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I, Joseph L. Amaral Jr., hereby submit this original work as part of the requirements for the degree of Doctor of Philosophy in Psychology.

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What Constrains Adaptive Behavior in ASD? Exploring the Effects of Non-Social and Social Factors on Hysteresis in Grasping

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What Constrains Adaptive Behavior in ASD? Exploring the Effects of Non-Social and Social Factors on Hysteresis in Grasping

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Abstract

Healthy development leads to a fluid integration of competing constraints. A marker of such fluid behavior is hysteresis, reflecting a multi-stable system that takes into account its immediate history. The current study investigates patterns of hysteresis in typically developing children and those diagnosed with autism spectrum disorder (ASD). The task was to grasp and lift an object. I manipulated the social context of the task, given that ASD is characterized by abnormal development in social domains. Results of the grasping task were also compared to a standardized clinical measure of mental flexibility: a computerized version of the Wisconsin Card Sorting Test, due to evidence that children with ASD have a tendency to demonstrate perseveration and rigid thought patterns. For the grasping task, a series of differently sized objects were designed that they could be picked up with one hand or two, marking a range of bi-stable behavior. Results of the grasping task show hysteresis in typically developing children, whether or not the task was situated in the social context. Analyses indicated a similar pattern for the children with ASD. However, there was a suggestive trend in the data that they may not have demonstrated hysteresis in the social context. For both diagnostic groups, perseveration on the Wisconsin Card Sorting Test did not correlate to the degree of hysteresis, regardless of the presence or absence of social cues. Results provide support to the idea that the analysis of behavior dynamics provides a unique window into typical and atypical development.
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Chapter 1: Introduction

Over the last few years, increased attention has been placed on better understanding the nature of Autism Spectrum Disorder (ASD). Much of the research that exists focuses on finding a core deficit that can explain symptomology. However, each of the core-deficit theories that have emerged have drawbacks, illustrated by conflicting research findings (for a review, see Amaral, Collins, Bohache, & Kloos, 2012). Ultimately, the hunt for a core deficit in ASD may lead to difficulty developing effective treatment methods. An alternative to a core-deficit approach may therefore be more fruitful. In my dissertation, I explore such an alternative approach, based on the idea that human functioning can be understood as patterns of coordination.

The coordination account of ASD may allow for understanding many of the discrepancies seen in previous research. It may additionally provide a more nuanced understanding of ASD functioning, which may lead to innovative intervention strategies. In what follows, I provide background information on ASD, including some of the issues surrounding contradictory research finding in areas relevant to the current study. Then, I overview a conceptualization of behavior that surrounds coordination, followed by evidence for conceptualizing autism under a similar framework. Next, I describe relevant aspects of dynamical systems theory and complexity. Finally, I provide a description of a study geared toward comparing the coordination patterns of typically developing children and children with ASD.

Overview of Autism Spectrum Disorder

Autism Spectrum Disorder (ASD) is a neurodevelopmental disorder that affects an estimated 1 in 68 children (Baio, 2014). It is technically a new diagnosis to the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5; American Psychiatric
Association, 2013). It combines three separate diagnoses from the previous diagnostic manual, the Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition, Text Revision (DSM-IV-TR; American Psychiatric Association, 2000): Autistic Disorder, Asperger’s Disorder, and Pervasive Developmental Disorder, Not Otherwise Specified. Although initially considered separate diagnoses, these conditions have long been conceptualized as falling along a unified spectrum and sharing many behavioral, diagnostic, and genetic similarities.

ASD is characterized by significant impairments in social communication/interaction and the presence of restricted patterns of behaviors and interests. Symptoms of social impairment may include poor eye contact, emotional reciprocity, and joint attention, together with difficulty understanding social cues and with communication. Communication impairments can involve language deficits and atypical use of non-verbal communication strategies (e.g., gesture, facial expressions). Children also often demonstrate repetitive, self-stimulating behaviors (e.g., arm flapping), abnormally intense, specific interests, and abnormal responses to sensory stimulation (American Psychiatric Association, 2013).

To date, no definitive cause of ASD has been identified. However, numerous theories have emerged to explain deficits seen among affected individuals. Some have argued that deficits seen in ASD may relate to an inability to take the perspective of others, known as Theory of Mind (e.g., Baron-Cohen, 1989; Baron-Cohen, Leslie, & Frith, 1985). Others have posited that many of the deficits seen in ASD may relate to a tendency of individuals with the disorder to focus on details in their environment, as opposed to typically developing (TD) individuals who focus on overall impressions (e.g., Frith, 1989; Happé & Booth, 2008; Happé & Frith, 2006). Still other research points to neurological differences in people with ASD that have been associated with deficits in socialization (e.g., McPartland, Wu, Bailey, Mayes, Shultz, & Klin,
Differences in the ability to share attentional focus with others (e.g., Meindl & Cannella-Malone, 2011), difficulty reacting to social cues (Loveland, 1991), and deficits in executive function (e.g., Ozonoff, 1997; Ozonoff & Jensen, 1999), have also all been argued to lie at the heart of ASD. A thorough discussion of the strengths and weaknesses of these theories is beyond the scope of this document (for reviews see Amaral et al., 2012; Rajendran & Mitchell 2008). However, a brief discussion of specific issues under the umbrella of social deficits and executive dysfunction in ASD which are relevant to the current study follows.

**Social Deficits in ASD.** Social deficits are often considered to be at the core of ASD (e.g., Dawson, Webb, & McPartland, 2005; Schultz, 2005). Indeed, most individuals “on the spectrum” demonstrate some form of atypical functioning during social interactions, are often ostracized by others, and deemed by others to be more socially awkward (Sigman et al., 1992; Travis & Sigman, 1998). Some have attributed these to deficits in social (joint) attention. Others have argued that the social impairments seen in individuals with ASD may stem from difficulty adapting their behavior to social contexts (e.g., Loveland, 1991), or misreading the actions and social cues of others (e.g., Baron-Cohen, 1988; Dawson, Meltzoff, Osterling, Rinaldi, & Brown, 1988).

**Social attention.** Deficits in joint attention are common among individuals with ASD (for a review, see Meindl & Cannella-Malone, 2011). Joint attention refers to the ability to utilize nonverbal behaviors (e.g., eye contact and gestures) to share attention toward an object or event of interest with another individual (Mundy, Sigman, Ungerer & Sherman, 1986, p. 657). This ability is critical for successful social interactions, setting up a context in which a child can learn from others. For example, a child needs to know the target of an individual’s gaze in order to understand to what a new label might refer. Indeed, joint attention has been studied extensively
in relation to children’s word learning (e.g., Baldwin, 1995; Mundy & Newell, 2007; Carpenter, Nagell, & Tomasello, 1998; Tomasello, 1995; see also Flom, Lee, & Muir, 2007). A common task involves presenting children with a set of objects, and an adult visibly looking at the one that is being named. Both the amount of time the participant follows the eye-gaze of the adult and the degree of labelling are thought to reflect the amount of joint attention that occurs between them. Indeed, numerous studies indicate that children with ASD not only demonstrate difficulty following the gaze of an adult in joint attention tasks, but that this deficit is related to impairments in learning the names of new objects (Baron-Cohen, Baldwin, & Crowson, 1997; McDuffie, Yoder, & Stone, 2006; Parish-Morris, Hennon, Hirsh-Pasek, Golinkoff, & Tager-Flusberg, 2007; Preissler & Carey, 2005).

Preissler & Carey (2005) explored how TD children and those with ASD learned the names of novel objects in two experiments. The first consisted of two conditions. In both, the experimenter and child each held a different novel object. In one condition, the experimenter directed their shared attention to the toy in the child’s hand while saying a label. In the other, they directed attention to the object in their own hand. Children were then asked to find the object from among distracters. Both TD children and those with ASD were able to identify objects correctly during the condition in which the label corresponded to the object in their own hand. However, the children with ASD performed significantly more poorly during the condition in which the labeled object was in the experimenter’s hand. Interestingly, in the second experiment, when the task involved both known and unknown objects, performance did not differ between diagnostic groups. This indicated that while children with ASD could use the process of elimination to identify an unknown object, they were less successful at using eye gaze.
Despite strong evidence in favor of ASD impairments in joint attention, findings from other research complicate the picture: participants with ASD appear perfectly capable of joint attention in some contexts, if not even more skilled than their typically developing counterparts (Chawarska, Klin, Volkmar 2003; Kylliainen & Hietanen, 2004; Vlamings, Strauder, van Son, & Mottron 2005). Consider, for example, a task in which participants have to press a corresponding button as soon as they see a target appear either at the top left or the bottom right of a monitor. A face was also shown in the center of the monitor. The gaze of the face was straight ahead, averted to the top left, or averted to the bottom right, 200ms before the target appeared. Findings show faster reaction time on trials in which the target appeared on the same side of the screen as the face’s gaze, with no difference between diagnostic groups (Kylliainen & Hietanen, 2004).

