task across both groups. It is more likely that the ASD group's average beta value of .33 is a reflection of this limitation, rather than a result of those with ASD exhibiting closer adherence to the law. What is critical here is that group differences in the same direction (ASD > TD) were observed for both tasks. This is the first study to investigate adherence to the 2/3 PL in autistic individuals and has demonstrated that those with ASD appear to show a steeper coupling of velocity and curvature than their TD counterparts across both tracing (highly constrained) and drawing (less constrained) trials.

In order to better interpret these group differences in beta value, we performed a split of the curvature variable at a pre-determined value of 1.5 (which corresponds to a relative cut-off between straight and curved sections of movement) for kinematic variables of velocity, acceleration and jerk. Both drawing and tracing trials showed similar trends and will be discussed together. For velocity, the main effect of curvature level (curved vs. straight) was expected based on the relationship modeled by the 2/3 PL equation, such that velocity was greater on the straight compared to curved portions. It also appears that the ASD participants moved more quickly compared to their TD counterparts across both trial types. Given that participants were instructed to choose whatever speed felt most comfortable to them, autistic participants may have simply preferred a faster speed in general. This finding supports previous literature showing that autistic individuals write and draw with higher velocity (Grace et al., 2017; Szu-Ching et al., 2019), however this finding may be task dependent.

Most important for parsing the group differences in beta value was the interaction between curvature level and group, which was significant in both drawing and tracing trials. This interaction effect was driven by a greater difference in velocity between straight and curved portions of movement in the ASD group compared to the TD group. In other words, the ASD group modulated their velocity to a greater degree based on the curvature of the movement than did the TD group. This is consistent with the interpretation of the elevated beta value across the entire segment (i.e., a higher/steeper beta value means greater modulation of velocity along the curvature range).

While the actual group differences in beta values are small, these exploratory analyses provide some information about what is driving these differences. The 2/3 PL prescribes a close relationship between curvature and velocity in curved movements, and indeed, we see this coupling between variables in both groups. However, it appears that autistic participants' movements resulted in higher beta values because their modulation of velocity between straight and curved portions of movement is more pronounced than it is in TD participants. The presence of this same characteristic during both drawing and tracing suggests that the way in which velocity is modulated may be inherent to autism, irrespective of the task constraints. This finding also points to a potential factor underlying the atypical motor control across a range of activities in ASD.

Acceleration and Jerk

In addition to our primary aim assessing adherence to the 2/3 PL in movement, we also examined kinematic metrics of acceleration and jerk. These are more commonly studied and generalizable characteristics of movement which allow us compare results from this study to other literature on motor control in ASD which employed these same metrics. Furthermore, compatibility between the 2/3 PL and minimum jerk model has been hypothesized (Viviani & Flash, 1995), as both models result in smooth, controlled movements. However, contrary to what we expected, we found no relationship between beta value and jerk. This was likely due to the fact that the jerk metric was computed as the average value across an entire trial, while the minimum jerk model is a cost function prescribing how to predict speed of movement based on a point along a path’s trajectory. As such, the jerk metric did not capture the complexity of the minimum jerk model. The beta value, on the other hand, is calculated using all the data points of curvature and velocity across a continuous movement and was better able to measure how closely the movement in its entirety adheres to the 2/3 PL. So, while these metrics were unrelated in our sample, they can each provide unique information about the kinematics (particularly the smoothness and control) of purposeful movement.

Our task did reveal group differences in jerk and acceleration, with ASD participants showing greater levels of acceleration and jerk on both drawing and tracing trials. Jerk is the third time derivative of finger position, the rate of change of acceleration. Lower jerk is associated with better control and greater "smoothness" of movement (Todorov & Jordan, 1998). It can be thought of analogously in terms of driving, wherein a driver with more experience is able to accelerate and decelerate the vehicle smoothly, whereas a less experienced driver may produce a jerkier ride. It has also been investigated as a key factor influencing whether movements are perceived as natural. Particularly relevant is a study by Aransih and Edison (2019), who found that jerk was the most significant factor in predicting neurotypical (NT) participants' judgements of naturalness of the movements made by both autistic and NT participants. Greater levels of jerk resulted in movements that appeared less natural, in contrast to smooth and controlled movements.

