Cognitive and Affective Control Deficits in Adults with Autism Spectrum Disorder

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COGNITIVE AND AFFECTIVE CONTROL DEFICITS IN ADULTS WITH AUTISM SPECTRUM DISORDER

by

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ABSTRACT

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Cognitive control constrains mental operations to prioritize information that reaches conscious awareness and is essential to flexible, adaptive behavior under conditions of uncertainty. However, cognitive control can be compromised by neurodevelopmental disorders such as autism spectrum disorder (ASD), which is characterized by the presence of social and communicative deficits, and restricted interests/repetitive behaviors. Although prior investigations have attempted to elucidate the nature of cognitive control deficits in ASD, whether there is an underlying deficit in cognitive and affective control associated with the symptom domains of ASD remains unclear. The present series of eight experiments presents an information theoretic framework for the study of cognitive control in high-functioning adults with ASD, and aims to investigate deficits in cognitive and affective control under conditions of uncertainty, and the relation of these deficits to ASD symptoms, to better understand the nature of symptoms and cognitive deficits in ASD.
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Chapter I

Research Objective

Introduction

At any given moment, the human brain is tasked with selecting among immense amounts of mental representations for further processing by the conscious mind. Much of this information contains uncertainty, which must be processed in order to formulate and execute goal-appropriate actions. Efficient information processing allows us to engage in voluntary control over cognition, flexibly adapt to different contexts, and behave in a goal-directed manner. In the existing literature, this function is commonly referred to as “cognitive control” and the ability to efficiently process incoming information and rapidly generate responses is largely dependent on its integrity (Badre, 2008; Fan, 2014; Kouneiher, Charron, & Koechlin, 2009; Mackie, Van Dam, Fan, Dam, & Fan, 2013; Miller & Cohen, 2001; Posner & Snyder, 1975).

Typically developing (TD) individuals are generally efficient in employing cognitive control, but in cases of neurodevelopmental disorders, cognitive control can be compromised, resulting in functional impairment (Burden et al., 2009; Durston et al., 2003; Minshew & Goldstein, 1998; Minshew, Johnson, & Luna, 2000; Poljac & Bekkering, 2012; Rowe, Lavender, & Turk, 2006; Shapiro, Wong, & Simon, 2013; Solomon et al., 2013; Solomon, Ozonoff, Cummings, & Carter, 2008; Vaidya et al., 2005; van Meel, Heslenfeld, Oosterlaan, & Sergeant, 2007). Autism spectrum disorder (ASD) is one such disorder, diagnosed in 1 in 68 children (Baio, 2014), and characterized by the presence of symptoms in the domains of social and communicative deficits, and
restricted interests/repetitive behaviors (American Psychiatric Association, 2013). One clear behavioral marker of this disorder is the rigid, inflexible way in which these individuals interact with the world, often with extreme negative reactions to novel or uncertain events (Gomot & Wicker, 2012). This inflexible style of cognition and behavior has been framed in terms of cognitive control deficits (D. V. M. Bishop, 1993; Bogte, Flamma, van der Meere, & van Engeland, 2008; Damasio & Maurer, 1978; García-Villamisar & Della Sala, 2002; Geurts, Corbett, & Solomon, 2009; Hughes, Russell, & Robbins, 1994; Lopez, Lincoln, Ozonoff, & Lai, 2005; Ozonoff, Pennington, & Rogers, 1991; Solomon et al., 2008; Turner, 1999, 1997; Yerys et al., 2009). However, studies aimed at examining cognitive control performance in ASD have provided vastly inconsistent results (Barnard-Brak, 2011; Geurts et al., 2009; Poljac & Bekkering, 2012; Russo et al., 2007; Solomon et al., 2008), and many questions remain regarding the cognitive profile of this disorder.

**Rationale for Study**

Contexts requiring cognitive control typically have relatively high information processing demands, and the flexibility allowed by cognitive control facilitates interactions with complex environments in adaptive ways to attend to and process goal-relevant information, as well to switch attention and further processing to other salient aspects of the environment if necessary (Fan, 2014; Mackie et al., 2013). It is therefore informative to study disorders with impairments in flexible control (such as ASD) in order to understand how cognitive control deficits shape interactions with an uncertain world.
The goal of this study is to extend the information theory approach to parametrically manipulate information related to cognitive and affective control in ASD. The significance of this study lies in theoretical contributions to the conceptualization of deficits in ASD, and in providing a framework to examine cognitive control processes with a computational approach.

**Research Questions and Hypotheses**

This study is designed to investigate whether reduced efficiency and capacity of cognitive control underlie the symptoms of ASD, particularly under uncertainty conditions associated with social and emotional contexts.

The aims of the present study are:

I. To further investigate the efficiency and capacity of cognitive control in ASD relative to TD controls, in relation to symptom presentation.

II. To investigate the efficiency of affective information processing in ASD relative to TD controls, in relation to symptom presentation.

The specific hypotheses to be tested are:

I. Individuals with ASD have reduced efficiency and capacity of cognitive control relative to TD controls, and have greater difficulty than TD controls with cognitive control as uncertainty increases.
   a. Deficits in cognitive control are negatively correlated with ASD symptom report (i.e., lower performance associated with higher symptom report).

II. Individuals with ASD have greater difficulty than TD controls with affective information processing, as uncertainty increases.
a. Deficits in affective information processing are negatively correlated with ASD symptom report.
Chapter II

Literature Review

Autism was first described by Kanner (1943) as a specific impairment in “affective contact”. Wing & Gould (1979) initially described the classic ‘triad’ of deficits in social engagement, communication, and stereotyped behavior that commonly defined the disorder. The repetitive behavior symptom domain was later expanded to include well-documented extreme and intense interests, and as features of the disorder became better understood, so came the expansion of diagnostic features to incorporate them (American Psychiatric Association, 2000). With the new DSM-5 diagnostic criteria, the social and communication symptoms are now subsumed into one symptom cluster, and restricted interests/repetitive behavior (RI/RB) into the other (American Psychiatric Association, 2013), though the content validity of these clusters is not without debate (S. L. Bishop, Richler, & Lord, 2006; Lam, Bodfish, & Piven, 2008; Leekam, Prior, & Uljarevic, 2011; Szatmari, Tuff, Finlayson, & Bartolucci, 1990).

ASD symptoms arise within the first few years of life, and it is considered a lifelong disorder (Duncan & Bishop, 2013; Fein et al., 2013). Recently there has been increasing focus on how the profile of the disorder may change with development. For example, deficits that were severe in childhood, may resolve or improve by adulthood, but these individuals do often have difficulties that persist into adulthood, such as social deficits, executive dysfunction, odd thinking, attention problems, and the psychiatric symptoms of anxiety and depression (Anderson, Liang, & Lord, 2013; Billstedt, Gillberg, & Gillberg, 2005; Farley et al., 2009; Fein et al., 2013; Helt et al., 2008; McGovern &
Sigman, 2005; Mundy, 1993). Even within the context of normal intellectual functioning, these deficits are associated with limits on functional independence (Anderson et al., 2013; Bal, Kim, Cheong, & Lord, 2015; Billstedt et al., 2005; Howlin, Goode, Hutton, & Rutter, 2004; Piven, Harper, Palmer, & Arndt, 1996). There also appears to be neural correlates to the evolution of symptoms across the lifespan, at least into early adulthood (Courchesne, Campbell, & Solso, 2011; Dajani & Uddin, 2015). While there has been a preponderance of research on the cognitive profiles of children with ASD, the cognitive profile of adults with the disorder remains understudied.

Existing explanations for ASD symptoms and associated features

There have been several theoretical approaches to explain the symptom presentation of ASD, with focus on social (e.g., theory of mind) and/or non-social (e.g., executive function, central coherence, complex information processing) deficits. More recently, computational approaches based on Bayesian inference (i.e., predictive coding) have been proposed to explain the full range of deficits and features. The most influential and/or comprehensive theories to date are reviewed below.

Theory of Mind. The theory of mind (ToM) account of ASD (Baron-Cohen, Leslie, & Frith, 1985) was one of the early frameworks to be proposed and tested. ToM refers to the ability to attribute mental states to others that are separate from one’s own, and to be able to infer those mental states, given contextual cues (Premack & Woodruff, 1978). Given that social deficits are so prominent in ASD, it has been described as a disorder of “mind-blindness”, (Baron-Cohen et al., 1985). Support for this theory comes from studies that show deficits relative to controls on tasks of false belief (Baron-Cohen
et al., 1985; Leekam & Perner, 1991; Phillips, Gómez, Baron-Cohen, Laá, & Rivière, 1995), tasks that require mental inferences (i.e., mentalizing) (Baron-cohen, 1989; Baron-Cohen, Wheelwright, Spong, Scahill, & Lawson, 2001), tasks requiring non-literal interpretations of language (Happé, 1994; Jolliffe & Baron-Cohen, 1999; Wang, Lee, Sigman, & Dapretto, 2006), inferring mental states from the eye region only (Baron-Cohen, Jolliffe, Mortimore, & Robertson, 1997), and naturalistic, dynamic film clips (Dziobek et al., 2006; Golan, Baron-Cohen, & Hill, 2006; Heavey, Phillips, Baron-Cohen, & Rutter, 2000). ToM performance is negatively correlated with ASD symptoms (Lerner, Hutchins, & Prelock, 2011), and individuals who show intact ToM performance in childhood tend to have good communication skills as adolescents (Bennett, Ramasamy, & Honsberger, 2013).

In terms of specificity, ToM is one deficit that appears to differentiate ASD from other neurodevelopmental disorders, and mindblindness is a common and prominent deficit in this population (U. Frith & Happé, 1994), though it has been demonstrated to not be universal. For example, some adolescents and adults with ASD perform within norm on false belief (Happé, 1995), second-order false-belief tasks (Happé, 1994; Ozonoff, Rogers, & Pennington, 1991) and mentalizing tasks involving facial stimuli (Ponnet, Roeyers, Buysse, De Clercq, & Van Der Heyden, 2004; Roeyers, Buysse, Ponnet, & Pichal, 2001) and geometric cartoons (Castelli, Frith, Happé, & Frith, 2002). Children with ASD tend to perform poorly on mentalizing tasks, whereas adults usually show deficits on the more dynamic, naturalistic tasks (Roeyers & Demurie, 2010). Given
these inconsistent findings in mentalizing ability, the nature of and mechanisms underlying theory of mind deficits in this population remain unclear.

Overall, this theory suffers from a lack of precise definition of what is involved in mindblindness and the type of information that participants with ASD have difficulty processing. Evidence of intact functioning for some suggests that it is not perspective-taking \textit{per se} that is impaired, but rather perhaps the unconstrained nature of some of these tasks and uncertainty related to task demands may impact performance beyond the ability to infer mental states (S. J. White, Burgess, & Hill, 2009). For example, existing second- and higher-order mentalizing tasks rely on the processing of recursive language structures (e.g. “Mary knows that John thinks…”), in which the amount of information to be processed increases with each level of mental inference. As uncertainty increases within each level, it may become more challenging for individuals with ASD to perform efficiently on these tasks. Consequently, the “pass”/ “fail” criterion often applied to these tasks does little to inform about differences in the processing of this type and amount of information, regardless of whether the result is a correct response.

\textbf{Weak Central Coherence}. The weak central coherence theory conceptualizes deficits associated with ASD in terms of a bias toward processing of local stimulus features, combined with diminished ability to integrate information into coherent concepts (U. Frith & Happé, 1994). The authors propose that individuals with ASD show diminished performance on tasks require taking gestalt or context into account, but enhanced performance on tasks that benefit from enhanced local processing. Support for this theory comes from evidence of impairment on perceptual and semantic tasks that rely
on context, for example using the context of a sentence to determine which pronunciation of a word to use when reading out loud (Booth & Happé, 2010; U. Frith & Snowling, 1983; Happé, 1997; Jolliffe & Baron-Cohen, 1999; López & Leekam, 2003; Snowling & Frith, 1986), but superior performance in ASD on tasks such as the Embedded Figures Test (Jarrold, Gilchrist, & Bender, 2005; Keehn et al., 2009; Shah & Frith, 1983) and Block Design (Shah & Frith, 1993). This account explains not only the deficits observed in ASD, but also areas of superior performance (albeit achieved via abnormal processing; U. Frith & Happé, 1994). However, the theory has been challenged by studies reporting intact global processing in ASD samples (Mottron, Burack, Iarocci, Belleville, & Enns, 2003; Ozonoff, Strayer, McMahon, & Filloux, 1994).