An argument could be made that different joint-attention tasks are not equally suited to capture the construct of joint attention. Maybe the reaction time task is a better reflection of joint-attention processes than a word-learning task. Such argument about what task might best reflect a stable factor is a common argument in the larger literature of cognition and cognitive development. However, it gets quickly overwhelmed as more context effects accumulate.

**Social affordances.** Whether it pertains to understanding the mental states of others or sharing the attentional focus of others, socialization involves reacting to non-verbal, verbal, and environmental cues. That said, some have argued that rather than being unable to understand the mental states of others, or being unable follow another’s attention, children with ASD demonstrate atypical “automatic” reactions in response to such social cues (e.g., Baron-Cohen, 1995; Frith & Frith, 1999). Jellema and colleagues (2009) compared the performance of TD children and those with ASD on a task in which they had to judge relative distances in the presence or absence of social cues. Two cartoon human figures flashed on a computer screen,
followed by a masking frame, and then again by a screen that showed two geometric shapes. The children then had to decide whether the figures were closer together than the shapes (“cartoons closer”) or farther apart (“cartoons farther”) than the shapes. Importantly, the distance between the stimuli was actually always the same.

For one task, the experimenters manipulated both the direction of implied motion of the figures (i.e., running toward each other vs. running away), and the directional gaze of the figures (i.e., looking at one another or looking away). This left four types of stimuli. TD children judged the figures that appeared to be both running toward, and looking at, each other to be closer together than the geometric shapes significantly more often than any of the other three types of stimuli. Children with ASD on the other hand, showed no difference in the proportion of “cartoons closer” and “cartoons further” judgments between the four types of stimuli. Thus, there was indication that the children with ASD were less affected by the cues afforded by the cartoon stimuli than the TD children.

The differences individuals with ASD demonstrate reacting to social cues have been conceptualized as atypical responses to social affordances (e.g., Loveland, 1991). An affordance is a relationship between an organism and factors in the environment that afford, or make possible, certain behaviors. A social affordance is a behavior that a certain item permits during a social interaction. Gonzalez and colleagues (2013) compared how TD children and those with ASD picked up various objects based on whether they were to use the objects themselves or hand them to another person. When TD children were told to give the objects to the other person who would then use it, they did so in a manner that would make the object more comfortably grasped by the other person, even if it sacrificed their own comfort. This occurred in every trial. Children
with ASD, on the other-hand, demonstrated much more variability, indicating less attunement to social affordances.

As in other areas of research, literature exploring the reactions of individuals with ASD to social cues and affordances demonstrate highly variable findings. This may again point to the lack of a specific core deficit. If one considers the contextual factors that affect performance between tasks, as well as the variable within-task performance demonstrated by individuals with ASD, it is possible to begin moving further from a core-deficit account of ASD.

**Executive dysfunction in ASD.** Executive functioning (EF) is an umbrella term to describe various higher level cognitive abilities. It is defined by Ozonoff, Pennington, and Rogers (1991) as:

“…the ability to maintain an appropriate problem-solving set for attainment of a future goal; it includes behaviors such as planning, impulse control, inhibition of prepotent but irrelevant responses, set maintenance, organized search, and flexibility of thought and action (p. 1083).”

Deficits in EF have been documented in individuals with ASD and have been thought to be associated with many attributes of the disorder, including the need for sameness, difficulty with switching attention, a tendency to perseverate, and a lack of impulse control. However, there are some conflicting findings, and documented deficits are not unique to the disorder (for a review see Rajendran & Mitchell, 2007).

Relevant to the current study are the EF concepts of mental flexibility and perseveration. Mental flexibility refers to the ability to shift one’s problem solving strategies in response to changing task constraints. Perseveration, in contrast, is the tendency to continue or repeat an act or activity after it is no longer appropriate.

Several studies have explored mental flexibility through the performance of individuals with ASD on the Wisconsin Card Sorting Test (WCST; e.g., Rumsey, 1985; Rumsey &
Hamburger, 1988; Ozonoff et al., 1994; Ozonoff & McEvoy, 1994). This task is thought to assess not only mental flexibility, but also concept formation, and problem-solving skills based on corrective feedback. The task is to match a series of test cards with one of four key cards, by placing each below the chosen key card. Each test card can be matched to the key cards based on one or more rules. The evaluator provides feedback as to whether a choice is correct or incorrect, based on a predetermined rule. However, no explicit information about the rule is provided. Participants are not allowed to change their choices once they are made. After the participant matches a certain number cards correctly by a given rule, it is changed without notice. This switch occurs numerous times (Heaton et al., 1993).

Several studies indicate that those with ASD produce more errors overall, more perseverative errors, and more perseverative responses than TD individuals (Rumsey, 1985) and that these deficits persist over time (Ozonoff et al., 1994; Ozonoff & McEvoy, 1994). However, not all studies have identified this group difference in perseveration (Rumsey & Hamburger, 1988).

Increased inconsistencies emerge when comparing the method by which the WCST is administered. The above studies all used a version of the WCST that involved the participants matching physical cards in the presence of an evaluator. However, there is also a standardized version in which a computer administers the task. Ozonoff (1995) compared the performance of TD individuals and those with ASD on the original and computerized versions of the WCST. In one experiment, children were initially administered the computerized version and then a year later, the original. She found that more performance variance could be accounted for by the test versions, rather than diagnosis.
As there was a possibility her results were confounded by test order, a separate cross-sectional experiment was conducted. Half of the participants with ASD and half of the TD children were given the standard WCST and the other half, the computerized version. Between-group analyses indicated significant differences for categories completed, total errors, and perseveration on the examiner-administered but not computer-administered version (although the main effect of perseveration across administration types still approached significance). Within-diagnostic-group analyses indicated that the pattern of performance was marginally better for individuals with ASD on the computerized test. However, TD children performed similarly on both. Further research also suggests similar performance between ASD and TD on computerized versions of the WCST (Kaland, Smith, & Mortensen, 2008).

**Behavior, Non-Linearity, and Dynamical Systems Theory**

Instead of viewing typical development as a matter of accumulated competencies, it can be characterized by degrees of coordination between multiple systems on multiple, nested levels. The idea of coordination, as used here, is drawn from dynamical systems theory, which argues that behavior arises from the complex interplay between microscopic and macroscopic factors and can be modeled through the use of differential equations. Patterns of coordination exist between various regions of the brain (e.g., Tognoli et al., 2007; Minshew & Keller, 2010) and between the movement of individuals during social interactions or cooperative task completion (e.g., Marsh et al., 2009). Further, TD individuals tend to demonstrate cognitive coordination by combining pieces of information into more coherent wholes (e.g., Kimchi, 1990, 1992), especially during problem solving tasks (Stephen et al., 2009).

The tendency for TD individuals to combine pieces of information into coordinated wholes can be seen during perceptual tasks (e.g., Kimchi, 1990; Navon, 1977). This may
manifest in the tendency to demonstrate Gestalt interference when focusing on individual details of an ordered array, such as in the classic Embedded Figures Test (e.g., Shah & Frith, 1983), or the Navon Task (Plaisted et al., 1999). In the classic Navon (1977) task, individuals are presented with arrays which consist of large letters made up of smaller letters. In these cases, the large and small letters either match (e.g., a large letter “S” made up of small “s’s”) or do not (e.g., a large letter “H” made up of small “s’s”). When TD children and adults are asked to identify the large letter, their accuracy and reaction time does not differ regardless of if the smaller letters match the large letter or not. However, when they are asked to identify the smaller letters, reaction time increases. The overall configuration interferes with their ability to focus on the details. Similar biases toward global features have been seen in visual pattern and illusion perception (e.g., Kimchi, 1990, 1992), and audio processing (Bonnel et al, 2003). Further evidence also comes from the domain of facial processing (Deruelle et al., 2006, Deruelle et al., 2008, Lopez, Donnelly, Hadwin, & Leekam, 2004).

Children also demonstrated global processing during a problem-solving task implemented by Stephen and colleagues (2009). TD children are presented with static images of gear sequences. An arrow indicates the supposed direction of rotation for the first gear in the sequence. The task is to indicate the hypothetical direction of rotation for the final gear. For early trials, children tended to use their fingers to trace the hypothetical rotation of each subsequent gear in the sequence in order to determine the answer. However, as the trials progressed, they eventually switch to counting the gears in pairs (e.g., clockwise/counterclockwise), which can be seen as a more global problem solving approach. In a second condition, a separate set of participants were presented with same task. However, in this condition, the static image randomly moved across the screen, thus making it more difficult to trace the gears. Results
indicated that the switch to global processing happened faster in this condition as hand movements became more erratic. Thus, it is possible that the task difficulty facilitated global processing and that global processing served an adaptive role in completing the task. Self-organization and coordination has also been demonstrated through participants’ movements during other types of problem-solving tasks (e.g., Anastas, Stephen, & Dixon, 2011; Stephen & Dixon, 2009).