The finding of increased jerk seems to be observed consistently in the literature on motor production in autism, across both gross and fine motor movements (Cook et al., 2013; Ferrara et al., 2016b; Nobile et al., 2011; H. C. Yang et al., 2014). These studies employ different paradigms, methods of movement capture and types of movements, so replicating the finding of increased jerk in our study expands upon this growing body of research. Furthermore, our results align with other studies that have examined other components of movement which are not explicitly labelled as jerk, but likely related. Research has shown that autistic children make more corrective adjustments (also known as movement units) during the execution of a goal-directed task (Anzulewicz et al., 2016; Forti et al., 2011; Wei Chua et al., 2021; Whyatt & Craig, 2013). If greater jerk (or acceleration) is conceptualized as more changes in acceleration (or velocity), greater corrective movements may similarly characterize this pattern of increased jerk. These findings overall point to a tendency for less efficiency in motor planning and execution.

Inter-individual variability in jerk and acceleration was also increased in the ASD group, suggesting that autistic individuals varied more in the amount of acceleration and jerk with which they performed these movements. This tracks with the greater heterogeneity that is commonly observed in autistic samples. Visual inspection of the tracing data (see Figure 13) reveals four outliers in the ASD group with extremely elevated levels of both acceleration (above 500 cm/sec^2) and jerk (above 25,000 cm/sec^3). These participants may represent a subset of autistic individuals with highly atypical movement kinematics. Although these outliers have contributed to the elevated average across the autistic group, they do not solely account for the increased levels of acceleration and jerk in the autistic group, as the group difference remains significant even when they are removed from analyses.

In addition to examining these metrics across the entire segments, the curvature-split procedure was used to explore how the kinematics of movement change across the duration of the elliptical drawing and revealed differential results for acceleration and jerk metrics. For both acceleration and jerk, there were main effects of group and curvature level: both metrics were greater in the curved compared to straight sections, and for autistic compared to TD participants. However, only jerk (but not acceleration) showed an interaction between curvature level and group, such that jerk increased by a greater degree on curved versus straight sections in the ASD group, as compared to the TD group. This finding indicates that jerk, more so than acceleration, may be a particularly important indicator of motor dysfunction in ASD. This finding could have implications for writing and drawing where the majority of movements performed are curved. If autistic individuals show increased jerk when performing curved movements, whether on a tablet, paper or in space, it would likely result in difficulties with motor control across a range of activities.

The findings from this iPad assessment related to acceleration and jerk, as well as adherence to the 2/3 PL, reveal clear differences between ASD and TD groups, suggesting that this novel methodology can provide useful insight by quantifiably characterizing the atypicalities of drawing movements in autistic individuals. It also helps to solve a methodological issue in the field, by objectively capturing movement kinematics in a way that circumvents the need for expensive and difficult-to-administer motion capture technology, while remaining fun and engaging for children.

Relationship to Motor Functioning and Age

As part of this aim, we hypothesized that variables of interest collected during the iPad activity would be related to broader motor functioning. For the most part, we did not find evidence across the various iPad metrics of such an association. However, one significant relationship emerged: less intra-individual variability in beta value was associated with better motor functioning. This suggests that consistency across trials may be the most important predictor of motor outcomes. Contrary to our expectations, it does not appear that the task specific metrics of beta value and jerk are linked to global fine motor skills. There are several possible reasons for this. First, the v-scale score of the fine motor subdomain has a narrow range (7 to 21 across the whole sample), and within each group, the ranges are even narrower. Additionally, fine motor skills were assessed by parent report through questions related to the use of scissors, coloring, and drawing letters and shapes, skills which are more commonly demonstrated in school and could potentially be better captured by teacher report. Alternatively, using a direct motor assessment such as the Movement Assessment Battery for Children or the Bruininks-Oseretsky Test of Motor Proficiency may have been more successful at detecting relationships between task-specific motor performance and global motor functioning. Lastly, the sample size may have been too small to detect an effect.