This framework has undergone several modifications since its inception. For example, in light of contradictory evidence, the theory has moved away from a “deficit” account, to describe weak central coherence as a “cognitive style”, with the implication that there is not necessarily a deficit in global processing, but rather a bias, which can be overridden by top-down control (Happé, 1999). Others argued that the deficit lies in reduced ability to conceptualize similarities among multiple pieces of information (i.e., “generalize” (Plaisted, 2001)). Others have recast deficits in terms of difficulty processing hierarchical stimuli (Mottron & Burack, 2001; Mottron, Dawson, Soulières, Hubert, & Burack, 2006). It has been demonstrated that when specifically instructed to pay attention to global features, participants with ASD are able to do so. However, the processing difference appears to lie in the direction of interference: Whereas typically developing individuals experience interference when switching from global to local
processing, this effect is reversed in ASD (Rajendran & Mitchell, 2007). Overall, the weak central coherence theory is a compelling account to explain a limited number of features of this disorder. This theory has received less attention in recent years, but some newer, more computational approaches described below (i.e., predictive coding) incorporate this point of view into a larger, more comprehensive framework.

**Executive Dysfunction.** The origins of this theory are based on the observation that the clinical presentation of ASD shares characteristics with frontal lobe dysfunction (Damasio & Maurer, 1978), and subsequently, the executive dysfunction theory of autism was posited to account for the range of behaviors observed in individuals with this disorder that could not be explained by the ToM account (Hughes et al., 1994; Ozonoff, Pennington, et al., 1991). This account asserts that deficits in higher-level cognitive processes such as planning, working memory, inhibition, shifting, and flexibility underlie the symptom presentation of ASD, including ToM deficits (D. V. M. Bishop, 1993; Hill, 2004b; Hughes et al., 1994; Ozonoff, 1995; Pennington & Ozonoff, 1996). In particular, the RI/RB domain has been explained in terms of executive dysfunction in generativity (Turner, 1997). However, although many studies have aimed to clarify the nature of executive function deficits in ASD, results have been largely inconsistent and there is not yet a clear neuropsychological profile (Geurts et al., 2009; Van Eylen et al., 2011).

Initial evidence for the executive dysfunction account of ASD came from deficits on tasks such as the Wisconsin Card Sorting Test (WCST) (Ambery, Russell, Perry, Morris, & Murphy, 2006; Goldstein, Johnson, & Minshew, 2001; Hill, 2004a; Lopez et al., 2005; Minshew et al., 2000; Ozonoff, Pennington, et al., 1991; Pascualvaca, Fantie,
Papageorgiou, & Mirsky, 1998); Tower of London (ToL) (Hughes et al., 1994; Ozonoff & McEvoy, 1994; Robinson, Goddard, Dritschel, Wisley, & Howlin, 2009; Rumsey & Hamburger, 1990); Tower of Hanoi (Ozonoff & Jensen, 1999); Trail Making Test (TMT) (Goldstein et al., 2001; Ozonoff & McEvoy, 1994; Prior & Hoffman, 1990; Rumsey & Hamburger, 1990; Shu, Lung, Tien, & Chen, 2001; Szatmari et al., 1990); and Cambridge Neuropsychological Test Automated Battery (CANTAB) Intradimensional/Extradimensional Shift (Yerys et al., 2009). Intact performance has generally (though not always) been found on the Stroop (Goldstein et al., 2001; Kleinhans, Akshoomoff, & Delis, 2005) and Go/No-Go (Happé, Booth, Charlton, & Hughes, 2006; Schmitz et al., 2006) tasks in ASD. Further complicating the story, different studies have reported inconsistent results for the same tasks, in child, adolescent, and adult samples (Geurts et al., 2009).

In these studies, cognitive control is often equated with executive functions, creating conceptual confusion. Various studies have attempted to isolate specific executive functions (e.g., response inhibition, task-switching, working memory) to demonstrate deficits in cognitive control. However, many tasks (most notably the WCST, on which much of the evidence for cognitive inflexibility lies) suffer from the problem of task impurity (Hill, 2004a; Van Eylen et al., 2011), and generally the executive functions are difficult to dissociate completely (Mackie et al., 2013; Miyake et al., 2000). Conversely, conceptualizing cognitive control as a broader construct may be useful in terms of understanding group differences relevant to ASD.
**Complex Information Processing.** To explain findings that ASD participants are not impaired in all cognitive domains, the complex information processing theory was proposed (Minshew, Goldstein, & Siegel, 1997; Williams, Minshew, & Goldstein, 2015). This account asserts that intact performance can be expected on tasks that require basic perception and low-level cognition, but that deficits would emerge on more “complex” tasks. This account refers to complexity in terms of the roughly estimated demand on the brain’s information processing resources by the nature and quantity of information to be processed, including constraints on processing time (Williams, Goldstein, & Minshew, 2006). Support for this account comes from studies using a variety of common neuropsychological tests with ASD groups showing impairment on complex tasks of memory, language, concept formation, reasoning, and skilled motor movements but intact performance on simple tasks of attention, memory, language, learning, and visuospatial skills (Minshew et al., 1997; Williams et al., 2006). However, within this framework, the distinction between “simple” and “complex” was made between different tasks assumed to have different information processing demands, rather than within-task complexity manipulations (Minshew et al., 1997), and it is unclear to what extent confounding factors were held constant for these comparisons.

Other support for the idea of an information-processing deficit comes from studies reporting deficits in ASD when information processing is challenged by the nature or parameters of the task. For example, whereas Go/No-Go performance has been shown to be generally intact in ASD, performance is impaired at a fast presentation rate (Raymaekers, Van Der Meere, & Roeyers, 2004). Similarly, others have asserted that
individuals with ASD have a more limited capacity for information processing, and consequently develop a cognitive style that is avoidant of higher-level processing and over-dependent on processing of lower-level features in order to avoid information overload (Belmonte et al., 2004; Burack, 1994). This information processing bottleneck is proposed to arise due to heightened arousal to sensory stimuli in concert with reduced target specificity in ASD (Belmonte et al., 2004).

Overall, it is clear that there is a difference in information processing in ASD compared to typically developing controls. However, this approach is lacking a precise definition of complexity that would facilitate an understanding of what aspect of the information is difficult for this population to manage. The distinction between “simple” and “complex” tasks is too rough to be meaningful.

**Predictive Coding Accounts.** Within the predictive coding framework, perception consists of hypothesis-testing of expectations within the context of Bayesian inference about the causes of sensory information (Feldman & Friston, 2010; see also Pellicano & Burr, 2012). Top-down predictions are compared to bottom-up sensory input, and a mismatch between these is known as a “prediction error”. Prediction errors are useful to learning, because they indicate to the organism that what has occurred is informative, and this information is fed back upstream to update existing representations to allow for better future predictions (Feldman & Friston, 2010). Prediction errors can lead to “precision”, by which sensory signals of interest are augmented in order to reduce uncertainty about the state of the world.
The first application of this framework to ASD (Friston, Lawson, & Frith, 2013; Lawson, Rees, & Friston, 2014) described the disorder as associated with attenuation of high-level precision, and augmentation of low-level (sensory) precision, to account for hyperfocus on low-level stimulus features (Lawson et al., 2014). Similarly, the High Inflexible Precision of Prediction Errors in Autism (HIPPEA) account (de Cruys et al., 2014) asserts that whereas typically developing individuals can effectively and flexibly distinguish between prediction errors that matter (reducible uncertainty) and those that don’t (irreducible uncertainty), this mechanism of weighting prediction errors is abnormal in ASD, leading to too much weight being placed on all prediction errors, with over-allocation of attention to irrelevant information. This results in inflexibility and abnormal processing that interferes with the ability to generalize learning to other situations.

Also within realm of Bayesian inference, the new predictive impairment in autism account (PIA) asserts that deficits in estimating conditional probabilities of events can explain many features of ASD (Sinha et al., 2014). In this model, the strength of associations and the time that lapses between events determines whether a relationship can be detected. This model comprehensively accounts for RI/RB, sensory hypersensitivity, failures of ToM, and savant abilities. For example, RI/RB is proposed to arise under conditions unpredictability, which are anxiety-provoking, and the behaviors are engaged as a coping mechanism. In this context, ToM is especially vulnerable to failure, as it requires deduction about causes of behaviors and prediction about what someone will do next based on an estimation of conditional probability with weak
associations. Islets of ability are framed in terms of being strongly rule-based, low in uncertainty (e.g., mathematics, music), increasing the likelihood of successful performance in ASD.

Overall, these Bayesian accounts of ASD have advanced the conceptualization of the disorder to a level that is more computational, comprehensive, with specifically testable hypotheses and predictions. Each of these accounts casts ASD symptoms as related to uncertainty management, at the level of differences between predicted and observed sensory information. However, empirical data to support these theories have not yet been published.

Summary. While there has been progress in terms of conceptualizing ASD deficits within a comprehensive framework, the contribution of information processing deficits to the presentation is still not well understood. It is clear that individuals with ASD interact with the world in a way that is markedly different from those who are typically developing, and empirical evidence to date suggests the presence of an inefficient processing style that contributes to cognitive and behavioral difficulties. The weak central coherence and theory of mind accounts are limited, and do not explain a sufficient range of deficits. The executive dysfunction theory is rife with inconsistent findings due to vast differences in tasks across studies, and the problem of task impurity. The definition of “information” within the complex information processing account is imprecise, and between-task comparisons of complexity make it difficult to determine where the “complexity” lies. The newer theories based on predictive coding present precise, comprehensive frameworks, with specific predictions for a wide range of
deficits, but evidence to support these theories is still lacking. Existing studies have not employed quantitative definitions of information or parametric within-task manipulations of cognitive load to investigate the effects of the nature or “amount” of information on information processing deficits in ASD. Parametric manipulations of information, quantified in computational units such as ‘bits’ would result in clearer comparisons between conditions in terms of how much information the cognitive control system is able to efficiently manage.

**An information theory account of cognitive control**

Information theory is concerned with the communication of information under uncertainty, with signals being transmitted from a source to a receiver across a noisy channel with limited capacity (Shannon, 1948). This framework provides a new perspective to the study of cognitive control in ASD, and complements predictive coding accounts described above. Here, cognitive control is a limited-capacity integrative interface between input and response that dynamically facilitates the processing of information by prioritizing the transfer of relevant information and suppressing the transfer of irrelevant information to further processing stages (Fan, 2014).

In a recent publication we proposed an information theory model of cognitive control in which it is engaged for uncertainty processing and the prioritization of task-relevant information for adaptive behavior (Mackie et al., 2013). From this perspective, uncertainty is conceptualized in terms of Shannon *surprise* and *entropy*, which are tied to probability of the occurrence of events (Shannon, 1948). These metrics, in units of ‘bits’ quantify the minimum amount of information that must be stored or transferred, in order
to make a judgment about the nature of an event. A ‘bit’ is a binary unit that is the basic
unit of information storage and transfer, and refers to the “amount” information under
consideration. The information transfer rate (the average amount of information
transmitted per unit time in bits per second) is related to the capacity of the channel.

*Surprise* refers to information contained in the occurrence of a certain type of
event, and is defined as: \[ I(x_i) = -\log_2 p(x_i), \]
where \( p(x_i) \) is the probability of the
occurrence of event \( x_i \). The base 2 log transformation results in information quantified in
units of bits. A low-probability event is associated with a high *surprise* value, and vice
versa. For example, in a sequence set that predominantly requires ‘left’ responses (e.g.,
87.5% left, 12.5% right), a stimulus requiring a ‘right’ response, would carry a higher
*surprise* value (3 bits) than the ‘left’ response (0.19 bits). *Entropy*, on the other hand, is
the information contained in a sequence of events, and is defined as:

\[ H(X) = E(I(X)) = \sum_{i=1}^{n} p(x_i) \log_2 p(x_i). \]

*Entropy* is therefore the weighted average of
*surprise* over all types of events. For a predictable sequence, *entropy* is low. For example,
in the sequence mentioned above, the entropy is 0.54 bits, with a very high probability of
a ‘left’ response event. For this scenario, entropy would be highest (1 bit) when ‘left’ and
‘right’ responses are equally probable (i.e., 50% left, 50% right; see Fan, 2014 for a
review) and events are less predictable. To summarize, the *entropy* expressed in bits is
the minimum amount of information one would need to process in order to respond to
this series of events with continuous probabilities.
Cognitive control is known to be a limited-capacity function (Posner & Snyder, 1975), and under circumstances in which the required rate of information transfer exceeds that of the channel capacity, there would be a breakdown in channel efficiency and increase in error, leading to diminished performance (Fan, 2014). Increased entropy is associated with a linear increase in RT, reflective of Hick’s law (Hick, 1952), and greater recruitment of the brain systems involved in uncertainty reduction (Fan, 2014). This increased processing time is not only a function of the number of stimuli to be processed, but rather how much information needs to be processed in the brain using certain mental algorithms that manage uncertainty. This is illustrated in the majority function task (Fan, Guise, Liu, & Wang, 2008), wherein participants must respond to the majority direction of a group of arrows. When set size is constant, RT differences occur between conditions with varying levels of directional congruence, and consequently, the stimuli carry different amounts of information (Fan et al., 2008; Mackie et al., 2013). In other tasks, including a task switch condition, presenting different types of stimuli on each trial, increasing the number of response alternatives, and increasing the required processing rate all increase the amount of information uncertainty involved in the task. Consequently, two tasks purporting to measure the same cognitive functions, may actually be manipulating entropy at different levels through differences in stimulus and response presentation.