In a research paradigm, adults completed a card sorting task under one of two conditions: during one, participants were explicitly told of the rule by which to sort the cards; in the other condition, they had to rely on experimenter feedback (similar to the WCST). During the task, the experimenters tracked each participant’s hand motions. Participants’ movements in the condition during which they had to use feedback to deduce the sorting rule demonstrated characteristics of self-organization and, as rules changed, reorganization. Those in the explicit rule condition did not demonstrate such behavior (Anastas, Stephen, & Dixon, 2011).

Finally, behavioral coordination has been widely documented between TD individuals during social tasks and is affected by the amount of coupling, or information, shared between pairs (e.g., Lumsden, Miles, Richardson, Smith, & Macrae, 2012; Riley, Richardson, Shockley, & Ramenzoni, 2011; Schmidt, Morr, Fitzpatrick, & Richardson, 2012). Marsh and colleagues (2009) describe studies in which pairs of participants either swung pendulums back and forward in the presence of one another (Marsh, Richardson & Schmidt, 2007) or were asked to sit and rock in rocking chairs next to each other (Marsh et al., 2006). In the pendulum paradigm, pairs either had equally weighted pendulums, or pendulums that differed in weight, which changed their natural rocking speeds. Thus, the degree of coupling was controlled by physical changes to the stimuli. Results indicated that pairs with equally weighted pendulums tended to swing them
in sync with one another significantly more than pairs whose pendulums differed in weight. In the rocking task of Marsh and colleagues (2006, as cited in Marsh et al., 2009), participants were sat side-by side in rocking chairs with a wall between them that only allowed a view of the arm rest of the other participant. They were instructed to either focus straight ahead on a dummy computer task or to focus on the arm rest of the other participant. In this case, it was each participant’s perceptual input, postulated to be modulated by the nervous system (Schmidt et al., 2011), that served as a coupler. Pairs who were told to focus on the arm rest of the other participant demonstrated higher levels of behavior synchrony than pairs who were instructed to look forward.

This interpersonal coordination research, which stems from previous work on coupled oscillators, provides a link between motor performance and neurological functioning. In essence, motor coordination research argues that much of the unintentional coordination described above arises in the same way that the pendulums of two clocks on a wall eventually will swing in sync. In the case of the clocks, the wall provides a coupling mechanism. That is, vibrations from one clock’s movements move through the wall and affect the other clock. Stronger coupling (through proximity or wall flexibility) leads to stronger synchrony. Schmidt and colleagues (2011) describe the factor that couples joint human behavior – the nervous system. Specifically, they argue that patterns of intrapersonal movement are better captured through a dynamic systems approach (i.e., conceptualizing joint movements as being coupled oscillators) than by research on the mirror neuron system, and that mirror neurons may be necessary, but not sufficient for coordination.
Conceptualizing Autism through Coordination

An alternative to searching for a core deficit in ASD is to view ASD through the lens of coordination described above. There is evidence that the various degrees of coordination described above may occur differently in autism spectrum disorders (ASD). Conceptualizing ASD in such a manner may avoid some of the pitfalls associated with other accounts (e.g., Amaral, Collins, Bohache, & Kloos, 2012) and may light on the nature of many of the symptoms and impairments experienced by individuals with the disorder (e.g., Happé & Booth, 2008; Marsh et al., 2009; Lai et al., 2010; Minshew & Keller, 2010).

Within the neurologic domain, much of the previous research has searched for specific, focal deficits associated in individuals with ASD – for example differences in specific brain regions associated with processing social stimuli (McPartland et al., 2011), or differences in the so-called mirror neuron system (e.g., Hadjekhani et al., 2010). However, there is growing evidence that ASD may be more related to diffuse, connective differences coupled with differences in neural activation patterns (e.g., Belmonte et al., 2003; for a review, see Minshew & Keller, 2010). In Minshew & Keller’s review of functional brain imaging studies, they cite multiple differences between how areas of the ASD brain coordinate as compared to the TD brain. For example, they indicate reduced frontal-posterior cortical connectivity among individuals with ASD and broader general cortical activation during higher-order problem solving tasks.

Similarly, Lai and colleagues (2010) found more randomized neural oscillations among individuals with ASD as compared to controls. They compared 18 individuals with ASD to 18 age and IQ matched controls. Using an fMRI protocol, they examined the activation patterns within the following regions of interest: medial-frontal cortex, cingulate, parietal lobe, temporal
lobe, amygdala, insula, thalamus, and caudate. They found that regularity of activation was associated with typical functioning. On the one hand, both the TD and ASD groups produced activation patterns that demonstrated complex fractal scaling. However, ASD activation significantly differed from TD activation in that it demonstrated a significant shift toward randomness. This finding is significant because research has indicated that specific patterns of coordinated neuronal activation may have such reaching impacts as to even be related to an individual’s feelings of social connectedness (Tognoli et al., 2007).

On a perceptual level, differences between TD and ASD coordination patterns have also been documented. For example, across various tasks involving a conflict between detail and Gestalt processing, children with ASD do not demonstrate as much interference from Gestalt configurations (e.g., Bonnel et al., 2003, Deruelle et al., 2008; Plaisted et al., 1999) as TD children. Within typical development, natural switches to Gestalt processing have been conceptualized as an adaptive response to compensate for task difficulty (Stephen et al., 2009). Further, many have hypothesized that differentiated global/local processing may be at the heart of ASD symptomology (e.g., Happé & Booth, 2008; Mottron et al., 2006).

Differences in coordination are evident in individuals with ASD during tasks that involve interpersonal motor coordination (e.g., Marsh et al., 2009). Specifically, Marsh and colleagues provide evidence from a task in which a child and caregiver sit in rocking chairs. The caregiver rocks in tempo with a metronome while they read a story to their child. The study found that TD children tend to rock at the same pace and in-phase with their caregiver (the child rocks forward as the parent rocks forward) more than children with ASD. This finding is significant because past research has indicated that the degree to which TD individuals unintentionally coordinate such behaviors with one another is related to subjective ratings of rapport and feelings of social
connectedness (e.g., Marsh, Richardson, & Schmidt, 2007; Marsh et al., 2006, as cited in Marsh et al., 2009). Motor coordination, then, may serve an important role in socialization.

Thus, there appear to be differences in brain activation, cognitive performance, and interpersonal motor coordination between individuals with ASD and TD, and these differences have all been associated with adaptive functioning in TD individuals. The fact that these patterns differ in ASD as compared to TD may relate to differences in their ability to function adaptively. Though not covered in the above descriptions, numerous studies have demonstrated that children with ASD have the capacity to demonstrate adaptive coordination – specifically within the domain of cognitive coordination (for a review, see Happé & Booth, 2008), depending on task constraints. Similarly, various contextual factors may affect how TD individuals coordinate physically (e.g., Marsh, Richardson, & Schmidt, 2009), and cognitively (Kimchi, 1990).

Flags of Non-Linearity

While the theory of coordination provides a viable approach to understanding autism, the discrepancy in moment-to-moment emergence of coordination has not been investigated. This is a problem, because such empirical support can help validate this theory, and possibly help to inform new intervention strategies. In what follows, I will briefly describe some of the characteristics of complex, non-linear systems as they relate to human behavior: sudden qualitative changes in a system’s functioning, bifurcations, control parameters, and hysteresis. Then, I will describe how these concepts relate to the experimental paradigm utilized in this study.

Often, patterns of behavior do not transition gradually. Instead, there are sudden switches from one mode of behavior to another. This is known as a phase transition and is an indicator of the presence of a non-linear system. Consider the transition between walking and
jogging/running in humans. It is not a gradual process that develops as speed increases. Instead, individuals tend to walk until they reach a certain speed, and then spontaneously transition to a running motion.

The example of the transition between walking and running also demonstrates the concept of order and control parameters, which are indicative of a non-linear system. Control parameters have been conceptualized as being somewhat similar to independent variables: they are factors that affect how a system evolves. Order parameters have been likened to dependent variables (e.g., Guastello & Liebovitch, 2009). In the above example, the relative phase between the limbs can be conceptualized as an order parameter and the walking speed as a control parameter. A switch between walking and running occurs at speeds where it conserves the most energy given the individual’s physical constraints (Diedrich & Warren, 1995).

The changes in coordination that occur between walking and running may demonstrate a bifurcation (e.g., Guastello & Liebovitch, 2009; Hillborn, 2011, p. 11; Kelso, 1995), or a pattern of instability, in which a system attains greater complexity by accessing new types of dynamical states (Guastello & Liebovitch, 2009; Nicolis & Prigogine, 1989). It is a point at which a system can jump from one attractor state to a new one as the latter becomes stronger than the former (in the above example, from walking to running; Kelso, 1995).