We also explored whether age showed any association to beta value (adherence to 2/3 PL) or other kinematic variables to determine whether these metrics capturing motor control would show a developmental progression. Given research that suggests early adherence to the 2/3 PL that may be further tuned by experience across development, as well as an understanding that motor control (which the 2/3 PL indexes) improves across development, we expected to observe an increase in beta value with age. However, we observed a negative association between beta value and age only in the TD group, such that older children showed lower beta values. This finding contradicts the only previous study that examined beta value as a function of age using a similar ellipse tracing task, which revealed a positive association. The authors found that across their sample of children ages 5 to 12, the beta value increased toward the “ideal” or adult level of .33, except the 5-year-olds did not fit the age-related trend (Viviani & Schneider, 1991). However, this study did not look at age continuously, rather in distinct age brackets with only 6 individuals in each, and in doing so, may have missed more fine-grained relationship between age and beta value. Furthermore, if we inspect our data visually, it does appear that the beta values derived from tracing trials hover closer to .33 for older children, while they appear to be elevated in younger children (mostly in the range of .34–.40). The fact that most of the younger TD participants and nearly all autistic participants show the same trend of beta value above .33 suggests that an elevated beta value could represent a delay in motor control, present in younger and autistic participants. Given that the range included in our sample was not designed to assess age, further studies with larger sample sizes should aim to better understand the developmental trajectories of this power law.

For more traditional metrics of jerk and acceleration during the drawing/tracing task, we expected an age-related decrease in these kinematic features. Indeed, both metrics significantly decreased with age across both drawing and tracing trials, in the TD group only. In general, smooth and controlled movement is associated with smaller higher-order derivatives (i.e., acceleration, jerk; Todorov & Jordan, 1998), so this finding suggests there was better motor control on this task with increasing age, which would be consistent with the interpretation of the beta value. Yet, this age-related trend was not present in the ASD group, which could indicate that the typical developmental progression of motor control is disrupted in autism.

Link Between Motion Perception and Motor Execution

The final aim of the project was to compare individual performance on eye-tracking (movement perception) and iPad (movement execution) tasks to determine whether links between motor and perceptual components could be observed in our data. Given previous work supporting the behavioral and neural link between perceptual and motor systems, we hypothesized that individuals with greater preference for motion adhering to the law would execute movement that more closely follows to this law. While the association between these tasks did not reach significance, the consistent negative trends observed across both groups indicate a potential relationship between preferential visual attention toward the 2/3 PL and adherence to this law in movement execution. Increased orienting and attention toward motion following this law seems to be associated with closer adherence to the law (as measured by deviation from the “ideal” beta value), in line with our hypotheses. Interestingly, the ASD group showed the strongest trend that nearly reached significance between deviation from the 2/3 PL and first fixation to the 2/3 PL, which may have been driven by the greater variability in the deviation metric, and speaks to the greater heterogeneity commonly observed in autistic samples.

We expected to see an association based on previous research that has identified links between perception of BM and motor performance in both autistic and TD participants (Freitag et al., 2008; Lindor et al., 2019; Price et al., 2012). However, the majority of these studies used general, standardized motor assessments of overall gross and fine motor skills, such as the Dean–Woodcock neuropsychological battery or Movement Assessment Battery for Children, and as such were examining broader motor proficiency as opposed to a specific kinematic feature of drawing movements. The one study that included a kinematic assessment of arm movements, in a similar way to ours, created an overall factor score comprised of values of jerk, acceleration and velocity (Cook et al., 2013), rather than a single metric (like adherence to the 2/3 PL) alone. Further, these authors employed a different approach to assessing BM perception, involving the identification of thresholds through overt response in a single presentation of more realistic stimuli (hand vs. tennis ball), while our eye-tracking task relied only on looking patterns which ultimately did not show any group differences in performance on the 2/3 PL condition. Lastly, all of these studies were conducted on adolescents and adults, while our sample was children.