**Application of information theory to existing tasks examining cognitive control in ASD.** Cognitive control is typically examined by way of tasks that manipulate conflict between stimulus dimensions or responses such as Stroop (Stroop, 1935) and
flanker (Eriksen & Eriksen, 1974) tasks. In these cases, cognitive control is involved to facilitate the constraint of the prepotent response that is inconsistent with task demands. From an information theory perspective, the conflict effect can be conceptualized as resulting from an increase in uncertainty from the congruent condition (only one possible stimulus-response representation) to the incongruent condition (two possible stimulus-response representations), corresponding to an entropy increase of 1 bit (base 2 log of 2 possibilities) between conditions. Increased RT (and decreased accuracy) is typically observed in the incongruent condition compared to the congruent condition, corresponding to an approximately 100 ms difference (Fan, 2014). In a recent study, a group of ASD adults performed significantly less accurately at a flanker task compared to typically developing adults, although there was a similar increase in RT for the incongruent condition (Fan et al., 2012).

Comparably, tasks that rely on response to infrequent occurrences, such as oddball and Go/No-Go tasks can also be understood in terms of uncertainty increases between conditions. In an oddball task, the low frequency oddball event, by definition has a high surprise value. In a Go/No-Go task, the No-Go trials (20%) are far less frequent than Go trials (80%), carrying a relatively high surprise value (~2.32 bits) compared to Go trials (~0.32 bits). Additionally, when the processing rate is increased on this task, the performance of participants with ASD declines (Raymaekers et al., 2004).

Task switching paradigms, to which participants with ASD have been shown to be particularly susceptible (Bogte et al., 2008; Geurts et al., 2009; Van Eylen et al., 2011), are associated with a performance cost due to a channel switch, and the relative
infrequency of ‘switch’ trials, relative to ‘stay’ trials. Some such tasks include random alternation of ‘switch’ and ‘stay’, which would represent the maximum entropy value, due to the equal likelihood of both trial types. Furthermore, channel switching (one task to the next) is associated with a performance cost (Fan, 2014). Task-switching paradigms often use unpredictable switches as a measure of cognitive flexibility (e.g., de Vries & Geurts, 2012), and find larger switch costs in ASD groups (Maes, Eling, Wezenberg, Vissers, & Kan, 2011; Yerys et al., 2009). However, it has also been noted that children with ASD do not show impairment when the switch is predictable (Stahl & Pry, 2002).

The Wisconsin Card Sorting Test, commonly applied to the study of cognitive flexibility in ASD (Van Eylen et al., 2011), involves sorting cards to one of four piles ($\log_2(4) = 2$ bits of information), according to rules the participant must infer based on feedback about whether a previous trial was correct or incorrect. There are three stimulus dimensions ($\log_2(3) = 1.58$ bits of information) on which the sort rule can be based, resulting in a minimum of 3.58 bits (uncertainty about piles + uncertainty about dimensions) of information on every trial until the participant infers the rule, at which point the information is reduced to 2 bits (uncertainty about piles only) for each trial on which the participant infers that the rule remains the same. After ten consecutive correct sorts, the rule changes to another one of the three stimulus dimensions, resulting in an increase of information to 3.58 bits plus the information contained in the channel switch (at least 1 bit), for a minimum of 4.58 bits on switch trials. It is unsurprising that this high-entropy task results in deficient performance in participants with ASD (Geurts,
Verté, Oosterlaan, Roeyers, & Sergeant, 2004; Kaland, Smith, & Mortensen, 2008; Minshew et al., 2000).

For many neuropsychology tasks used to investigate the cognitive profile of ASD, it is difficult to estimate the behavioral effects of entropy due to the nature of responses required. For example accumulated evidence of deficits for “complex” information (Williams et al., 2015) includes tasks that are high in uncertainty, such as non-literal language and semantic judgments with multiple representations and tasks involving channel switching, such as Trails B. The use of a computational approach to quantify the amount of information to be processed would likely be a better indicator of complexity, and is possible within an information theory framework (discussed below).

**ASD symptoms can be explained by inefficient cognitive control.** Uncertainty is present by definition in variables, which take on more than one value. As the number of possible outcomes increases, so does the uncertainty associated with that variable. The presence of uncertainty indicates the need for cognitive control to facilitate information processing and prioritization of information for further computation (Fan, 2014; Mackie et al., 2013; Mushtaq, Bland, & Schaefer, 2011). Efficient functionality depends on the ability to process uncertainty in order to formulate appropriate thoughts or actions, based on the information available. Cognitive control processes may include either uncertainty reduction, to infer the value of a variable at a given time, or uncertainty inflation, to allow for generalization to other contexts. These processes work in concert to allow for adaptive behavior across various situations. If cognitive control is less efficient in ASD,
dynamically dealing with uncertainty should therefore be problematic, contributing to the clinical presentation of the disorder.

**Social-communication deficits.** The domain of social communication requires cognitive control for the efficient allocation of brain resources in constraining information to be processed, and to avoid information processing overload under incredibly uncertain conditions (Gomot & Wicker, 2012). According to uncertainty reduction theory (based upon information theory, Berger & Calabrese, 1975), people undertake several steps to reduce uncertainty in social situations. For example, theory of mind requires using information from the verbal and nonverbal communication of others in the context of situational cues to form an inference about the person’s mental state. Variables related to the causes of mental states and the mental and emotional effects of situational causes notoriously have one-to-many (and vice versa) mappings that also vary depending on the individual. In communication, there is uncertainty inherent in semantic ambiguity associated with false belief tasks, irony, sarcasm, and other non-literal interpretations of language (e.g., Jolliffe & Baron-Cohen, 1999). The reduction of multiple pieces of (sometimes conflicting) information into a ‘gist’ concept bears heavily on our ability to interact with others according to the emotional states that they convey (related to the idea of weak central coherence, Cashin, Gallagher, Newman, & Hughes, 2012). Reciprocal communication, which is clearly deficient in this population (C. D. Frith & Frith, 2012), requires rapid information processing, idea generation and response, as well as ongoing processing of non-verbal information. Therefore, successful social behavior requires flexible adaptation to variable social contexts (Cañadas, Rodríguez-
Bailón, Milliken, & Lupiáñez, 2013; Cashin et al., 2012; Dichter & Belger, 2008; Happé & Frith, 2006; Kenworthy, Case, Harms, Martin, & Wallace, 2010). Lower efficiency of cognitive control, combined with a reduced upper limit of information processing capacity, may negatively impact the cognitive flexibility required for smooth social interaction in dynamic contexts, and therefore set the stage for the emergence of social and communicative deficits (Mackie & Fan, 2015).

The processing of emotional information in social situations presents a special challenge to individuals with ASD, who are deficient in recognizing the emotional component of a social stimulus (Adolphs, Sears, & Piven, 2001; Boraston, Blakemore, Chilvers, & Skuse, 2007; Castelli, 2005; Dalton et al., 2005; Dawson et al., 2004; Hadjikhani, Joseph, Snyder, & Tager-Flusberg, 2007). Theory of mind deficits have been argued to be strongly related to emotion processing, and information about the thoughts and feelings of others come from social interactions (Cashin, 2005). In studies of emotional processing, there are often ceiling effects for emotion recognition tasks, or failure to find differences between ASD and typically developing groups (Adolphs et al., 2001; Baron-Cohen et al., 1997; Cassidy, Ropar, Mitchell, & Chapman, 2013; Spezio, Adolphs, Hurley, & Piven, 2007). However, group differences are found for more nuanced stimuli that are dynamic, or show emotions of lower intensity (Baron-Cohen et al., 1997; Baron-Cohen, Wheelwright, Spong, et al., 2001; Golan et al., 2006; Roeyers et al., 2001).

Inconsistencies on tests of emotion recognition suggest that the deficit is not in emotion recognition per se may be explained by differences in response structure. For
example, in forced-choice tasks, the number of alternatives available impacts the amount of uncertainty, consistent with the relationship between uncertainty and number of possible responses. In this sense, performance on a task that presents only two choices may be better than on a task with five choices, even though the stimulus is the same, due to increased uncertainty associated with the response. Furthermore, emotion recognition depends on use of information provided by combinations of facial action units that represent an emotion. However, some these individual action units are not emotion-specific and are shared across different emotional expressions resulting in increased uncertainty, particularly as it relates to compound and complex emotional expressions (Du, Tao, & Martinez, 2014). In summary, difficulty with uncertainty processing can thus account for deficits in social communication, including emotion processing, theory of mind, and verbal and nonverbal communication.

**Restricted Interests/Repetitive Behaviors.** Uncertainty is a relatively aversive state (Hirsh, Mar, & Peterson, 2012) and this may be amplified in those with impaired cognitive control. “Intolerance of uncertainty” has been shown to be strongly related to anxiety disorders (Carleton, 2012; Carleton et al., 2012; Dugas, Gagnon, Ladouceur, & Freeston, 1998), which are also highly comorbid with ASD (S. W. White, Oswald, Ollendick, & Scahill, 2009; Wood & Gadow, 2010). The symptom domain of restricted interests/repetitive behaviors may thus be reflective of an attempt to avoid uncertainty by restricting interests and activities to a confined, predictable set (Baron-Cohen, Ashwin, Ashwin, Tavassoli, & Chakrabarti, 2009). It has been also proposed that repetitive behaviors may be used as a calming coping mechanism in uncertain, anxiety-provoking
situations (Gillott, Furniss, & Walter, 2001; Happé & Ronald, 2008; Sinha et al., 2014; Turner, 1997). Both may serve as a protective mechanism (conscious or unconscious) to avoid the subjective frustration associated with information overload (Hutt, Hutt, Lee, & Ounsted, 1965; Markram, Rinaldi, & Markram, 2007; O’Connor & Kirk, 2008; Valla & Belmonte, 2013). Furthermore, deficits in the domain of restricted interests and repetitive behaviors may serve to compensate for a diminished cognitive control capacity. By restricting interests to predictable sequences and familiar domains, individuals with ASD are able to avoid cognitive control overload.

**Brain correlates of cognitive control**

The frontoparietal network, with the anterior cingulate (ACC) and anterior insular (AIC) cortices as core regions, in addition to activation in other regions such as the frontal eye fields and areas near or along the intraparietal sulcus, is typically associated with tasks of cognitive control (Fan, 2014). It has been specifically proposed that dysfunction in structures containing von economo neurons (such as ACC and AI) result in impaired cognitive control for uncertainty reduction in ASD, resulting in a diminished ability to quickly respond in dynamic situations, with reliance instead on a slower, rule-based method in social situations (Allman, Watson, Tetreault, & Hakeem, 2005). This deficit in cognitive control feeds into other high-level systems such as ToM, and social behavior producing further deficits, but is also observable in non-social tasks (Allman et al., 2005).

We have demonstrated an absence of activation of the ACC in ASD during conflict processing (Fan et al., 2012). The ACC is involved in baseline state uncertainty
monitoring, and abnormal recruitment of this crucial network hub could underlie the inefficient performance demonstrated in our experiments (Fan et al., 2014). In addition to region-specific neural differences, there is also evidence for differences in connectivity within the frontoparietal network in ASD, resulting in inefficient information transfer between anterior and posterior areas (Belmonte et al., 2004; Just, Cherkassky, Keller, & Minshew, 2004; Just, Keller, Malave, Kana, & Varma, 2012; Kana, Keller, Cherkassky, Minshew, & Just, 2006), related to symptom presentation (Uddin et al., 2014). In information theory terms, this disturbance in functional connectivity has been described as lower information “bandwidth” or data transfer rate within the cognitive control neural network in ASD relative to healthy controls (Just et al., 2004, 2012).

**Advantages of the information theory approach**

Applying information theory to the study of cognitive control under uncertainty in ASD provides a new, explicitly computational approach to understanding the mechanisms underlying social and non-social deficits in ASD. It is widely accepted that a major function of the brain is “information processing”, but to date, this concept has remained vague and elusive. The inconclusive search for a neuropsychological profile of ASD may be because this is not a ‘focal’ disorder, but rather a systems-level disorder in the brain networks that are involved in cognitive control. The information theory approach allows for the quantification of the amount of information that individuals need to (and can) efficiently process under various conditions. The development of tasks with systematic and parametric manipulations of information entropy within-task allows us to investigate the efficiency and capacity of cognitive control both in healthy controls and
various patient populations, as well as the brain systems involved. Application of this model to ASD has provided some insight into the nature of information processing deficits in this population, although to this point, only within the context of non-social information.