Finally, such human systems often demonstrate hysteresis. Hysteresis is defined as “the lagging of changes in an effect behind the changes in its cause over time” (Guastello & Liebovitch, 2009). For example, in a classic physics experiment, a magnetic field is applied to a metal. As the strength of the field is increased, the metal becomes magnetized and will stay magnetized indefinitely, even after the field is removed. In order to demagnetize the metal, a field in the opposite direction must be applied. Interestingly, the point at which a metal becomes
magnetized due to an increasing current is not the same as the point at which it becomes demagnetized due to an opposing current. In order to demagnetize the metal, the opposing magnetic field must be stronger than that which originally magnetized the metal (Ewing, 1882). Hysteresis demonstrates how a system’s current pattern of behavior is affected by its immediate history. Other transition patterns are possible, however. When a system’s changes precede changes to the causal factor, it is known as enhanced contrast (Kelso, 1995, p. 203), indicative of anticipation of future task requirements. Transitions between cause and effect that mirror one another (e.g., transition at the same point regardless of initial state) are known as critical point transitions and suggest that neither the system’s immediate history, nor future, affect its current behavior.

Both hysteresis and enhanced contrast are often considered evidence for the self-organization of patterns of coordination and, therefore, flags of a complex system (e.g., Guastello & Liebovitch, 2009; Kelso, 1995; Savelsbergh, van der Kamp, Davis, & Wimmers, 1999; Van der Maas & Molenaar, 1992; Thom, 1975). Each can be conceptualized as a discontinuous phase transition (bifurcation) between two mutually exclusive, competing stable attractors (e.g., walking and running). In the case of the running example, if an individual’s speed is gradually increased to a point where they transition from walking to running, this transition occurs at a greater absolute speed than the transition from running to walking (as speed decreases), thus demonstrating hysteresis (Friedrich & Warren, 1995).

Hysteresis has been demonstrated in perception of speech categorization (Tuller, Case, Ding & Kelso, 1994), and during tasks in which individuals were asked to judge whether or not they could stand upright on ramps of varying slopes (Fitzpatrick, Carello, Schmidt, & Corey, 1994) Most notably though, research has demonstrated that human grasping also exhibits
hysteresis and, therefore, suggests the presence of a non-linear system (e.g., Frank, Richardson, Lopresti-Goodman, & Turvey, 2009; Lopresti-Goodman, Richardson, Baron, Carello, & Marsh, 2009; Richardson, Marsh, & Baron, 2007; Savelsbergh et al., 1999; van der Kamp et al., 1998).

**Grasping as a Non-Linear System**

Various grasping tasks have been used frequently in the past to explore the dynamics of TD grasping behavior (e.g., Frank, Richardson, Lopresti-Goodman, & Turvey, 2009; Lopresti-Goodman, Richardson, Baron, Carello, & Marsh, 2009; Richardson, Marsh, & Baron, 2007; Savelsbergh et al., 1999; van der Kamp et al., 1998). Typically, individuals are asked to pick up a series of objects of various sizes, presented one at a time. These objects are presented in two orders: one in which the objects start out as being very small and then gradually increase in size, and a second in which the objects decrease in size (van der Kamp et al., 1998). In such paradigms, the changes in the ways in which individuals pick up objects demonstrate properties of a non-linear dynamic system and self-organizing coordination (Frank, Richardson, Lopresti-Goodman, & Turvey, 2009).

First, the ways in which objects can be picked up can represent bi-stability between two, distinct patterns of coordination. Grasping can require one hand or two hands, depending on the size of the object that is being grasped. Up to a certain size, any object can be picked up with either one or two hands: both are possible. When a system demonstrates bi-stability, the same input (in this case, the size of an object), can produce two distinct outputs (in this case, one-handed or two-handed grasping). Next, transitions in grasping styles demonstrate rapid, qualitative changes to the system, much like in the previous example of locomotion. Grasping patterns are mutually exclusive: one cannot use 1.5 hands to pick up an object. Therefore, when grasping patterns change, they cannot do so in a gradual fashion. Gradual changes are a
necessary component of linear rather than non-linear systems (Frank, et al., 2009; van der Kamp et al., 1998).

Transitions in grasping patterns are also affected by control parameters. We see that when objects are increasing in size, the transition from one-handed to two-handed grasping is governed by physical constraints. Specifically, the size of the object relative to the size of the hand acts as a control parameter and determines whether the object can be picked up with one or two hands (Frank, et al., 2009; van der Kamp et al., 1998). At a certain point, a transition must occur if grasping begins with only one hand. Note that this is not the case in the opposite direction. Since the increasingly small objects can all be picked up with two hands, there is no physical constraint as when objects are increasing in size. The transition between two- to one-handed grasping with objects that descend in size is, therefore, governed more by the acting organism (e.g., Frank et al., 2009). Thus, there is no set point where this transition must occur, if at all. This leads to the possibility of an asymmetry in grasping transitions. For TD individuals, the transition between one- and two-handed grasping usually occurs at larger object sizes when objects are presented in an ascending order as compared to a descending order, meaning that TD individuals demonstrate hysteresis on this task (e.g., Richardson, Marsh, & Baron, 2007; van der Kamp et al., 1998).

Said differently, as an object’s size increases, the one-handed grasping pattern becomes less stable, until physical limitations make it impossible. At this point, the system must spontaneously transition to the two handed grasping attractor. When objects are presented in a descending order, no such transition must occur, although the one handed grasping pattern becomes more likely to occur as objects continue to decrease in size (Frank, Richardson, Lopresti-Goodman, & Turvey, 2009). However, there is a period during which both patterns of
behavior are similarly viable behavior possibilities. Hysteresis can only occur during such periods of instability between two stable states.

Specific Aims and Hypotheses

The current study explores behavioral dynamics of TD children and those with ASD. It also explores how these dynamics relate to two areas of common impairment for children with ASD. Specifically, it compares how grasping hysteresis in children with ASD and TD is affected by the presence or absence of social factors. It also examines how measures of mental flexibility may relate to transitions in coordination patterns. It is hypothesized that children with ASD will demonstrate different grasping patterns from those with TD (i.e., much more hysteresis or little-to-no hysteresis). In addition, TD children will be more affected by social cues than those with ASD, due to the evidence that children with ASD orient to social stimuli in an atypical manner. Further, mental flexibility is predicted to correlate negatively with the degree of hysteresis children demonstrate.
Chapter II: Methods

Participants

The sample consisted of 41 children ages 6:0 to 10:11 years who met diagnostic criteria for ASD and 42 typically developing children group-matched to the ASD sample based on their chronological age. Children were recruited as part of a larger research project at the Cincinnati Children’s Hospital Medical Center. Diagnoses of ASD were confirmed by trained clinicians who administered the Autism Diagnostic Observation Schedule, Second Edition (ADOS-2; Lord, Rutter, Dilavore, Risi, Gotham & Bishop, 2012). In the ASD group, overall scores on the ADOS-2 ranged from 1 to 24, with a mean of 11.18 ($SD = 4.79$). For Module 3 of the ADOS-2 (used for all but one child), the total autism cutoff is 10 and the autism spectrum cutoff is 7. Thirty-one children met the ADOS-2 cutoff for “autism spectrum” and 3 children met the cutoff for “autism” (85%). Of the reminding children, one child met the criteria for “mild autism,” and five children met the criteria for “non-spectrum.” However, these children were included because experienced clinicians felt confident of the diagnoses on the basis of history and symptom presentation. ADOS-2 scores were not available for one child, but this individual was also included based on history and presentation. Although DSM-IV-TR (American Psychiatric Association, 2000) criteria were used to determine the diagnoses, children were not separated by individual diagnosis (e.g., Autistic Disorder vs. Asperger’s Disorder). Rather, diagnoses were combined and treated as being part of a spectrum. Non-spectrum children did not receive the ADOS-2, but received all other clinical measures (described below).

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1 The details of this and all other tests mentioned in this section are described in Standardized Measures.
All aspects of this study were approved by the Cincinnati Children’s Hospital Medical Center Institutional Review Board. Parents or legal guardians of the participants signed written informed consent and children provided verbal assent.

For TD children, the mean age was 8:2 years ($SD = 1:6$ years), with a range of 6:3 to 10:11 years. For children with ASD, the mean age was 8:6 years ($SD = 1:5$ years) with a range of 6:2 to 10:9 years. There was no difference in age ($p = .2$). TD children had a mean IQ of 108.55 ($SD = 14.82$) with a range of 77 to 141. ASD children had a mean IQ of 98.87 ($SD = 14.46$), with a range of 63 to 130. Overall, TD children had had a higher IQ than ASD children, $t(81) = 3.04$, $p = .003$. It should be noted, however, that the mean IQ of both groups fell into the clinically average range.

A measure of mental flexibility was obtained for a subset of children (85% of the TD group and 78% of the ASD group), using age-corrected standard scores for the number of perseverative errors (PERS) on the Wisconsin Card Sorting Test, Computerized Version 4. The average age of children who obtained a PERS ($M_{TD} = 8:2$ years, $M_{ASD} = 8:8$ years) and their average IQ ($M_{TD} = 108.78$, $M_{ASD} = 98.63$) were comparable to those of the entire group, replicating the IQ difference between diagnostic groups, $t(66) = 2.77$, $p = .007$. Reasons for missing scores include technical errors administering the test, time constraints on the part of the family, disinterest of the child, and failure to follow task instructions.