Given these important methodological departures from previous literature, it is unsurprising that the associations in our study did not reach significance. In creating both study tasks using the 2/3 PL as the representation of BM, we hoped to identify a new metric by which to compare across these domains. Given our null findings, we can conclude that this law of motion may be too fine-grained a metric by which to study the association between perceptual and motor domains. Alternatively, it could be the case that modifying the control stimuli used in the eye-tracking task could result in a starker visual difference between stimuli and more conclusive looking behavior that tracks more closely with motor execution. It is also possible that the sample sizes in each group were not large enough to detect significant relationships.

Furthermore, research examining perception-action coupling suggests that implicit motor representations are used to process visual displays of biological motion. While our 2/3 PL stimuli represented a biological motion profile, it did not resemble human action (as a single elliptically moving dot) and thus the putative mechanisms underlying the connection between perception and execution of human movement (action-observation network) may not have been at work. While this power law does appear to have some utility in distinguishing groups on the kinematics of their motor performance, it failed to produce group differences in preferential attention patterns, as well as significant relationships across domains. Therefore, we are unable to make strong conclusions about the nature of the relationship between perceptual and motor domains with respect to the 2/3 PL.

Limitations and Future Directions

There are a number of limitations to this study, as well as areas for further exploration. All analyses would benefit from larger sample sizes, especially in the ASD group. Autism is known to be heterogeneous and this was reflected in the increased variability across nearly every metric assessed. Recent research approaches have taken to parsing this heterogeneity by identifying subgroups with differential behavioral or biological signatures. Future investigations may benefit from such an approach but would require much larger sample sizes. A related approach would be to examine whether any of the task metrics track with autism symptomology. However, due to testing limits during COVID, we relied on existing diagnostic reports and did not have ADOS scores available for all participants to use in this way.

Additionally, groups differed in IQ: the TD group had higher full-scale and verbal IQ and a trend toward higher performance IQ. While IQ was taken into account for group comparisons, it is still possible that cognitive level influenced performance across tasks. We attempted to include participants with a wide range of cognitive abilities and did not exclude based on IQ, however, the tasks did require a certain level of verbal comprehension and attention, making it challenging for those with low cognitive functioning or intellectual disability to participate. As such, it is difficult to extrapolate the findings to autistic individuals who are entirely non-verbal or who have very high support needs. It may be useful if future studies included another comparison group, with more closely matched IQ and/or other developmental delay to determine whether observed differences in perceptual and motor performance are specific to autism or related to more general cognitive functioning.

There were also a few limitations to the eye-tracking task used to assess attention toward BM and non-BM stimuli. As previously discussed, the control stimuli utilized in preferential looking paradigms is crucial. In the single-point condition, only one non-BM comparison stimulus (constant motion) was used, which differed minimally from the 2/3 PL motion and likely contributed to the lack of discrimination observed in our data. Future research should employ comparison stimuli that diverges from the 2/3 PL incrementally in both directions to include profiles that represent an inverted coupling of velocity and curvature (e.g., beta = -.33) and those that represent an exaggerated coupling (e.g., beta = .66). Including a greater range of divergence from the power law as well as more increments would facilitate the determination of a threshold at which a difference between stimuli can be detected. This would provide a better measure of sensitivity to visual differences with respect to the 2/3 PL. However, more stimuli would necessitate more trials, longer runs and more attention, which can be difficult for children.

In the PLW conditions, BM stimuli was limited to walking movements. Going forward, it would be important to include more movement patterns such as jumping and dancing or more socially relevant stimuli like waving, both to prevent the habituation (and in turn a novelty preference for scrambled stimuli) and to broaden the conclusions that can be drawn. Conversely, it would be interesting to breakdown the PLW stimuli by isolating the back-and-forth opponent “swinging” motion of limbs using far fewer points, rendering the stimuli less human-like, but considerably more interesting and complex than a single point in motion. By then manipulating the moving points’ adherence to the 2/3 PL, such an investigation could tease apart the importance of temporal adherence to the 2/3 PL within the context of human movement that is deemed most salient to BM processing (Casile & Giese, 2005).