An explanatory theory must be able to provide a full causal account of the disorder (U. Frith & Happé, 1994). Thus far, approaches attributing ASD to deficits in a single domain have been largely unsuccessful at explaining all aspects of the disorder. It is also likely that the best account of ASD may be a multiple-deficit account (Rajendran & Mitchell, 2007). Within the information theory approach, it remains unclear to what extent it accounts for information processing at lower levels (i.e., primary sensation) for which there are well-documented group differences. Currently, the more specific predictive coding accounts are better able to account for sensory-level abnormalities. Furthermore, like executive dysfunction, cognitive control deficits are not specific to ASD. However, this information theory approach makes it possible to quantify upper limits of information processing under time constraints in different cognitive domains, which may characterize the ASD from other disorders. This approach may also be able to explain savant skills beyond what has been previously proposed in predictive coding theories, by examining the uncertainty of the information. The idea that the subject areas for which such skills are demonstrated comprise highly rule-based information with low uncertainty (and usually only one possible outcome) is consistent with the information theory approach.
Reconciling the information theory and predictive coding accounts of ASD. 

The information theory and predictive coding accounts of uncertainty are similar, with some overlapping predictions for both healthy controls and as applied to ASD. Both accounts consider the involvement of high-level brain systems (rather than structures) in uncertainty management. For example, both approaches have proposed that uncertainty reduction is achieved via brain structures underlying attentional functions, notably the frontoparietal network (Fan, 2014; Feldman & Friston, 2010; Mackie et al., 2013). However, while the predictive coding account is concerned with what follows the detection of a prediction error (i.e., “precision”), the information theory account is more concerned with questions about information processing efficiency and capacity, and the precise quantification of information.

These accounts are reconciled in considering that precision is related to the probability of making a choice, and that high precision serves to reduce uncertainty by placing greater weight on task-relevant information, relative to competing noise. In this way, optimizing precision allows for brain systems to minimize “free energy” or the amount of prediction error (Friston, 2010), which bounds the limits of surprise in the system. It has been argued that individuals are not able to directly estimate surprise (as they do not know all the possible states of the world) but can avoid surprising situations by attempting to minimize free energy, which has a value that is always greater than surprise (Friston, 2010).

Context for the present study
We aimed to demonstrate that individuals with ASD have a generally lower efficiency of cognitive control under uncertainty, with a reduced capacity under time constraints, compared to controls. We further proposed that these cognitive deficits also contribute to deficits in affective and social contexts that require processing of complex emotional states and recursive theory of mind inferences, which map more representatively onto the established symptom domains. To improve upon previous investigations of emotion processing deficits in ASD, an information theory approach will allow for a parametric manipulation of uncertainty about emotional states, and the quantification of uncertainty inherent in higher-order recursive theory of mind and intentionality. A finding that individuals with ASD are less efficient than typically developing controls in emotion processing and mentalizing under increasingly uncertain conditions would support this account. Furthermore, a significant correlation between cognitive control capacity and efficiency and performance on social-emotional tasks would support the idea that cognitive control deficits contribute to deficits in social and emotional processing in ASD.
Chapter III

Investigation of Cognitive Control Deficits in ASD

We propose that individuals with ASD have a reduced efficiency and capacity for cognitive control under conditions of uncertainty, and that these deficits are related to ASD symptom presentation. To test this hypothesis, we developed a series of cognitive control tasks that parametrically manipulate uncertainty and information processing rate.

Method

Participants

Fifteen adult participants diagnosed with ASD and fifteen typically developing (TD), right-handed, control participants between the ages of 18-43 were matched with ASD participants on average full scale intelligence quotient (IQ), age, and gender.

Table 1

Demographic and questionnaire data (range) of ASD and TD groups.

<table>
<thead>
<tr>
<th>Participant characteristics</th>
<th>ASD (n = 15)</th>
<th>TD (n = 15)</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>26.0 (18 - 42)</td>
<td>27.6 (19 - 43)</td>
<td>-.59</td>
<td>.56</td>
</tr>
<tr>
<td>Full Scale IQ</td>
<td>110 (87- 143)</td>
<td>115 (96 - 132)</td>
<td>-.87</td>
<td>.39</td>
</tr>
<tr>
<td>ASD diagnosis</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ADI-R

Social                        | 18.8 (1 - 28) |
Verbal communication           | 15.7 (8 - 22) |
Repetitive behavior            | 5.9 (1 - 12)  |
Development                    | 2.9 (0 - 5)   |

ADOS-G (n = 14)

Communication + Social         | 9.7 (5 - 16)  |
Restricted and repetitive behaviors | 1.4 (0 - 4)  |
Total                          | 12.1 (8 - 18) |

Note: 1n = 14 ASD, 13 TD;
Participants with ASD were diagnosed by trained clinicians at the Seaver Autism Center of the Icahn School of Medicine at Mount Sinai (ISMMS), according to the *Diagnostic and Statistical Manual of Mental Disorders*, fifth edition (DSM-5). Diagnoses were confirmed by the Autism Diagnostic Interview – Revised (Lord, Rutter, & Couteur, 1994) and Autism Diagnostic Observation Schedule – Generic (Lord et al., 2000). IQ scores were obtained using the Wechsler Abbreviated Scale of Intelligence, second edition (WASI-II; Wechsler & Hsiao-pin, 2011). All participants had full scale IQ scores > 70, i.e., no intellectual disability. Because all participants were high-functioning and verbal, it was not necessary to match on nonverbal IQ. Independent samples t-tests were used to confirm that the groups did not differ on age or IQ.

Exclusion criteria include history of epilepsy, a lifetime history of substance/alcohol abuse or dependence, or schizophrenia. Additional exclusion criteria include history of encephalitis, phenylketonuria, tuberous sclerosis, fragile X syndrome, anoxia during birth, neurofibromatosis, hypomelanosis of Ito, hypothyroidism, Duchenne muscular dystrophy, and maternal rubella. Participants were also excluded for history of head injury with loss of consciousness or other neurological disorders. TD participants were screened for developmental disorders and psychiatric disorders and were also excluded based on systemic medical or neurological disorders.

**Protection of Human Subjects.** All participants provided written informed consent, approved by the Institutional Review Boards of QC and ISMMS. All data were participant coded and identifying information was kept separately in a locked cabinet in a secure location.
Recruitment. ASD participants were recruited from the Seaver Autism Center at ISMMS, Interactive Autism Network (IAN), and from the greater New York City area through advertisements placed in community publications. Control participants were recruited from the Seaver Center’s matched control pool, or via flyers posted at Queens College and ISMMS and ISMMS Department of Psychiatry email listserv advertisements.

Screening Materials and Questionnaires

Autism Diagnostic Interview – Revised (ADI-R). The ADI-R is a semi-structured diagnostic interview for caregivers of children and adults for whom autism may be a possible diagnosis (Lord, Rutter, & Le Couteur, 1994) and is a gold standard diagnostic instrument for ASD. Items cover the domains of communication, social development and play, repetitive and restrictive behaviors, and general behavioral problems, and are meant to capture caregiver descriptions of the actual behavior of the subject as it has occurred in daily life. The instrument is scored on an ordinal scale from 0 (“no definite behavior of the type specified”) to 2 (“definite abnormal behavior of the type described in the definition and coding”), with an occasional code of 3 to indicate extreme severity. Each item is scored for current behavior, except for behaviors that are restricted to particular developmental periods (e.g., “imaginative play”). A diagnosis of ASD is determined when scores exceed cutoff scores in each domain. The cutoff is 8 for verbal individuals in the communication domain, 10 for social items, and 3 for restricted interests and repetitive behaviors. This instrument demonstrates adequate reliability ($\kappa = .62 – .89$) and internal consistency ($\alpha = .69 – .95$ for domain subscales) (Lord et al.,
The measure also has good sensitivity and specificity with receiver operating characteristics curve discriminability values (area under the curve) of .77 - .84 for the clinical classification of ASD vs. non-ASD (De Bildt et al., 2013).

**Autism Diagnostic Observation Schedule – Generic (ADOS-G).** The ADOS-G is a semi-structured, standardized assessment of the domains of social interaction, communication, and imagination for individuals who may have ASD (Lord et al., 2000). ADOS-G items are scored on a 3-point ordinal scale from 0 (“no evidence of abnormality related to autism) to 2 (“definite evidence”). Some items may be coded as 3 to indicate severe abnormality that interfered with observation. ADOS-G classifications of ASD are given when each of the respective three thresholds are met or exceeded (social = 4; communication = 2; and social + communication = 7). Because the ADOS-G is limited to a small window of time, restricted and repetitive behaviors are not assessed, although recorded if present. This measure shows good internal consistency (α = .91 – .94 for social + communication), and good inter-rater reliability (r = .82 – 93), but test-retest reliability is questionable (r = .59 - .82), though generally higher for the social and communication subscales relative to the restricted and repetitive behavior subscale. Receiver operating characteristic curves show sensitivity of .90 and specificity of .93 for ASD vs. non-ASD comparisons (Lord et al., 2000).

**Autism Quotient (AQ).** The AQ is a 50-item self-report questionnaire assessing social skills, attention switching, attention to detail, communication, and imagination (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001). This measure is scored on a 4-point Likert scale from “definitely agree” to “definitely disagree”, and scores can
be collapsed into two categories ("agree" and "disagree"). Test re-test reliability is adequate ($r = .70$), inter-item consistency is marginally adequate ($\alpha = .63 - .77$). Recommended cutoff of $> 32$ has sensitivity of $.95$ and specificity of $0.52$ for ASD vs. non-ASD comparisons (Woodbury-Smith, Robinson, Wheelwright & Baron-Cohen, 2005).

**Structured Clinical Interview for DSM-IV (SCID-IV).** The SCID-IV is a semi-structured clinician-administered interview for making DSM-IV Axis I diagnoses, including modules on mood, anxiety, psychotic, substance use, somatoform, eating, and adjustment disorders (First, Spitzer, Gibbon, & Williams, 1998). Inter-rater reliability is adequate ($\kappa = .61 - .83$). Information about sensitivity and specificity is not available.

**Social Responsiveness Scale - 2 (SRS-2).** The SRS-2 (Constantino & Gruber 2012) is a 65-item, self-report, ordinal-scale measure (1 = “not true” to 4 = “almost always true”) that measures the severity of autism traits in the domains of Social Awareness, Social Cognition, Social Communication, Social Motivation, and Autistic Mannerisms. Internal consistency is good ($\alpha = .95$), strong test-retest reliability ($r = .88 - .95$) and inter-rater reliability ($r = .61 - .92$)(Bruni, 2014). Responses are converted to normative $T$ scores. Total Scores of $T > 75$ are indicative of potential ASD, with specificity of $.60$ and sensitivity of $.86$ for ASD vs. non-ASD comparisons (Mandell et al., 2012).

**Wechsler Abbreviated Scale of Intelligence-2 (WASI-2).** The WASI-II (Wechsler & Hsiao-pin, 2011) is a brief measure of cognitive ability used to estimate full scale intelligence quotient (FSIQ), comprised of a verbal comprehension index score
(crystallized abilities), and a perceptual reasoning index score (fluid abilities). This measure has good test-retest reliability ($r = .90 - .97$), and subtests and index scores can distinguish between mild intellectual disability and matched controls.

Cognitive Control Tasks

**Entropy Variation Task (EVT).** The EVT examines the baseline cognitive control performance effect of both entropy ($H$) and surprise ($I$) in a single task for sequential information processing. Left- or right-pointing arrows appear randomly at one of eight possible locations arranged around a central fixation cross (Figure 1). Following a 0 to 500 milliseconds (ms) randomly varied fixation interval on each trial, the target arrow appears for 1500 ms, followed by a variable post-target fixation period, with a total trial time of 3000 ms. Participants must indicate the direction of the target arrow. This is a single-trial and block mixed design. For each block type, entropy has different values, 

![Figure 1. Schematic of Entropy Variation Task](image)
with manipulation of the probability of left-pointing arrows (p), or right-pointing arrows (q), and therefore surprise for each trial type has different values. There are four block types: 1) arrows point in a single direction throughout the entire sequence (\(H = 0\) bits; \(p/q = 0\) or 1; \(I = 0\) bits); 2) alternating sequence of left- and right-pointing arrows, e.g. “LRLRLR…” and vice versa (\(H = 0\) bits; \(p = 1\); \(q=1\); \(I = 0\) bits); 3) arrows point in one direction more frequently than the other (\(H = 0.54\) bits; \(p/q = 0.125\), \(I = 3\) bits or \(p/q = 0.825\), \(I = 0.19\) bits); and 4) randomly presented left- and right-pointing arrows with equal probability (\(H = 1\) bits; \(p = q = 0.5\); \(I = 1\) bits). Therefore, entropy is manipulated on three sequence levels (0, 0.54, and 1 bit) and surprise on four event type levels (0, 0.19, 1, and 3 bits). There are 8 runs, with 4 blocks each (Latin square counterbalanced), each block has 32 trials, for a total of 1024 trials. Each run lasts approximately 6 minutes, beginning and ending with a 30 s fixation period, with 5 s fixation periods between each block. Total task time is approximately 50 minutes.