**Cognitive Measures**

The Differential Ability Scales, 2nd Edition was administered to estimate overall verbal and nonverbal cognitive abilities (DAS-II; Elliott, 2007). Depending on their age, children completed either the Early Years or the School-Aged core batteries of the DAS-II. The core subtests of the DAS-II load onto three clusters: Verbal, Nonverbal Reasoning, and Spatial. They
combine to produce a General Conceptual Ability (GCA) score, which was used as a proxy for Full-Scale IQ.

The Autism Diagnostic Observation Schedule, Second Edition was administered to confirm ASD diagnosis (ADOS-2; Lord et al., 2012). It is a standardized, semi-structured observational assessment during which a trained clinician provides standardized prompts and scenarios. These are designed to elicit specific social behaviors that are then rated by the clinician (e.g., eye contact, repetitive behavior, etc.). There are four modules of the ADOS-2 appropriate for children in the present age range. Module 1 is used with nonverbal individuals or those who cannot speak in phrases; Module 2 is used with children who can use phrases, but are not fluent speakers; Module 3 is for children who are verbally fluent but have not reached adolescence; and Module 4 is used with adolescents and adults who are verbally fluent. Scores from the “Social Affect” and the “Restricted Repetitive Behavior” domains are summed and applied to cut-offs to produce diagnostic classifications, which are provided above in the Participants section only for descriptive purposes.

The Wisconsin Card Sorting Test, Computer Version 4, Research Edition (WCST: CV4; Heaton, 2005) was administered to measure perseveration and mental flexibility. The task is to match a series of test cards with one of four key cards, by using a mouse to click on the chosen key card. Each test card can be matched to the key cards based on one or more rules. The computer provides feedback as to whether a choice is correct or incorrect, based on a predetermined rule. However, no explicit information about the rule is provided. Participants are not allowed to change their choices once they are made. After the participant matches a certain number of cards correctly by a given rule, that rule is changed without informing the participant. This change occurs several times (Heaton et al., 1993). Among other scores, the WCST:CV4
includes a perseverative error score that is standardized to correct for age (PERS; $M = 100$, $SD = 15$), which was selected as the unit of measure for this study. This score is based on the inverse of the number of perseverative errors committed; thus a higher PERS equates to better performance (i.e., fewer errors committed).

The WCST:CV4 is considered a research edition because at the time of its publication there was not a standardization sample that had taken both the traditional and computerized versions of the test, and the normative sample for the traditional card sort was used to determine standard scores (Heaton, 2005). The age range for the standardization sample is from 6 years, 6 months-old through older adulthood. For younger participants (6-0 to 6-5) in the study, scores were based on normative data published by Rosselli and Ardila (1993).

**Grasping Task**

**Materials.** Stimuli consisted of cubes cut out of white foam board. They ranged in size from 2 to 20 cm wide, with 1 cm difference in cube width between adjacent cubes (yielding 19 cubes in total). The foam board made it possible for cubes to be very light, allowing children to pick them up easily (with either one or two hands). No participants indicated any difficulty lifting the cubes.

A low table was used, with two black curtains positioned on the table in such a way that they met at an angle (see Figure 1 for a schematic of the experimental setup). Each curtain was 30 cm high, partially occluding the front and right view of the child. A rotating wooden dolly, 36 inches in diameter, was used in the non-social context. It was placed on the table to the child’s left, such that part of its surface was occluded by one of the curtains. For trials in which the dolly was not needed (social context), it was removed, along with the curtain directly in front of the child.
**Design and procedure.** Participation required two visits. During the first visit, children were administered a battery of clinical measures, beginning with the DAS-II and ending with the ADOS-2 (when applicable). During their second visit, children completed a battery of experimental tasks, followed by the WCST:CV4.

![Diagram of experimental setup showing the table, the rotating dolly, and the curtains. The X on the dolly was a mark visible to the child, whereas the + on the table was not.](image)

*Figure 1.* Diagram of experimental setup showing the table, the rotating dolly, and the curtains. The X on the dolly was a mark visible to the child, whereas the + on the table was not.

For the Grasping Task, two experimenters were present: E1 and E2. The child sat across from E1, with E2 sitting to the child’s right (see Figure 1). During a trial, E2 moved a cube through the curtain towards the child, approximately at the position marked with + in Figure 1 (the + mark was not present in the actual setup). In the non-social context, the child was asked to pick up the cube and place it on the X marked on the dolly. In the social context, the child had to pick up the cube and hand it to E1 (who held out either one hand or two, depending on condition). E1 attempted to position his hands so that they corresponded to the same location as the X on the turntable. For each trial, E1 recorded whether the child picked up the cube with one or two hands. Cubes were presented in two orders. In the ascending phase, participants were first presented with the 2cm cube, and then each successively larger cube. In the descending
phase, they first saw the 20 cm cube, with each of the following trials presenting a smaller cube than the last.

Table 1

*Excluded participants, including their ages, IQs, PERS, ADOS-2 scores, and their performance patterns across the conditions of experimental task.*

<table>
<thead>
<tr>
<th>Excluded TD Children</th>
<th>Non-Social Context</th>
<th>Social Context</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase:</td>
<td>Ascending</td>
<td>Descending</td>
</tr>
<tr>
<td>Excluded TD Children</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8:3 years; IQ = 103; PERS = 122</td>
<td>No switch</td>
<td></td>
</tr>
<tr>
<td>9:5 years; IQ = 104; PERS = 99</td>
<td></td>
<td>No switch</td>
</tr>
<tr>
<td>9:4 years; IQ = 119; PERS = 99</td>
<td>Switched back</td>
<td></td>
</tr>
<tr>
<td>8:4 years; IQ = 92; PERS = 99</td>
<td></td>
<td>Switched back</td>
</tr>
<tr>
<td>10:3 years; IQ = 103; PERS = 110</td>
<td></td>
<td>Switched back</td>
</tr>
<tr>
<td>9:1 years; IQ = 112; PERS = 113</td>
<td>Switched back</td>
<td>No Switch</td>
</tr>
<tr>
<td>7:0 years; IQ = 120; PERS = &lt; 55</td>
<td>Switched back</td>
<td>No switch</td>
</tr>
<tr>
<td>10:7 years; IQ = 104; PERS = 110</td>
<td>No switch</td>
<td></td>
</tr>
<tr>
<td>Excluded ASD Children</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8:7 years; PERS = IQ = 89; &lt; 55; ADOS = 18</td>
<td>No switch</td>
<td>No switch</td>
</tr>
<tr>
<td>10:6 years; IQ = 103; PERS = 98; ADOS = 10</td>
<td>Switched back</td>
<td></td>
</tr>
<tr>
<td>7:9 years; IQ = 103; PERS = 67; ADOS = N/A</td>
<td></td>
<td>No switch</td>
</tr>
</tbody>
</table>

The maximum number of cubes presented was 19 for each of the phases. However, the number of cubes presented to each child differed as a function of the following rules: an ascending phase ends when five cubes in a row are picked up with two hands. A descending phase ends when five cubes in a row are picked up with one hand. To be included in the study,
children’s grasping method on the first cube of a phase had to differ from the grasping method of the last cube of that phase; planned statistical analyses could not be conducted on data for children who did not transition (see Results). Thus, children were excluded who either did not switch grasping method in at least one phase, or who switched back to their initial grasping method in at least one phase. Table 1 provides detailed information about the grasping methods of the excluded children (17% of the entire group of children tested).

Figure 2. Experimental task in schematic form. All children first participated in the non-social context of the task first. Half of these children were presented with the ascending phase before the descending. The reverse was true for the other half. During the social context, these groups were subdivided based on the type of presentation by the experimenter (1 vs. 2 hands).

All participants completed both the non-social and social contexts in a fixed order, with the non-social always first. Each participant was randomly assigned to one of two presentation order conditions (ascending phase first or descending first) and one of two hand conditions (examiner extends one hand or two hand in anticipation of the cube). Thus, the study implemented a 2 (diagnosis) X 2 (ascending/descending order) X 2 (hands) X 2 (social context) mixed design. Figure 2 shows the design schematically. The number of participants was
balanced across presentation order (ascending trials first; descending trials first) and condition (one-hand presentation; two-hand presentation) \((N \geq 19\) per cell).
Chapter 3: Results

The central questions related to whether children showed hysteresis, as determined by whether their grasping pattern changed at a larger cube in the ascending phase than the descending phase. A transition point was calculated in each phase, to determine the change in grasping pattern during that particular phase, following procedures described in the literature (e.g., Lopresti-Goodman, Richardson, Baron, Carello, & Marsh, 2009; Richardson et al., 2007; Van der Kamp et al., 1998). Specifically, I first identified two cubes per phase: (1) the largest cube that was grasped with one hand (with all smaller cubes being grasped with one hand), and (2) the smallest cube that was grasped with two hands (with all larger cubes being grasped with two hands as well). The transition point was the average of these two values. For example, for a particular phase, if a child used one hand for all cubes 10 cm and smaller, and used two hands for all cubes 11 cm and larger, the transition point for that phase was 10.5 cm. If this child did not consistently use two hands until the 12 cm cube, the transition point for that phase was 11 cm (i.e. the average of 10 and 12). There were four transition points for each child: one for the ascending phase and one for the descending phase in both the non-social and social contexts.