In addition, more fine-grained analytical approaches would be useful. For example, drawing smaller AOIs around specific regions of the PLW figure (i.e., legs, arms) would allow us to determine whether certain clusters of dots in the BM stimulus capture more attention, whether these differ across temporally and spatially scrambled conditions, and how that may differ across groups. Furthermore, the behavioral data obtained using eye-tracking only provides one piece of information about overt attention and does not inform us about how the brain may respond to these different motion profiles. Future research should employ neuroscientific methods in conjunction with eye tracking, to examine neural sensitivity to various forms of BM across groups.

This research may help guide interventions focused on increasing children’s attention to social input in the form of BM. Recent studies have demonstrated that fMRI-based stratification of activity in response to BM in neural circuits underlying social information processing accurately predicted response to evidence-based behavioral treatment, including Pivotal Response Training and Social Cognition Training (Yang et al., 2016; 2017). This work highlights the potential for BM sensitivity to be used as an objective neurobiological marker to identify subgroups of young children likely to respond to specific treatments. These studies, however, were conducted with older children and young adults with methods not suitable for toddlers and children. Identifying atypical sensitivity to BM earlier in development, using passive eye-tracking paradigms could be useful in identifying autistic children who may be most likely to improve with specific types of intervention. As is well documented in the literature, interventions which are implemented early have the best chance of minimizing adverse outcomes (Landa, 2018; Sigafoos & Waddington, 2016). Given the selective impairment in detecting temporal manipulations of BM as highlighted by our data, special consideration should be paid to the visual sensitivity to these features in particular.

The iPad task also presented some limitations. First, the elliptical shape drawn by participants is not common to everyday movements, and therefore lacked full ecological validity. For the purposes of investigating adherence to the 2/3 PL, it was important to use an ellipse both to build upon prior literature and to standardize across participants. However, other studies assessing motor movements using more ecologically valid approaches show the same velocity-curvature relationship (Adi-Japha et al., 1998; Fetters & Todd, 1987; Hofsten & Rönnqvist, 1993). Thus, we would hypothesize that the findings observed in our task, with respect to the power law and jerk, are likely to extend to other curvilinear movements. Another constraint of this paradigm was that participants were able to select the speed with which they performed the movements, limiting the degree to which we can compare velocity across participants. However, metrics related to the power law, acceleration and jerk are independent of average velocity and therefore still provide meaningful insight into group differences in motor control.

Despite these shortcomings, this novel iPad task provided some unique insight into the kinematic differences of movements generated by autistic individuals. Technology like this is being used more frequently to systematically assess various features of motor performance, as it provides a more precise, objective, and quantifiable measure of motor functioning, beyond simply neuropsychological assessments or parent report measures. A similar approach using different drawing games on an iPad was successfully able to identify distinct patterns of movement kinematics, an "autism motor signature," using machine learning algorithms (Anzulewicz et al., 2016; Lu et al., 2022; Wei Chua et al., 2021). While the diagnostic utility of a tool like this remains contentious, it still presents opportunities to better understand the motor atypicalities present in autism, especially early in development. Further, it can offer the potential for better motor intervention. As previously discussed, a large majority of autistic children present with motor impairment, but many go undiagnosed and untreated (Bhat & Narayan Bhat, 2020). An assessment like this may be able to detect specific motor profiles or identify those with the most divergent kinematic profiles (e.g., the four autistic outliers with respect to jerk), and implement more targeted, individualized intervention in order to improve motor skills and bolster motor learning (Holloway et al., 2022). Further exploration is required to determine whether these features are consistent with motor delays more generally, and what the underlying mechanisms leading to this disruption may be.

The goal of this study was to examine differences in the perception and execution of BM, as represented by the 2/3 PL, a kinematic regularity of human-generated movement. While no direct association between these domains with respect to the law was found, the assessments did reveal differences in perceptual and motor performance in autism, including atypical attention toward temporally manipulated stimuli and atypical kinematics like greater velocity modulation and increased jerk. The 2/3 PL holds promise as a way to systematically capture the biological quality of human movement, but further research will be critical in exploring whether the law can further our understanding of BM and its underlying mechanisms in autism.

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