**Majority Function Task (MFT).** The MFT systematically manipulates uncertainty with computational load (estimated as information entropy) over a wide range to capture the effects of cognitive control for each target event, independent of the sequence (Fan et al., 2014; Fan, Guise, Liu, & Wang, 2008; Wang, Liu, & Fan, 2011). In this task, groups of arrows (set sizes 1, 3 or 5, corresponding to 3 types of blocks) are randomly presented at 8 possible locations arranged around a central fixation cross (Figure 2). The arrows are presented simultaneously, pointing either left or right, and participants must indicate the direction in which the majority of arrows point. There are six conditions, indicating the ratios of arrows pointing in the same direction to arrows
pointing in the opposite direction: 1:0 for set size 1; 3:0 and 2:1 for set size 3; and 5:0, 4:1, and 3:2 for set size 5. Trials begin with a variable fixation period of 0 to 1000 ms. Stimuli are then presented for 2500 ms, followed by a variable 1500 to 2500 ms post-stimulus fixation period. Each trial lasts 5 seconds. There are six runs with six blocks each (two for each set size), each block has 12 trials with the same set size, and each run has 72 trials, lasting 395 s. There are 5 s fixation periods at the beginning and end of each run, as well as 10 s between blocks in each run. The order of the blocks is counterbalanced with reversed repetition for each run. Total trial number is 432, with a total time of approximately 40 minutes. Previous algorithmic and computational modeling analyses of MFT performance revealed estimated computational loads for the six conditions are 1.00, 2.00, 3.58, 2.58, 3.91, and 5.91 bits, respectively, including an

Figure 2. Sample stimuli in the Majority Function Task
additive 1 bit for the response (Fan et al., 2008; Wang et al., 2011).

**Dual Conflict Task (DCT).** This task examines the impact of the bottleneck of cognitive control capacity by manipulating both conflict processing and time constraints. On each trial, following a 0 to 500 ms randomly varied fixation interval, two tasks (Task 1 and Task 2) are presented sequentially for 750 ms each with a variable Task 1 to Task 2 stimulus onset asynchrony (SOA) of 100 and 1000 ms (Figure 3). The 750 ms task duration is used to avoid the attentional blink effect, which would interfere with detection of the second target if a shorter (e.g., 500 ms) duration were used. For Task 1, the stimulus is presented in one of two locations, aligned vertically, either above or below the central fixation cross, and consists of a central target arrow, flanked by 4 direction-congruent or incongruent arrows (2 on each side), pointing either up or down. For Task 2, the stimulus is presented either to the left or right of the central fixation cross and similarly includes a central target arrow flanked by 4 direction-congruent or incongruent arrows, pointing either left or right. Task 2 is followed by a variable post-target fixation (2000 – 2500 ms), with total trial time of 5000 ms. Participants must make an up/down response to the central arrows for Task 1 using the left hand buttons, and a left/right response for Task 2 using the right hand buttons, sequentially. There are 8 blocks, with 64 trials per block. Each block lasts approximately 6 minutes, and the total task time is approximately 50 minutes.
Computational loads for Tasks 1 and 2 are approximately 1 bit (which is \( \log_2 2 \) for 2 possible response directions) respectively under the congruent condition, and greater than 1 but less than 2 under the incongruent condition. The conflict resulting from task-irrelevant flankers can be estimated as less than or equal to a difference of 1 bit between conflict and no-conflict conditions (Fan, 2014; Wang et al., 2011). The two possible locations of the target for each task contribute to a computational load of 1 bit. Therefore, for Task 1 and Task 2, the minimum and maximum computational loads are 2 and 3, respectively. In a previous pilot study it was demonstrated that under the 1000 ms SOA the computational load of Task 2 is not significantly affected by Task 1, indicating that the information processing involved in each task does not overlap, resulting in sequential task processing. However, under the 100 ms SOA, the tasks occur in much quicker succession, resulting in task processing overlap, with the computational load during Task 2 processing approaching the sum of the computational load of Tasks 1 and 2, an additive

*Figure 3. Schematic of Dual Conflict Task*
effect based on RT pattern. Therefore, under the 100 ms SOA, the minimum (Task 1 congruent, Task 2 congruent, CC) and maximum (Task 1 incongruent, Task 2 incongruent, II) computational loads for Task 2 are 4 and 6 bits, respectively. Therefore, for the whole task (including both 1000 and 100 ms SOA conditions), the minimum and maximum computation loads are 2 bits for the 1000 SOA CC condition and 6 bits for the 100 SOA II condition, respectively. The estimated loads for Task 2 under different conditions are shown in Table 2.

Table 2

Experimental conditions and estimations of input information and computational load under both SOAs of the DCT

<table>
<thead>
<tr>
<th>Stimulus condition and load in bits</th>
<th>Load during Task 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1000 ms</td>
</tr>
<tr>
<td>Task 1 load</td>
<td>Task 2 load</td>
</tr>
<tr>
<td>C 2</td>
<td>C 2</td>
</tr>
<tr>
<td>C 2</td>
<td>I 3</td>
</tr>
<tr>
<td>I 3</td>
<td>C 2</td>
</tr>
<tr>
<td>I 3</td>
<td>I 3</td>
</tr>
</tbody>
</table>

Note: C: congruent; I: incongruent.

**Masked Majority Function Task (MFT-M).** This task was designed to investigate the capacity of cognitive control under time constraints aimed at computation of cognitive control bandwidth, with methods that have been previously published (Wu, Dufford, Mackie, Egan, & Fan, 2016). In this task, groups of arrows with set sizes of 1, 3, and 5 are simultaneously randomly presented at 8 possible locations arranged as an octagon centered on a fixation cross (see Figure 4). Each arrow points either to the left or right, and participants must indicate by button press the majority direction of the arrows. The ratios of majority and minority directions are as described for the MFT above. There
is a variable fixation period of 0 to 500 ms at the start of each trial, followed by the target arrow set. Exposure time (ET) to the target arrows is varied by manipulating stimulus onset duration and then applying backward masking. Exposure time can be 250, 500, 1000, or 2000 ms, followed by the mask for 500 ms. The mask consists of 8 diamond shapes presented at the same 8 possible target locations. The length of the arrows and diameter of diamond shape are kept constant at 6.5 mm. The offset of the mask initiates a varied post-stimulus fixation period, such that the total duration of the arrow set, mask, and post-stimulus fixation periods is 2500 ms. Participants are instructed to make a response as quickly and accurately as possible to indicate in which direction the majority of the arrows point by pressing one of two mouse buttons with the index or middle finger of the right hand. Responses must be made within a 2500 ms response window from the onset of the target arrow set. Participants are encouraged to guess when they fail to find the majority direction. Feedback is presented on each trial for 750 ms, with a variable post-feedback fixation period. Each trial is 5750 ms in duration.

The task consists of 12 blocks of trials in which each block is comprised of one of the set sizes and ETs. The presentation of the blocks is in random order and each block consists of 36 trials, also presented in random order. Within each block, there are the same number of trials in each congruence condition, with equal numbers of trials requiring left and right responses: 36 trials for 1:0 in a 1-arrow block; 18 trials for 3:0 and 2:1 in a 3-arrow block; and 12 trials each for 5:0, 4:1, and 3:2 in a 5-arrow block. There is a 3 s fixation period at the beginning and end of each block, and each block has a total duration of 213 s. The total number of trials in this task is 432, with a total task duration
of approximately 43 minutes. In a previous study investigating the capacity of cognitive control in healthy control participants using performance on the MFT-M, we tested various mental algorithms for performance and estimated the capacity of cognitive control to be approximately 3-4 bps, and detailed methods related to the estimation of capacity can be found therein (Wu et al., 2016). In the present study, we predicted that the estimated capacity of cognitive control would be significantly lower for the ASD group relative to the TD group.

**Procedure**

For the first three tasks, all participants completed: 1) EVT; 2) MFT; and 3) DCT, in the same order. The MFT-M was completed in Phase II of this study with a different sample meeting the criteria above. Participants were instructed to respond as quickly and
accurately as possible and took self-initiated and self-terminated breaks as needed between runs within each task, as well as between each task, to control for fatigue.

Data Analysis

For all four tasks, the primary independent variable is Entropy (cognitive load) in bits, manipulated across various levels within each task. The MFT-M also manipulates Exposure Time at four levels. The primary dependent variable is efficiency (Accuracy/RT, reflecting the probability of a correct response per unit time in seconds), taking both speed and accuracy into account. Average efficiency >1 typically indicates high accuracy and/or RT <1 s. Efficiency <1 typically reflects lower accuracy and/or RT >1 s. For group comparisons, a higher efficiency score indicates better performance. In the interest of readability, only ANOVA results for efficiency are reported below. All RT and accuracy ANOVA results are reported in Appendix B.

Data were tested for normal distributions and homogeneity of variance (Levene’s test). For within-subjects factors where Mauchley’s test indicated a violation of the assumption of sphericity, univariate analyses of variance with Greenhouse-Geisser correction were reported.

We also estimated the best-fit regression line for all tasks (where applicable) to obtain the slope and intercept of performance as a function of cognitive load for each participant, and use independent t-tests to examine group differences in both baseline performance and rates of change in performance. A lower efficiency intercept indicates a lower level of cognitive control efficiency at baseline. With efficiency scores plotted against information entropy in bits, efficiency scores decrease as information increases,
resulting in a negative slope. A more negative number is indicative of a faster rate of
decline in performance with increasing information. For each task mixed factorial
analyses of variance (ANOVA) were conducted with Group as the between-subjects
factor.

Non-parametric correlation analyses (Kendall’s tau) were performed to assess the
relationship between efficiency on the tasks where applicable and symptom report on
ADI-R, ADOS-G, AQ, and SRS. False discovery rate corrections were applied to control
for Type I error. One-tailed statistical tests were utilized to test our directional
predictions.

Results

Cognitive control for sequential stimuli: Results of the EVT

For this analysis, we excluded one TD participant whose overall accuracy on this
task was 62%, drastically below the group accuracy mean of 96% (final n = 15, ASD; n =
14 TD). This participant’s performance was within normal limits relative to his group on
both the MFT and DCT. Efficiency performance on the EVT for both entropy and
surprise is presented in Table 3 and Figure 5. Means of performance across all conditions
are reported in Table 3.

Table 3

Mean (SD) performance on the EVT in terms of efficiency, RT, and accuracy.

<table>
<thead>
<tr>
<th></th>
<th>Efficiency</th>
<th>RT (ms)</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TD</td>
<td>ASD</td>
<td>TD</td>
</tr>
<tr>
<td>Entropy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2.50 (0.30)</td>
<td>2.24 (0.41)</td>
<td>402 (45)</td>
</tr>
<tr>
<td>0.54</td>
<td>2.20 (0.21)</td>
<td>2.04 (0.30)</td>
<td>420 (111)</td>
</tr>
</tbody>
</table>
Cognitive control efficiency for sequential stimuli – entropy. Results are presented in Figure 5a. The main effect of Group was marginally significant ($F(1,27) = 4.18, p = .05, \eta^2_p = .13$), reflecting less efficient performance in the ASD group ($M = 1.97 \pm 0.28$) than the TD group ($M = 2.17 \pm 0.22$). For entropy, sphericity had been violated, $\chi^2(2) = 19.07, p < .001, \varepsilon = .66$, and with correction the main effect was significant ($F(1.32, 35.53) = 81.88, p < .001, \eta^2_p = .75$). Pairwise comparisons (Bonferroni-corrected) revealed significant decreases in efficiency for each entropy value point, all $ps < .001$). There was no significant Group by entropy interaction ($F < 1$). Intercept was significantly lower for the ASD group ($M = 2.24 \pm 0.41, R^2 = .92$) than for the TD group.
(M = 2.48 ± 0.29, R² = .95), t(27) = -1.85, p < .05. There was no significant difference in slope between groups (t(27) = 0.981, p = .34).

**Cognitive control efficiency for sequential stimuli – surprise.** Results are presented in Figure 5b. The main effect of Group was significant (F(1,27) = 5.32, p < .05, \( \eta_p^2 = .16 \)), with less efficient performance in the ASD group (M = 1.94 ± 0.41) than the TD group (M = 2.14 ± 0.37). For surprise, sphericity was violated, \( \chi^2(5) = 71.80, p < .001, \varepsilon = .41 \), and with correction the main effect was significant (F(1.23, 33.19) = 81.06, p < .001, \( \eta_p^2 = .75 \)). Pairwise comparisons with Bonferroni corrections revealed significant decreases in efficiency for each surprise value point (all ps < .001). The Group by surprise interaction for efficiency was not significant (F < 1). Intercept was significantly lower for the ASD group (M = 2.17 ± 0.36, R² = .89) than for the TD group (M = 2.38 ± 0.26, R² = .87), t(27) = -1.77, p < .05. There were no significant group differences in slope (t(27) = 0.26, p = .80).