In a preliminary analysis, I sought to determine whether our order manipulation (ascending-first vs. descending-first) had an effect on transition points. Collapsing across the two phases within a context, two average transition points were calculated for each child, one for the non-social context and one for the social context. For each diagnostic group (TD, ASD) and context (non-social, social), a 2 X 2 between-groups ANOVA was conducted, with order and condition as factors. I did not expect an effect of order or condition for the non-social context.

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2 Condition (i.e., whether E1 held out one or two hands to receive the cube in the social context) did not affect the procedure in the non-social context (when the child had to place the cube on the dolly).
and I did not expect an effect of order for the social context (cf., Lopresti-Goodman et al., 2009). These predictions were confirmed for the non-social context: There was no effect of order or condition, nor was there an order-condition interaction, whether for TD children, \( ps > .12 \), or for ASD children, \( ps > .27 \). In the social context, there was a marginal effect of order for TD children, \( F(1,38) = 3.17, p = .08^3 \), but no order effect for ASD children, \( p = .86 \). There was no significant interaction with order for either group of children, \( p > .27 \) for both comparisons. For subsequent analyses, I collapsed data across order and condition for the non-social context, and I collapsed data across order for the social context.

Figure 3. Mean transition point, in centimeters, for the non-social and social context, separated by ascending versus descending trials, and separated by diagnostic group: TD (A) vs. ASD (B).

Figure 3 shows the average transition points obtained for the two different contexts (non-social and social), separated by condition in the social context (one-hand vs. two-hand), separated by phases (ascending versus descending), and separated by diagnostic group (TD vs. ASD). To address the overall question of the current study: to what extent is hysteresis present

\(^3\) The mean transition point was 10.04 cm (\( SD = 2.24 \)) for ascending-first order and 11.05 cm (\( SD = 1.90 \)) for the descending-first order.
in TD children versus those with ASD, and how does performance compare between social and non-social contexts, a 2 (diagnostic group) X 2 (phase; ascending vs. descending) X 2 (context; social vs. non-social) mixed-model ANOVA was conducted. It revealed a significant main effect of phase, $F(1,81) = 23.97, p < .001$, with both diagnostic groups transitioning higher in the ascending phase ($M = 11.04$) than the descending phase ($M = 9.98$). The main effects of context and diagnosis were not significant, $p_s > .14$. However, there was a significant interaction between context and diagnosis, $F(1,81) = 3.99, p = .049$, with TD children transitioning on larger cubes in the non-social compared to the social context (regardless of phase) and children with ASD transitioning on similarly sized cubes in both contexts. No other interactions reached statistical significance, $p_s > .13$.

Although the three-way interaction between diagnostic group, phase, and context failed to reach significance, a trend appeared to emerge in the data that that suggested that hysteresis may decrease for both groups in the social context, but moreso for the children with ASD. I therefore chose to qualitatively examine the effect of hysteresis for each diagnostic group within each context separately.

In what follows, I first address the questions of hysteresis in the non-social context: to what extent was hysteresis evident in TD versus ASD children? To illuminate possible trends, a 2 X 2 (phase by diagnosis) mixed-design ANOVA was conducted. Then, two $t$ tests were implemented, comparing the transition points of the ascending and descending contexts for each diagnostic group. I then turn to the effect of condition in the social context: to what extent is the transition point affected by the one-hand versus two hands condition? For this, 2 X 2 (phase by condition) mixed model ANOVAs were conducted for each diagnostic group. Finally, I compare the emergence of hysteresis between the social and non-social contexts for both diagnostic
groups. Two 2 X 2 (context x phase) repeated measures ANOVAs were conducted to accomplish this, one for each diagnostic group. Finally, I analyze the extent to which hysteresis is relate to perseveration errors in the card sorting task.

**Non-Social Context**

The first question was whether the ordering of cubes yielded hysteresis when children had to place the cubes on a dolly. A 2 x 2 mixed-design ANOVA was carried out, with diagnostic group as between-group factor (TD vs. ASD), and phase as the within group factor (ascending vs. descending). As anticipated, there was a main effect of phase, $F(1,81) = 22.33, p < .001$, with a higher transition point in the ascending phase ($M = 11.25$) than in the descending phase ($M = 9.87$). Importantly, there was no interaction between diagnostic group and phase, $p > .73$. However, there was a main effect of diagnostic group, $F(1,81) = 5.66, p = .02$, with a higher transition point for TD children ($M = 11.10$ cm) than for ASD children ($M = 10.02$ cm). In other words, although both groups showed hysteresis, TD children, as a group, transitioned on larger cubes than ASD children.

As can be seen in the nonsocial-context columns of Figure 3A, TD children transitioned on a larger cube size in the ascending phase (from one- to two-handed grasping) than in the descending phase (from two- to one-handed grasping), paired sample $t(41) = 3.99, p < .001$. A similar finding was obtained for ASD children (see nonsocial-context columns in Fig. 3B). ASD children transitioned on a larger cube size in the ascending phase than in the descending phase, paired sample $t(40) = 3.01, p = .004$. Thus, like their TD counterparts, children with ASD also demonstrated hysteresis during the non-social grasping task. This is consistent with what was documented in the omnibus analysis.
Social Context

The second question was whether the ordering of cubes yielded hysteresis when children had to hand the cubes to the experimenter, depending on the number of hands presented. Considering TD children first (see social-context columns in Fig. 3.1A), a 2 x 2 mixed-design ANOVA was conducted, with condition (one-hand vs. two-hand) as the between-group factor, and phase (ascending vs. descending) as the within-group factor. As expected, I found a significant effect of phase, $F(1,40) = 5.73, p = .022$, with a higher transition point in the ascending phase ($M = 11.20$) than in the descending phase ($M = 9.89$). There was no effect of condition, $p > .30$, and no significant interaction with condition, $p > .50$. Thus, regardless of whether the experimenter held up one or two hands when receiving the cube, TD children showed evidence of hysteresis.

This finding mimics what I found for TD children in the non-social context. Indeed, a 2 by 2 (context x phase) repeated-measure ANOVA (with data collapsed across condition) revealed an effect of phase, $F(1, 41) = 22.19, p < .001$, an effect that held up when TD data was analyzed separately for each condition (one-hand condition: $F(1,22) = 10.46, p = .004$; two-hand condition: $F(1,18) = 11.36, p = .003$). Importantly, there was no phase-context interaction, whether in the analysis collapsed across conditions, $p > .97$, or in the analyses within each separate condition, $ps > .27$.

Now consider ASD children (see social-context columns in Fig. 2B). I again conducted a 2 x 2 mixed-design ANOVA (condition x phase), but this time there was no effect of phase, $p > .76$, nor an interaction with phase, $p > .66$. Whether cubes were presented in ascending or descending order, the transition point did not change. There was no effect of condition, $p > .48$.

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4 Collapsed across conditions, there was a marginally significant effect of context, $p = .084$ ($M_{Non-Social} = 11.10$ cm; $M_{Social} = 10.56$ cm), which disappeared when TD data was analyzed separately for condition, $ps > .16$
These results should be only interpreted qualitatively, as the three-way interaction in the omnibus analysis failed to reach significance. With this in mind, there is a trend that across both social conditions, children with ASD transitioned on similarly sized cubes in both the ascending and descending phases, failing to demonstrate hysteresis in the social context. These results are qualitatively different from what was found with ASD participants in the non-social context. A 2 by 2 (context x phase) repeated-measures ANOVA (with data collapsed across condition) indicated a significant interaction between phase and context, $F(1,40) = 5.05, p = .03$. Thus, there is suggestion that the ASD group’s performance was not equal between the non-social and social contexts.\(^5\)

**Individual Patterns of Performance**

Are group results of hysteresis supported by individual patterns of performance? To address this question, I determined the difference between ascending-phase transition point and descending-phase transition point for each child. A positive transition difference indicates hysteresis (i.e., later transition in the ascending than the descending phase). By comparisons, no difference indicates that the child is switching grasping method at the same sized cube for both ascending and descending phases. A negative transition difference indicates that a child is switching earlier on the ascending phases than on the descending phases. This is known as enhanced contrast (Kelso, 1995, p. 203), indicative of a child’s anticipation of the upcoming cube sizes.

Figure 4 shows the distribution of transition differences for the above sample in the non-social and social contexts, separated by condition and diagnostic group. The top right quadrant of a scatterplot shows children who demonstrated hysteresis in both the social and the non-social

\(^5\) The phase-context interaction was also found when the analysis was conducted for the two-hand condition only, $F(1,21) = 8.17, p = .003$. It was not found, however for the one-hand condition, $p > .78$. 