**Cognitive control for non-sequential stimuli: Results of the MFT**

Results are presented in Table 4 and Figure 6. The main effect of Group was significant (F(1,28) = 12.70, p < 0.001, \( \eta_p^2 = .31 \)), such that the ASD group (M = 0.91 ± 0.12) demonstrated decreased overall performance efficiency compared to the TD group (M = 1.06 ± 0.11). Sphericity was violated for entropy, \( \chi^2(14) = 103.46, p < 0.001, \varepsilon = .41 \), and with correction, the main effect was significant, F(2.1,57.5) = 509.25, p < 0.001, \( \eta_p^2 = .95 \). The Group by entropy interaction was significant, F(2.1,57.5) = 3.68, p < 0.05, \( \eta_p^2 = .12 \). Pairwise comparisons (Bonferroni-corrected) indicated the TD group had significantly higher performance on each MFT condition compared to the ASD group.
For the six conditions of 1:0, 3:0, 2:1, 5:0, 4:1, and 3:2, \( t(28) = 2.38, 2.73, 4.61, 3.18, 2.97, \) and 2.17, respectively, all \( ps < .05 \). We also found a significant difference in slope between the two groups \( t(28) = 2.37, p < .05 \), such that TD group \((M = -0.28 \pm 0.04, R^2 = .92)\) had a higher rate of decreasing performance efficiency than ASD group \((M = -0.24 \pm 0.05, R^2 = .91)\). The ASD group had a significantly lower intercept \((M = 1.42 \pm 0.20)\) than the TD group \((M = 1.66 \pm 0.20)\), \( t(28) = -3.18, p < .01 \).

Table 4

Mean (SD) performance on the MFT in terms of efficiency, RT, and accuracy.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Efficiency</th>
<th>RT (ms)</th>
<th>Accuracy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TD</td>
<td>ASD</td>
<td>TD</td>
</tr>
<tr>
<td>1:00</td>
<td>1</td>
<td>1.76 (0.24)</td>
<td>1.54 (0.27)</td>
</tr>
<tr>
<td>3:00</td>
<td>2</td>
<td>1.38 (0.19)</td>
<td>1.19 (0.18)</td>
</tr>
<tr>
<td>2:01</td>
<td>3.58</td>
<td>0.78 (0.10)</td>
<td>0.67 (0.09)</td>
</tr>
<tr>
<td>5:00</td>
<td>2.58</td>
<td>1.26 (0.16)</td>
<td>1.01 (0.13)</td>
</tr>
<tr>
<td>4:01</td>
<td>3.91</td>
<td>0.73 (0.07)</td>
<td>0.65 (0.08)</td>
</tr>
<tr>
<td>3:02</td>
<td>5.91</td>
<td>0.44 (0.06)</td>
<td>0.38 (0.09)</td>
</tr>
</tbody>
</table>

Note: \( H = \) entropy

Figure 6. MFT efficiency results
Cognitive control capacity under time constraints: Results of the DCT and MFT-M

DCT. DCT performance efficiency as a function of computational load of Task 2 is shown in Table 5 and Figure 7. Additional analyses are also presented in Mackie & Fan (2015). The main effect of Group was not significant ($F(1,28) = 2.72, p = .11, \eta^2_p = .09$). Sphericity was violated for entropy $\chi^2(9) = 44.65, p < .001, \epsilon = .67$, and with correction there was a significant main effect ($F(2.70,75.52) = 376.16, p < .001, \eta^2_p = .93$). Pairwise comparisons (Bonferroni-corrected) indicated significant decreases in efficiency for each increasing value of entropy, all $ps > .001$. The interaction between entropy and Group was significant ($F(2.70,75.52) = 4.78, p < .01, \eta^2_p = .15$), with greater efficiency decrease in the ASD group compared to the TD group as a function of cognitive load. There were no significant group differences for intercept ($t(28) = -0.64, p = 0.26$) or slope ($t(28) = -1.08, p = 0.14$). The groups did not differ significantly in

![Figure 7. DCT efficiency results for Task 2](image)
performance at baseline (Task 1, CC 1000 ms SOA, 2 bits) \((F < 1)\), but the ASD group performed significantly less efficiently than the TD group at high cognitive load (Task 2, II 100 ms SOA, 6 bits), \(F(1,28) = 7.48, p < .05\).

Table 5

*Mean (SD) performance on Task 2 of the DCT in terms of efficiency, RT, and accuracy.*

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>SOA (ms)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td>1000</td>
<td>TD</td>
<td>ASD</td>
<td>TD</td>
<td>ASD</td>
<td></td>
</tr>
<tr>
<td>Task 1</td>
<td>Task 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>congruent</td>
<td>congruent</td>
<td>0.91 (0.17)</td>
<td>0.89 (0.19)</td>
<td>1.71 (0.23)</td>
<td>1.65 (0.30)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>congruent</td>
<td>incongruent</td>
<td>0.77 (0.17)</td>
<td>0.63 (0.22)</td>
<td>1.30 (0.17)</td>
<td>1.05 (0.37)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>incongruent</td>
<td>congruent</td>
<td>0.80 (0.16)</td>
<td>0.75 (0.24)</td>
<td>1.65 (0.22)</td>
<td>1.56 (0.35)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>incongruent</td>
<td>incongruent</td>
<td>0.72 (0.18)</td>
<td>0.50 (0.25)</td>
<td>1.27 (0.20)</td>
<td>1.05 (0.38)</td>
<td></td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>RT (ms)</th>
<th>SOA (ms)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td>1000</td>
<td>TD</td>
<td>ASD</td>
<td>TD</td>
<td>ASD</td>
<td></td>
</tr>
<tr>
<td>Task 1</td>
<td>Task 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>congruent</td>
<td>congruent</td>
<td>1099 (177)</td>
<td>1052 (146)</td>
<td>596 (88)</td>
<td>606 (135)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>congruent</td>
<td>incongruent</td>
<td>1221 (209)</td>
<td>1152 (163)</td>
<td>763 (99)</td>
<td>802 (169)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>incongruent</td>
<td>congruent</td>
<td>1224 (184)</td>
<td>1156 (158)</td>
<td>614 (88)</td>
<td>643 (145)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>incongruent</td>
<td>incongruent</td>
<td>1266 (194)</td>
<td>1313 (312)</td>
<td>782 (126)</td>
<td>814 (191)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Accuracy (%)</th>
<th>SOA (ms)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
<td>1000</td>
<td>TD</td>
<td>ASD</td>
<td>TD</td>
<td>ASD</td>
<td></td>
</tr>
<tr>
<td>Task 1</td>
<td>Task 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>congruent</td>
<td>congruent</td>
<td>97 (4)</td>
<td>91 (10)</td>
<td>100 (1)</td>
<td>97 (5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>congruent</td>
<td>incongruent</td>
<td>91 (7)</td>
<td>71 (23)</td>
<td>97 (3)</td>
<td>79 (22)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>incongruent</td>
<td>congruent</td>
<td>95 (7)</td>
<td>84 (21)</td>
<td>100 (1)</td>
<td>95 (7)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>incongruent</td>
<td>incongruent</td>
<td>88 (9)</td>
<td>62 (28)</td>
<td>97 (2)</td>
<td>81 (20)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
MFT-M. In the MFT-M, the primary dependent variable is accuracy as a function of cognitive load and exposure time (ET). Results are presented in Table 6 and Figure 8. In terms of accuracy, the main effect of ET was significant \((F(3, 72) = 36.09, p < .001, \eta_p^2 = .60)\), such that accuracy increased with increasing ET. Pairwise comparisons revealed that while there was no significant increase in accuracy between the 250 and 500 ms conditions, accuracy increased significantly between the 500, 1000, and 2000 ms conditions \((ps < .01)\). Sphericity was violated for Entropy \((\chi^2(2) = 7.54, p = .02, \epsilon = .78)\), and the main effect was significant with correction \((F(1.56, 37.51) = 499.50, p < .001, \eta_p^2 = .95)\), such that there was a significant decrease in accuracy with each increase in entropy \((ps < .001)\). The ET by Entropy interaction was significant \((F(6, 144) = 9.61, p < .001, \eta_p^2 = .29)\), such that the extent to which accuracy decreased with entropy became lesser as ET increased. The main effect of Group trended toward significance \((F(1,244) = 2.81, p = .06, \eta_p^2 = .11)\). The ET by Group \((F < 1)\), Entropy by Group \((p = .13)\), and ET by Entropy by Group \((F < 1)\) interactions were not significant.

**Cognitive control capacity.** For the capacity estimation, one participant from each group was excluded for inadequate accuracy performance. The estimated capacity of the TD group was 3.98 bps on average (range = 3.04 to 4.92), and 3.38 bps for the ASD.

![Figure 8](image-url). Results of MFT-M for accuracy and cognitive control capacity.
group (range = 2.31 to 4.89). An independent samples $t$-test revealed that the capacity of the ASD group was significantly lower than the TD group ($t(26) = -1.95, p = .04$, one-tailed; Figure 8c). Please refer to Appendix B for RT results as a function of entropy and exposure time.

Table 6

Means (and SE) of RT and accuracy for all conditions of the MFT-M

<table>
<thead>
<tr>
<th>ET (ms)</th>
<th>Ratios</th>
<th>5:0</th>
<th>4:1</th>
<th>3:2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TD</td>
<td>ASD</td>
<td>TD</td>
<td>ASD</td>
</tr>
<tr>
<td></td>
<td>RT (ms)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>502 (24)</td>
<td>543 (43)</td>
<td>618 (48)</td>
<td>654 (61)</td>
</tr>
<tr>
<td>500</td>
<td>540 (29)</td>
<td>566 (29)</td>
<td>724 (43)</td>
<td>727 (47)</td>
</tr>
<tr>
<td>1000</td>
<td>560 (21)</td>
<td>625 (35)</td>
<td>820 (33)</td>
<td>885 (64)</td>
</tr>
<tr>
<td>2000</td>
<td>620 (27)</td>
<td>701 (44)</td>
<td>952 (56)</td>
<td>1119 (89)</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>Accuracy (%)</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>250</td>
<td>99 (1)</td>
<td>96 (2)</td>
<td>82 (2)</td>
<td>81 (3)</td>
<td>64 (3)</td>
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<td>98 (1)</td>
<td>88 (2)</td>
<td>85 (2)</td>
<td>64 (3)</td>
<td>62 (3)</td>
</tr>
<tr>
<td>1000</td>
<td>99 (0)</td>
<td>99 (0)</td>
<td>94 (1)</td>
<td>91 (2)</td>
<td>71 (3)</td>
<td>67 (3)</td>
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<tr>
<td>2000</td>
<td>99 (0)</td>
<td>99 (0)</td>
<td>96 (1)</td>
<td>93 (2)</td>
<td>80 (2)</td>
<td>73 (3)</td>
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</table>

Relationships between task performance and symptom domains

Correlation coefficients are presented in Table 7. Because the value for efficiency slope is negative, a negative correlation suggests that a more negative (steeper) efficiency slope, or faster rate of decrease in efficiency as a function of cognitive load (entropy), was associated with greater ASD symptom report. Due in part to small sample size and restricted variance of symptom scores, none of these correlations survived false discovery rate correction.

Table 7
Kendall’s tau correlation coefficients for relationships between behavioral efficiency and ADI-R and ADOS-G subscales.

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>ADI-R S</th>
<th>ADI-R C</th>
<th>ADI-R B/I</th>
<th>ADOS-G S</th>
<th>ADOS-G C</th>
<th>ADOS-G B/I</th>
</tr>
</thead>
<tbody>
<tr>
<td>EVT(^1)</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>entropy slope</td>
<td>-.27</td>
<td>-.41*</td>
<td>.15</td>
<td>-.21</td>
<td>-.44*</td>
<td>.15</td>
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<tr>
<td>entropy intercept</td>
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<td>.16</td>
<td>-.17</td>
<td>.23</td>
<td>.00</td>
<td>-.37*</td>
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<tr>
<td>surprise slope</td>
<td>-.10</td>
<td>-.33*</td>
<td>-.03</td>
<td>-.14</td>
<td>-.27</td>
<td>.12</td>
</tr>
<tr>
<td>surprise intercept</td>
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<td>.06</td>
<td>-.09</td>
<td>.14</td>
<td>-.12</td>
<td>-.42*</td>
</tr>
<tr>
<td>Overall</td>
<td>-.36*</td>
<td>-.07</td>
<td>-.12</td>
<td>.35</td>
<td>-.18</td>
<td>-.24</td>
</tr>
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<td>MFT</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Slope</td>
<td>.53**</td>
<td>.20</td>
<td>.07</td>
<td>.11</td>
<td>.12</td>
<td>.57**</td>
</tr>
<tr>
<td>Intercept</td>
<td>-.53**</td>
<td>-.06</td>
<td>-.19</td>
<td>-.04</td>
<td>-.17</td>
<td>-.49*</td>
</tr>
<tr>
<td>Overall</td>
<td>-.43*</td>
<td>-.06</td>
<td>-.26</td>
<td>.04</td>
<td>-.10</td>
<td>-.30</td>
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<tr>
<td>DCT(^2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>.32*</td>
<td>.32*</td>
<td>.08</td>
<td>.23</td>
<td>.01</td>
<td>.11</td>
</tr>
<tr>
<td>Intercept</td>
<td>-.31</td>
<td>-.31</td>
<td>-.19</td>
<td>-.09</td>
<td>-.07</td>
<td>-.12</td>
</tr>
<tr>
<td>Overall</td>
<td>-.23</td>
<td>-.22</td>
<td>-.15</td>
<td>.11</td>
<td>-.02</td>
<td>-.12</td>
</tr>
</tbody>
</table>

* \(p < .05\), ** \(p < .01\) (one-tailed)

Note: S = social; C = communication; B/I = Behavior/Interests; \(^1\) \(n = 14\), except for overall efficiency analysis; \(^2\) \(n = 14\) for ADOS-G. None of the correlations survived false discovery rate correction

**Discussion**

In this study we tested our hypothesis that individuals with ASD implement cognitive control less efficiently than TD adults with a lower capacity for cognitive control, and that these deficits possibly contribute to the clinical presentation of the disorder. On tasks designed to systematically manipulate uncertainty and test cognitive control efficiency, the ASD group showed a lower baseline efficiency of information processing for sequential events, a general reduction in efficiency for non-sequential...
events over a wide range of uncertainty, and a lower capacity for cognitive control under time constraints.