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context. The bottom left quadrant, in contrast, shows children who failed to demonstrate hysteresis in any of the two contexts. Finally the two remaining quadrants show children who demonstrated hysteresis either in the social context (top left) or the non-social context (bottom right). By glancing at the figures, a difference in distributions is suggested; while the distribution of scores along the x-axis is comparable across the two diagnostic groups (non-social context), there is indication of a shift in values along the y-axis (social context).

Considering the non-social context first, first, note that a majority of TD children showed hysteresis in the non-social context (25/42 = 60%). Nine of the remaining TD children had a transition difference of zero (21%), and eight children showed enhanced contrast (19%). A comparable distribution of scores was found for ASD children (Fig. 4B): a majority showed hysteresis in the non-social context (27/41 = 66% ASD), with four ASD children having a transition difference of zero (10%), and ten ASD children showing enhanced contrast (24%). Consistent with the aggregate results, hysteresis was common for both TD and ASD children in the non-social context.

Figure 4. Scatterplot of transition differences in the non-social and social contexts for TD children (A) and children with ASD (B).
Now consider how children performed across both contexts: for TD children, one third showed hysteresis in both contexts (14/42 = 33%), while eight children showed no hysteresis in either context (19%). The same pattern held for ASD children: about one third showed hysteresis in both contexts (12/41 = 29%), while only nine children showed no hysteresis either context (22%). About the same number of the remaining TD children showed hysteresis in the non-social context only (11/42 = 26%) versus in the social context only (9/42 = 21%). In contrast, there were three times more ASD children who showed hysteresis in the nonsocial (15/41 = 37%) compared to social context only (5/41 = 12%). Analyses revealed that the correlation in transition difference-scores between non-social and social context was not significant for TD children, $r(40) = -.23, p = .14$, nor for ASD children, $r(39) = .10, p = .53$. While these findings are not statistically significant, much like the above analyses, qualitatively, they hint at a possible trend toward differentiated performance.

**Hysterisis vs. Perseveration**

**WCST:CV4 Performance.** Before comparing performance on the Grasping Task to perseveration, I first examined performance on the WCST:CV4 across diagnostic groups and in relationship to other measures. There was a marginally significant difference between diagnostic groups, $t(66) = 1.73, p = .09$, with higher PERS (fewer perseverative errors) for TD children ($M = 104.33, SD = 15.47$) than ASD children ($M = 98.00, SD = 14.67$). However, it should be noted that the average performance for both groups fell well within the clinically normal range. Age was positively correlated to PERS for TD children, $r(34) = .40, p = .016$, but not for ASD children, $r(30) = .14, p = .45$. Higher IQ was marginally correlated with fewer perseverative errors for TD children, $r(34) = .28, p = .093$, and significantly correlated for children with ASD, $r(30) = .41, p = .019$. 
Comparing Hysteresis and Perseveration. To what extent are the processes underlying hysteresis the same processes that govern perseveration and difficulty with cognitive set-shifting? To answer this question, I compared the PERS and transition differences in both the non-social and social contexts for each participant who completed both the Grasping Task and the WCST (36 TD children and 32 with ASD).

**Figure 5.** Transition Difference for TD children (A) and children with ASD (B) in the non-social context (B) by PERS, separated by condition.

I first confirmed that this subset of participants performed similarly on the Grasping Task to the larger sample. For the non-social context, repeated measures analysis indicated a significant effect of phase for TD children, $F(1,35) = 13.25, p = .001$, and a marginal effect of phase for children with ASD, $F(1,31) = 3.75, p = .06$, and therefore, similar performance as the larger sample. For the social context, two 2 by 2 (phase x condition) mixed model analyses conducted for each diagnostic group indicated a significant main effect of phase for TD children, $F(1,34) = 5.6, p = .02$, and no significant main effects of phase or condition for children with ASD in the social context. The main effect of condition was not significant for TD children, and the interaction was not significant for either diagnostic group. Thus, performance patterns were
similar between the subset of children with WCST:CV4 data and the larger sample across contexts.

Next, I examined the possible correlation between PERS and transition-point difference scores. Figure 5 shows the PERS for each participant plotted against their respective transition difference obtained in the non-social context. If hysteresis and perseveration have similar underlying processes, I would expect to see a negative correlation between transition differences and PERS (recall that PERS is the standardized inverse of the number perseverative errors). There is no evidence for such correlation, either for TD children, \( r(34) = -0.24, p = 0.15 \) or for children with ASD, \( r(30) = 0.21, p = 0.25 \). In fact, considering children with ASD only, the correlation between PERS and transition difference is in the opposite direction of what would be predicted by a model that equates hysteresis with perseverative error. When considering only children from each diagnostic group who demonstrated hysteresis, transition difference and PERS were not significantly correlated for TD children, \( r(10) = 0.14, p = 0.67 \) or for ASD children, \( r(7) = 0.36, p = 0.34 \).

To confirm my findings, I compared the raw number of perseverative errors committed by each participant on the WCST:CV4 with their transition differences in the non-social context. Raw perseverative errors did not significantly correlate with transition difference for both the TD children, \( r(34) = 0.22, p = 0.19 \), and children with ASD, \( r(30) = -0.18, p = 0.34 \).

Considering next the performance patterns from the social context, the transition difference-score and PERS were not significantly correlated with for TD children, \( r(34) = -0.003, p = 0.97 \), nor for children with ASD, \( r(30) = 0.21, p = 0.26 \). Similarly, when considering only the

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The negative correlation between PERS and transition score for TD children is likely to be an artifact of correlation between age and PERS for this group of children \( r = 0.4, p < 0.05 \) and the correlation between age and transition difference, \( r = -0.42, p < 0.05 \).
subset of children who demonstrated hysteresis, the transition difference-score and PERS were not correlated for either diagnostic group (TD: $r(10) = -.216, p = .50$; ASD: $r(7) = -.13, p = .74$).

Finally, social context difference-scores and the raw number of perseverative errors committed on the WCST:CV4 were not correlated for either diagnostic group, $r(34) = .23, p = .17$, and $r(30) = -.26, p = .16$, for TD children and children with ASD, respectively.
Chapter IV: Discussion

Results of the current study suggest that in the absence of social cues, children with ASD tended to transition on smaller sized boxes in both the ascending and descending trials than TD children. However, when comparing the transition points between ascending and descending trials within subjects, both groups tended to transition on larger cubes in ascending trials. Thus, both TD children and those with ASD demonstrated hysteresis. Omnibus analyses indicated that hysteresis occurred in the social context for both groups as well. However, there was the hint of a possible trend toward differentiated performance. Further exploratory analyses were conducted and qualitatively, it appeared that in the social context, only TD children demonstrated hysteresis. Children with ASD did not. Instead, on average, they appeared to transition on the same sized cube in both the ascending and descending trials.

Hysteresis is often considered to be an indication of the way in which a system (in this case, an individual) transitions between two, adaptive stable patterns in the face of changing environmental constraints (i.e., picking up various sized objects). For the current paradigm, this adaptive pattern is maintained in TD children across nonsocial and social contexts. Although the omnibus analysis indicated that this is true for children with ASD as well, there is suggestion of less hysteresis the presence of what could be argued to be very minimal social cues.

In typical development, the degree to which individuals demonstrate hysteresis during grasping tasks can be affected by contextual factors. For example, the faster objects are presented, the more hysteresis individuals exhibit. In contrast, slower object presentation often leads to diminished or absent hysteresis (Lopresti-Goodman et al., 2009). Additionally, when individuals are presented with a cognitive task that distracts from their grasping, they again demonstrate more hysteresis. It is possible that in the presence of a social situation, children with
ASD actually focused more on the task than they did in its absence. However, this is speculative, as no measurements that could shed light on attentional focus (e.g., eye gaze) were gathered.

The current results may provide preliminary evidence for a non-reductionist account of ASD and may also demonstrate an interplay between seemingly un-related domains. That is, children with ASD were able to complete the task in both the non-social and social conditions. However, their performance patterns may be sensitive to the presence or absence of a social cue. Thus, the presence of a social cue may have affected the way in which they completed the task, but did not determine whether or not they could complete it. As opposed to providing evidence for global deficits in either social or motor functioning, findings suggest differing patterns of coordination between domains.

It was hypothesized that the degree to which a child demonstrated hysteresis during the grasping task would correlate to the amount of perseveration they exhibited on the WCST:CV4. On the one hand, hysteresis occurs when a system utilizes previous information to inform its current state, but will transition when conditions become suitable (Kelso, 1995). Perseveration, on the other hand, is often seen as maladaptive, demonstrating a system getting “stuck” (Helm-Estabrooks, 2004). However, although hysteresis is conceptualized as a sign of adaptability, I questioned whether in a more extreme or pronounced state, it may be analogous to perseveration. However, hysteresis and perseverative errors were not correlated for either diagnostic group in either the social or non-social contexts. Previous work has argued that hysteresis and perseveration are separate concepts (e.g., Hock, Kelso, & Schöner, 1993; Van Bers, Visser, van Schijndel, Mandell, & Raijmakers, 2011). The current results may provide more evidence for this differentiation.
When considering the implications of this study’s results, one must do so within the context of its limitations. First, with regards to the Grasping Task: the non-social and social contexts were in a fixed order, with the non-social context always coming first. This was initially chosen because of the fact that, to my knowledge, no prior studies had explored hysteresis in ASD utilizing a grasping paradigm. Therefore, it was thought that if children ended their participation early, data would still be available for the non-social context. This would at least provide basic information about grasping hysteresis in ASD. Thus, it would then be possible to still conduct a second study exploring the effects of social cues on grasping patterns. However, this design posed a potentially significant limitation.