The performance of ASD relative to TD can be considered in terms of three hypothetical efficiency performance models (Figure 9): (a) The ASD group has a lower baseline than controls, both groups decrease in efficiency as uncertainty increases, and the ASD group has a lower upper limit than TD (Figure 9a, Model A); (b) The ASD group has a lower baseline than controls, the performance difference remains somewhat constant across increasing uncertainty values, with performance finally converging with TD at the highest levels of uncertainty (Figure 9b, Model B); and (c) The ASD group and controls have similar baseline performance and then diverge as uncertainty increases, with ASD efficiency beginning to decrease at a lower uncertainty level compared to TD (Figure 9c, Model C).

Figure 9. Hypothetical performance models of ASD relative to TD

The EVT results fit best with Model A, with relatively lower efficiency in the ASD group across the full range of uncertainty values when the task involved sequential information. The MFT results fit Model B, for non-sequential information processing,
performance was less efficient for the ASD group at low uncertainty levels, converging toward a similar level as TD at high uncertainty levels. At first glance, the EVT and MFT results might appear to be at odds with existing information processing theories that predict equivalent group performance at low load levels (e.g., (Minshew & Goldstein, 1998; Minshew et al., 2001). However, we speculate that differences at baseline may be explained by additional uncertainty due to spatial location (1/8 possible locations for ~3 bits) in these tasks. This possibility is highlighted in the DCT results, which best fit Model C, and show that the ASD group performed less efficiently than controls at the high capacity condition rather than at the low capacity condition. In the EVT and MFT, participants are required to shift attention from fixation to one of eight possible target locations, whereas in the DCT, target stimuli appear in fewer possible locations (4 possible locations for Tasks 1 and 2 combined). It is possible then, that the additional attentional orienting requirement contributed to group differences at baseline for the EVT and MFT, but not for the DCT. These results are consistent with theories that propose that deficits in ASD arise at more demanding levels of information processing, and provide further support for the idea of a greater limitation on information processing capacity in ASD compared to TD (Belmonte et al., 2004; Just et al., 2012). Taken together, it appears that Model C is the most plausible, and can best explain performance in these experiments.

The observed group differences in cognitive control under uncertainty suggest that deficits in control of information processing may contribute to ASD symptoms, as social and communicative processing involves dealing with uncertainty at various levels,
such as decoding a linguistic message or inferring the mental states/intentions of others. According to uncertainty reduction theory (based upon information theory (Berger & Calabrese, 1975)), people undertake several steps to reduce uncertainty in social situations. In ASD, lower efficiency in sequential and non-sequential information processing in concert with a reduced upper limit of information processing capacity, may negatively impact the ability to effectively engage in this uncertainty reduction, resulting in social and communication deficits. Furthermore, deficits in the domain of restricted interests and repetitive behaviors may serve to compensate for a diminished uncertainty-reduction capacity. This is supported by strong correlation with a large effect size between MFT performance and the restricted interests repetitive behaviors domain in this study (though this did not survive false discovery rate multiple comparison correction). By restricting interests to predictable sequences and familiar domains, individuals with ASD are able to avoid cognitive control overload.

Cognitive control of information processing is supported by the frontoparietal network, with the anterior cingulate (ACC) and anterior insular (AIC) cortices as core regions, in addition to other regions such as the frontal eye fields and near/along the intraparietal sulcus (Fan, 2014; Fan et al., 2014). Reduced cognitive control efficiency in ASD may be related to a deficiency in this network. We have previously shown that there is a lack of activation of the ACC in ASD during conflict processing (Fan et al., 2012). ACC is involved in baseline state uncertainty monitoring, and abnormal recruitment of this crucial network hub could underlie the inefficient performance demonstrated in our experiments. In addition to region-specific neural differences, there is also evidence for
differences in connectivity within the frontoparietal network in ASD, resulting in inefficient information transfer between frontal and parietal areas (Matthew K. Belmonte et al., 2004; Just et al., 2004; Just et al., 2012; Kana, Keller, Cherkassky, Minshew, & Just, 2006), contributing to symptom presentation (Uddin et al., 2014).

Limitations and alternative explanations

A primary limitation in this study is the relatively small size of the sample. Further, given that participants in the ASD group were relatively high-functioning and all male, there are limits to the generalizability of these findings. However, one might expect that lower-functioning individuals would show even greater relative impairment on the tasks described in this study. ASD is often comorbid with other conditions, and two of our participants were previously diagnosed with ADHD. We do not believe that this significantly affected the results due to the small proportion of participants involved. Ideally, these findings should be replicated in a larger sample, free of comorbidity, to address these limitations.

One could argue that the differences we observed in performance might be attributed to motor slowing previously documented in ASD (Kenworthy, Yerys, Weinblatt, Abrams, & Wallace, 2013; Williams, Goldstein, & Minshew, 2013). While we did not directly examine motor speed, it is notable that there were no significant group differences in overall RT for the DCT; EVT overall RT difference trended toward significance; and MFT overall RT was significantly faster for the ASD group. This unclear pattern of RT differences makes it difficult to draw conclusions about generalized slowing in the ASD group. Previous work has suggested that slowness to respond in ASD
may result from use of psychoactive medications (Bogte et al., 2008). However, our sample was unmedicated at the time of participation in the study. Additionally, we presented a large number of trials across tasks, which could potentially result in differential fatigue effects between groups. However, failure to find group differences in RT on the third task, the DCT, rules out this possibility.

**Conclusion**

This study represents a preliminary step in the investigation of cognitive control in ASD and the relationship between cognitive control deficits and the symptom presentation of ASD. We found participants with ASD had a generally lower efficiency of cognitive control, with a reduced capacity under time constraints, compared to controls. Of three possible explanations of group differences in performance, the model in which the ASD group is less efficient than controls as cognitive control load increases best fit the present data. While this study has targeted the processing of stimuli not typically encountered in daily life, it would be beneficial for future studies to investigate the role of cognitive control deficits as they arise in more ecologically valid tasks that require higher-level cognition, such as language and theory of mind, which map more representatively onto the established symptom domains.
Chapter IV

Investigation of Affective Cognitive Control in ASD

We propose that individuals with ASD have greater difficulty than TD controls with affective cognitive control as uncertainty increases, and that these deficits are related to ASD symptom presentation. To test this hypothesis, we developed a series of social and affective information processing tasks that parametrically manipulate uncertainty and information processing rate.

Method

Participants

The affective information processing tasks were implemented with a sample of participants meeting the same inclusion criteria as described in Chapter III. Some were those included in the previous study (roughly half) and some were new recruits through the Seaver Center and the greater New York City area.

Table 8

*Means of demographic data (range) of ASD and TD groups.*

<table>
<thead>
<tr>
<th>Participant characteristics</th>
<th>ASD (n = 15)</th>
<th>TD (n = 15)</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>32.6 (21-49)</td>
<td>30.4 (21-47)</td>
<td>0.73</td>
<td>.47</td>
</tr>
<tr>
<td>Full Scale IQ</td>
<td>100.5 (82-123)</td>
<td>100.1 (83-119)</td>
<td>0.09</td>
<td>.93</td>
</tr>
<tr>
<td>ASD diagnosis</td>
<td>15</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADOS-G (n = 15)</td>
<td>--</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communication + Social</td>
<td>9.6 (7-12)</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Restricted and repetitive behaviors</td>
<td>2.4 (1-3)</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>20.9 (9-38)</td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRS Total</td>
<td>62.5 (50-89)</td>
<td>49 (41-64)</td>
<td>3.58</td>
<td>.001</td>
</tr>
<tr>
<td>AQ Total</td>
<td>27.43 (15-36)</td>
<td>13.4 (6-23)</td>
<td>5.00</td>
<td>.000</td>
</tr>
<tr>
<td>EQ Total</td>
<td>30.0 (16-47)</td>
<td>47.3 (27-62)</td>
<td>-3.92</td>
<td>.001</td>
</tr>
</tbody>
</table>
Note: SRS = Social Responsiveness Scale; AQ = Autism Quotient; EQ = Emotion Quotient

Tasks

Complex Emotion Recognition Task (CERT). This task was designed to parametrically manipulate uncertainty in emotion recognition by displaying facial emotion expressions that vary in complexity (basic or compound; Figure 10). The complexity factor manipulates how readily one might be able to identify the emotion displayed. For basic emotions, happiness, sadness, fear, disgust, surprise, and anger are represented (6 total). In the compound condition, the emotions represented reflect combinations of basic emotions, that are presumed to occur naturally along the spectrum of human emotional expression (e.g., angrily disgusted, happily surprised) as described in a recent publication (Du et al., 2014). While the labels ascribed to these emotions may not be typically used by individuals to describe their emotional state, the presence of such combinations of emotions as part of the human experience is intuitive. The task utilizes a two-alternative forced-choice) response structure in which an emotional face is presented along with the label of a basic emotion, and the participant must indicate (Yes or No) whether they identify that emotion in the facial expression presented. That is, all emotion types are presented with labels of basic emotions, and participants must determine whether the prompted emotion can be found in the emotional display. The purpose of this design was to induce a component of response inhibition in the emotional domain. For instance, if the prompt reads “happy?”, and the emotion displayed is happily surprised, the participant must inhibit detection of task-irrelevant features related to the emotion of
surprise, and focus attention on the task-relevant features related to happiness, and likewise for all other combinations of basic and compound emotions.

**Figure 10.** Sample stimuli in the Complex Emotion Recognition Task

The emotional stimuli are static photographs chosen from a database developed using facial action unit coding to represent 6 basic emotion and 12 compound emotions (Du et al., 2014). Each trial begins with a variable fixation period of 0 – 1000 ms, followed by the target stimulus, which remains present for the duration of the response window (2500 ms). Following the response, there is a variable post-stimulus fixation period such that the total trial time is 4500 ms. There are 3 blocks of 72 trials, with equal numbers of basic and compound stimuli, equal numbers of trials for which the response is True and False, presented in random order. There is a 3 second fixation period at the beginning of each block, and a 20 s fixation period between blocks. The total task duration is approximately 20 minutes.

**Multiple Emotion Processing Task (MEPT).** This task was designed to investigate behavioral effects related to emotional complexity manipulated by the number of individuals for whom emotional states must be inferred. This task parametrically
manipulates complexity of emotional information for three set sizes of actors (1, 2, and 3; see Figure 11). Within each set size, the congruence of emotion is also manipulated, resulting in six conditions. For set size 1, there is only one face portraying 1 emotion (1 face: 1 emotion condition), and congruence is not relevant. This condition can be considered a measure of basic emotion recognition that is necessary for adequate performance in the other conditions. For set size 2, the faces either show the same emotion (2 faces: 1 emotion condition) or different emotions (2 faces: 2 emotions condition). Presumably, individuals are more likely to respond more quickly and accurately when both emotions are the same; considering different emotional states for different individuals is assumed to be more challenging. For set size 3, the faces either all show the same emotion (3 faces: 1 emotion condition), two show the same emotion and one shows a different emotion (3 faces: 2 emotions), or all three show different emotions (3 faces: 3 emotions). For each condition we can consider the amount of information under consideration to be a product of these two factors (without considering the uncertainty in the response). Consequently, for the 1:1 condition, participants must consider 1 piece of information, for the 2:1 condition, 2 pieces of information, and so on. Notably, the 3:1 condition carries less information (3 pieces) than the 2:2 condition (4 pieces), despite being of a larger set size. The resultant levels of information corresponding to the 1:1, 2:1, 2:2, 3:1, 3:2, and 3:3 conditions are 1, 2, 4, 3, 6, and 9, respectively.
At the beginning of each trial, participants are shown a statement describing either:

- **Set size 1**:  
  A is fearful  
  (1 face : 1 emotion)

- **Set size 2**:  
  A is sad because B is sad  
  (2 faces : 1 emotion)  
  A is surprised because B is angry  
  (2 faces : 2 emotions)

- **Set size 3**:  
  A is disgusted because B is disgusted because C is disgusted  
  (3 faces : 1 emotion)  
  A is fearful because B is fearful because C is surprised  
  (3 faces : 2 emotions)  
  A is sad because B is disgusted because C is surprised  
  (3 faces : 3 emotions)

*Figure 11. Sample stimuli in the Multiple Emotion Processing Task*
the emotional state of an actor (1:1 condition) or the emotional states of multiple actors, dependent on conditions as described above. After 5000 ms, the photo depictions described above appear, and participants must judge whether the facial expressions shown match the statement displayed (True or False). There are 3 blocks of 108 trials each. Within each block, there are the same number of trials in each congruence condition, with equal numbers requiring True and False responses: 36 for 1:1, 18 each for 2:1 and 2:2, and 12 each for 3:1, 3:2, and 3:3. Total task duration is approximately 30 minutes.