The design of the Grasping Task limited the ability to determine whether performance in the social context may have been related to an effect of order. As noted above, previous research has demonstrated that attentional focus has an effect on the emergence of hysteresis in TD, with individuals demonstrating more hysteresis when they are not paying as much attention to a task (Lopresti-Goodman et al., 2009). On the one hand, it would be plausible that an order effect might actually correspond to more hysteresis due to task disengagement. However, if learning occurred, it is possible that children began to anticipate each successive cube, and therefore be more likely to demonstrate enhanced contrast. It is difficult to make a conjecture in either direction given that the diagnostic groups did not perform similarly across contexts.

Considerations must also be made when examining performance on the Grasping Task as compared to the WCST:CV4. Although the WCST:CV4 is thought to assess problem solving and mental flexibility, it involves other cognitive processes which may affect performance. For example, attention, working memory, and behavioral inhibition may all play a role in how a child succeeds at the task (e.g., Bond & Buchtel, 1984; Dehaene & Changeux, 1991; Perrine, 1993).
Second, most participants from the TD and ASD groups demonstrated IQs and WCST:CV4 scores which were considered to be in an unimpaired range of performance, clinically. Past work as suggested that ASD performance on the WCST may be related to intellectual functioning (e.g., Kaland et al., 2008; Turner, 1995, as cited in Turner, 1997). Indeed, Kaland and colleagues found that individuals with High Functioning Autism performed as well as their TD peers on perseveration measures of the computerized WCST. It is possible that the limited range of the current sample’s intellectual functioning may have played a role in the results, as most children’s IQs were within normal limits. In a similar vein, the limited range of difference scores on the grasping task may have also had an effect. Finally, there is some evidence individuals with ASD perform better on the computerized version of the WCST than the standard version (e.g., Ozonoff, 1995). In the current study, the computerized version was utilized due to its ease and speed of administration and scoring. It is possible that results may have differed if the experimenter-administered version of the test had been used.

Future work should explore whether the current study’s results were due to the order in which the task was conducted (i.e., non-social context before social context). Counterbalancing the social and non-social conditions or introducing a distractor task (such as a condition in which the blocks are presented in a random order) would be beneficial. To address issues with the WCST:CV4, future work may consider either including groups of children with wider ranges of functioning, or consider a model in which half of the children take the computerized WCST and the other the standard version. Alternately, it might be helpful to include other measures of perseveration or other areas of executive functioning.

Subsequent studies should also include physical measurements of participants’ hands. Past research has described body-scaled characteristics associated with the transitions between
grasping styles in TD children. That is, transition points from one-handed to two-handed grasping occur at a relatively consistent ratio of cube to hand size. Such scaling provides evidence that such behavior emerges as a result of complex self-organization that occurs between organisms and their environments in the absence of conscious cognition (e.g., Frank et al., 2009; Van der Kamp et al., 1998). Thus, examining the grasping data within the context of hand size will help determine whether or not the same body-scaling occurs for children with ASD as TD, which may provide more evidence for the coordination account of autism.

More broadly, as noted above, the current study may indicate a reason to re-evaluate previous ASD research with a focus on process rather than performance. Take for example, Theory of Mind tasks. Traditionally, the end result, or the child’s answer to a test question, is the metric of focus, thought to indicate whether a child possesses ToM or not. Take one version of the classic “Sally and Anne” task (e.g., Baron-Cohen, Leslie, & Frith, 1985). In it, a child is presented with a scene involving two puppets (other versions may use actors, cartoons, etc.), Sally and Anne, as well as two containers (e.g., a box and a bag). The child learns that Sally has found a small object (e.g., a marble) and has decided to place it inside one of the containers (e.g., the box). Sally then leaves the scene to go play elsewhere. While she is gone, Anne takes the marble out of the box and places it in the other container, the bag. Sally then returns. The child is asked to point to the container in which Sally will most likely first look for the marble (the box), rather than the container that actually contains the marble. The child’s answer is thought to represent whether or not they understand Sally’s perspective. Presumably, Sally has no knowledge that the marble had been moved, and therefore should look in the box. If a child points to the bag, they are answering based on their own perspective and knowledge.
Research analyzing eye gaze, and more specifically, the amount of time spent fixating on aspects of the display during false-belief tasks, indicates that children who typically fail to explicitly identify the correct answer may still have an understanding of ToM (Ruffman, Gurnham, Import, & Connolly, 2001). This has led some to argue for the existence of two separate ToM systems, an implicit system, and an explicit system, the latter involving more diffuse cognitive processes (Apperly & Butterfill, 2009).

However, more recent findings may be more consistent with a coordination account. Specifically, increasing cognitive load (through secondary tasks) during the Sally and Anne task affects not only explicit performance, but also the targets of participants’ eye gaze patterns, which has been considered a proxy for an implicit understanding (Schneider, Lam, Bayliss, & Dux, 2012). This suggests that instead of two separate processes, ToM involves a complex interplay of various mental systems in relation to task context. This may be somewhat parallel to grasping research showing how attentional factors affect whether or not an individual demonstrates hysteresis (Lopresti-Goodman et al., 2009). In both cases, exploring how the task was completed shed light on the coordination between various domains.

A process approach to conceptualizing task performance may also be applicable for tasks thought to assess problem-solving and Executive Functioning. Take, for example, the WCST:CV4, employed in the current study. While the metric we chose assesses levels of performance, it is possible to combine this with a more process-oriented measure, such as computer mouse movement. On computerized decision-making tasks, the trajectories of participants’ mouse movements differ depending on whether they are answering an ambiguous question or a clearer one (McKinstry, Dale, & Spivey, 2008). Other work has demonstrated that motor movements become more chaotic before individuals switch between decision-making
strategies (Stephen, Dixon, & Isenhower, 2009). Thus, tracking mouse movements during the WCST:CV4 may shed light as to how behaviors differ between correct and incorrect responses, perseveration, and during periods when individuals shift between matching strategies.

The degree to which the performance patterns of children with ASD was affected by social cues raises questions regarding intervention strategies, as most naturally involve interacting with another human. However, there is increased interest in using technology as a therapeutic interface (for a review, see Boucenna et al., 2014), with focus being given to the potential therapeutic utility of robotics (Diehl et al., 2012). Diehl and colleagues (2012) point out that some of the rationales for the use of therapeutic robots include the theory that children with ASD connect with the physical world better than the “social world,” evidence that they may respond to feedback from technology better than humans (e.g., Ozonoff, 1995), and that children with ASD may be more interested in technology-based treatments (Robins, Dautenhahn & Dubowski, 2006). However, they note that to date, much of the research surrounding the use of robotics in ASD interventions has been limited by small sample sizes, variable inclusion criteria for participants, limited outcome measures, and a tendency to focus on technical/developmental aspects of the technology. Given these limitations, and the variability in research results, this domain may still be a fruitful area for further research. Further, current study may lend support to this idea that providing children with interventions delivered in a non-social context may be beneficial. It may be possible to utilize technology (such as robots) to initially scaffold behavior with the intention of gradually transitioning to more naturalistic contexts (e.g., Scassellati, 2007, Tapus et. al, 2007).

Given its limitations, the current project was able to shed some light onto the way coordination emerges in ASD as it compares to TD. It adds to the existing literature in important
ways. First, it takes a novel conceptualization in studying ASD. It does not take a reductionist approach to symptomology, instead favoring a developmental approach stemming from a dynamic systems perspective. Such a novel viewpoint may help unify many of the conflicting findings associated with ASD task completion. The varied performance of individuals with ASD on different tasks as often considered problematic because of the search for a core deficit. If such tasks are approached through the lens of the coordination account, focus shifts to the effect of contextual factors on how tasks are completed. Thus, differences in performance can be explained through a common phenomenon. This may facilitate the development of new assessment and intervention modalities in the future. Second, hysteresis, a concept typically reserved for typical child and adult cognition (e.g., Lopresti-Goodman, Richardson, Baron, Carello, & Marsh, 2009; Richardson, Marsh, & Baron, 2007; Rostoft, Sigmundsson, Whiting, & Ingvaldsen, 2002; van der Kamp et al., 1998) was applied to questions of atypical development in ASD. This not only adds to the knowledge of ASD, but may help us better understand typical development, as well. Expanding further, applying similar research strategies may aid in our understanding of other neurodevelopmental and genetic disorders.
References