**Recursive Theory of Mind Task (R-ToM).** This task is based upon the perspective-taking task developed by Stiller (2010, personal communication). In this task participants read three short stories of approximately 200 words in length (see Appendix A for a sample story). Participants are instructed to read each story carefully as they will be asked questions about the content. There are three blocks, one for each story. At the beginning of each run, the story is displayed, along with instructions to read it carefully and remember it. Participants are instructed to push the spacebar when they are ready to proceed to the questions. Each story is followed by 20 statements, to which the participant must respond “True” or “False”. The 20 types statements correspond to the Levels of embedding (1-5), the Information Type (Fact, Intention), and the correct response (True, False), with one of each type within a block, presented in random order. The fact questions control for comprehension of complex sentences and short-term memory capacity. The total task duration is approximately 15 minutes.
**Majority Function Task – Emotional (MFT-E).** The emotional majority function task was designed to examine the effect of emotional information with different information values upon cognitive processing. In this task, stimuli consist of a group of three faces that appear randomly in three of eight possible locations centered around a fixation cross (Figure 12). Twenty fearful and neutral faces were selected from the Pictures of Facial Affect (Ekman & Friesen, 1975), where 10 of the faces were of males, and 10 of females with 5 neutral, and 5 fearful faces for each gender respectively. On each trial, participants must indicate the majority gender of the faces as quickly and accurately as possible via mouse click. When participants detected a majority of male faces they clicked the left mouse button, and when the majority was female, they clicked the right mouse button.

Three independent variables are manipulated in this experiment: 1) Cognitive load (low, high); 2) Emotional Valence (fearful, neutral); and 3) Frequency of emotional information (0%, 16%, 50%, 84%, 100%). The cognitive load manipulation was implemented in the ratio of same: other gendered faces presented on each trial. The 3:0 condition in which all faces were of the same gender was the low load condition, and the 2:1 condition with two faces of one gender and one of the other was the high load condition. Fear was selected as the emotional stimulus as it is considered to be an informative emotion which has been demonstrated to elicit a strong amygdala response (Melcher, Born, & Gruber, 2011; Melcher, Obst, Mann, Paulus, & Gruber, 2012; Shafritz, Bregman, Ikuta, & Szeszko, 2015). The frequency manipulation was intended to manipulate the entropy associated with the occurrence of fearful faces in a given...
sequence (i.e., a block of trials in this case). Consistent with the discussion of entropy in Chapter II, the 50% fearful condition with random presentation would have the highest emotional entropy in a sequence.

The task begins with fixation on a central fixation cross presented for 3000 ms. There is a variable jittered response window between 2000-3000 ms. Each trial lasts approximately 5 seconds. Altogether, there are 2 runs of 5 blocks, corresponding to the 5 frequencies. Each block contains 24 trials presented in random order, except for the 0%, and 100% blocks, which have 12 trials each. The order of the blocks was counterbalanced with reversed repetition between each run. The total trial number in this task is 240, and the task takes approximately 22 minutes to complete.

![Figure 12. Emotional MFT Stimuli](image)

**Procedure**

This study was conducted at the Icahn School of Medicine at Mount Sinai (ISMMS). Because we are interested in between-group comparisons for each task and not
within-subject comparisons across tasks, all participants completed the tasks in the same order. All tasks were compiled, and run using E-Prime 2.0™ software (Psychology Software Tools, Pittsburgh, PA) with a 17” display. Participants were encouraged to take breaks between runs in each task, as well as between tasks, to control for fatigue.

**Data Analysis**

RT and accuracy data were collected for all tasks, and efficiency was computed as described in Chapter III. In the interest of readability, only results for analyses on efficiency will be presented in the following sections. RT and accuracy results are available for review in Appendix B. For each task, response times were recorded for accurate trials, and trials with RTs ± 3 standard deviations of the mean were excluded from further analysis. Means (±SEM) of behavioral performance were calculated and analyzed. Data were tested for normal distributions and homogeneity of variance (Levene’s test). For within-subjects factors where Mauchley’s test indicated a violation of the assumption of sphericity, univariate analyses of variance with Greenhouse-Geisser correction were reported. For each task, mixed factorial analyses of variance (ANOVA) were conducted with the respective within-subjects factors and Group as the between-subjects factor. To investigate the potential influence of IQ on task performance, exploratory analyses of covariance (ANCOVA) were also conducted with IQ as a covariate. A significance level of .05 was selected. For statistical tests of specific, directional hypotheses, one-tailed *p*-values are reported, and will be indicated as applicable.
Non-parametric correlation analyses (Kendall’s tau) were performed to assess the relationship between efficiency on the three tasks and symptom report on, ADOS-G, SRS, and AQ (non-continuous variables). False discovery rate correction was applied to control for Type I error. One-tailed statistical tests were utilized to test our directional predictions.

**Results**

**CERT**

Results of a 2 (Complexity) x 2 (Group) ANOVA revealed that (see Figure 13), the main effect of Complexity on efficiency was significant ($F(1,28) = 139.86, p < .001, \eta_p^2 = .83$), with more efficient performance for basic emotions ($M = .60 \pm .02$) compared to compound emotions ($M = .48 \pm .02$). The main effect of Group ($F<1$) was not significant. The Complexity by Group interaction was significant ($F(1,28) = 4.45, p = .04, \eta_p^2 = .14$), such that the extent to which efficiency decreased for compound emotions

![Figure 13. CERT efficiency results](image-url)
was greater for the TD group compared to the ASD group (Table 8). ANCOVA with IQ as a covariate did not improve the model.

Table 9

CERT efficiency, RT and accuracy (SEM) results

<table>
<thead>
<tr>
<th></th>
<th>TD</th>
<th>ASD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basic</td>
<td>Compound</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.61 (0.03)</td>
<td>0.48 (0.03)</td>
</tr>
<tr>
<td>RT (ms)</td>
<td>1365 (59)</td>
<td>1453 (60)</td>
</tr>
<tr>
<td>Accuracy (%)</td>
<td>80 (2)</td>
<td>67 (2)</td>
</tr>
</tbody>
</table>

MEPT

Results of a 2 (Group) x 6 (Level) ANOVA (see Figure 14) revealed that assumption of sphericity was violated for Level, ($\chi^2(14) = 59.91, p < .001, \epsilon = .46$); with correction the main effect was significant ($F(2.3,64.9) = 56.75, p < .001, \eta_p^2 = .67$), such that efficiency decreased as level increased (Table 10). The main effect of Group was not

![Figure 14. MEPT efficiency](image-url)
significant ($F(1,28) = 1.26, \ p = .27, \ \eta_p^2 = .04$). The Level by Group interaction trended toward significance ($F(1,28) = 1.93, \ p = .09, \ \eta_p^2 = .07$). ANCOVA with IQ as a covariate did not improve the model. There were no significant group differences in efficiency slope ($t(1,28) = 1.62, \ p = .17$) or intercept ($t(1,28) = -1.28, \ p = .21$).

**Table 10**

**MEPT efficiency, RT, accuracy (SEM) results**

<table>
<thead>
<tr>
<th>Information</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>6</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Efficiency</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TD</td>
<td>0.51 (0.06)</td>
<td>0.44 (0.05)</td>
<td>0.41 (0.05)</td>
<td>0.34 (0.04)</td>
<td>0.31 (0.04)</td>
<td>0.28 (0.03)</td>
</tr>
<tr>
<td>ASD</td>
<td>0.41 (0.06)</td>
<td>0.34 (0.05)</td>
<td>0.34 (0.05)</td>
<td>0.29 (0.04)</td>
<td>0.27 (0.04)</td>
<td>0.24 (0.03)</td>
</tr>
<tr>
<td><strong>RT (ms)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TD</td>
<td>2081 (307)</td>
<td>2471 (390)</td>
<td>3272 (662)</td>
<td>3249 (431)</td>
<td>4085 (701)</td>
<td>4237 (614)</td>
</tr>
<tr>
<td>ASD</td>
<td>2393 (307)</td>
<td>2874 (390)</td>
<td>3755 (662)</td>
<td>3188 (431)</td>
<td>3886 (702)</td>
<td>4276 (614)</td>
</tr>
<tr>
<td><strong>Accuracy (%)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TD</td>
<td>82 (1)</td>
<td>88 (2)</td>
<td>95 (2)</td>
<td>82 (2)</td>
<td>87 (2)</td>
<td>87 (2)</td>
</tr>
<tr>
<td>ASD</td>
<td>80 (1)</td>
<td>84 (2)</td>
<td>90 (2)</td>
<td>80 (2)</td>
<td>84 (2)</td>
<td>87 (2)</td>
</tr>
</tbody>
</table>

**R-ToM**

For this task the results for level 5 were not consistent with the trend across the other levels and were not considered to be valid. Consequently, only levels 1 through 4 were included in the analysis for a 2 (Group) x 4 (Level) ANOVA (see Figure 15). The assumption of sphericity was violated for Level ($\chi^2(5) = 18.25, \ p < .01, \ \eta = .65$), and with correction the main effect was significant ($F(2.1, 57.4) = 91.61, \ p < .001, \ \eta_p^2 = .77$). Pairwise comparisons revealed significant decreases in efficiency with each increasing
level of information (all $ps < .001$, see Table 11). The main effect of Type was significant ($F(1, 28) = 72.00, p < .001, \eta^2_p = .72$), with less efficient performance overall for theory of mind questions ($M = .14 \pm .01$) compared to factual questions ($M = .21 \pm .02$). The main effect of Group was not significant ($F(1, 28) = 1.36, p = .25, \eta^2_p = .04$). The Level by Group interaction was significant ($F(3, 84) = 3.30 p = .02, \eta^2_p = .11$) such that the extent to which efficiency decreased as a function of Level was greater in the TD group compared to the ASD group. The Type by Group ($F < 1$), Level by Type ($p = .28$), and three-way ($F < 1$) interactions were not significant. ANCOVA with IQ as a covariate did not improve the model.

![Graph](image)

*Figure 15. RTom results*

### Table 11

**RTom efficiency, RT, and accuracy (SEM) results**

<table>
<thead>
<tr>
<th>Level</th>
<th>Type of Information</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fact</td>
<td>TD</td>
</tr>
<tr>
<td>1</td>
<td>Fact</td>
<td>0.35 (0.04)</td>
</tr>
</tbody>
</table>
Results of a 2 (Group) x 2 (Uncertainty) x 6 (Frequency) ANOVA (see Figure 16) revealed that the main effect of Uncertainty was significant \(F(1,28) = 118.81, p < .001, \eta_p^2 = .82\), with lower efficiency in the high uncertainty condition \((M = .70 \pm .03)\) compared to the low uncertainty condition \((M = .83 \pm .04)\). The main effects of Frequency \((F(1,28) = 1.59, p = .18, \eta_p^2 = .06)\) and Group \((F(1,28) = 1.98, p = .17, \eta_p^2 = .07)\) were not significant. The Frequency by Group \((F(1,28) = 1.30, p = .56, \eta_p^2 = .05)\), Frequency by Uncertainty \((F<1)\), and Uncertainty by Group \((F(1,28) = 1.92, p = .18, \eta_p^2 = .07)\) interactions were not significant. The Frequency by Uncertainty by Group interaction was significant \((F(4,104) = 2.34, p = .03, \eta_p^2 = .08)\), such that the effect of fearful face frequency differed between the two groups (see Table 12). Specifically, within the 50% condition, which is estimated to have the highest overall entropy, the
effect of cognitive load on efficiency was larger in the TD group (low – high $M = .18$) compared to the ASD group (low – high $M = 0.05$). ANCOVA with IQ as a covariate did not improve the model.

Table 12

*MFT-E efficiency, RT, and accuracy results*

<table>
<thead>
<tr>
<th>Frequency of fearful faces (%)</th>
<th>Efficiency</th>
<th>Uncertainty</th>
<th>Low TD</th>
<th>Low ASD</th>
<th>High TD</th>
<th>High ASD</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.87 (0.06)</td>
<td>0.77 (0.06)</td>
<td>0.75 (0.04)</td>
<td>0.67 (0.04)</td>
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Correlations between task performance and ASD symptoms

Correlation coefficients are presented in Table 13. Rate of change in efficiency across levels of the MEPT was positively associated with AQ scores such that as rate of change in performance became less negative, AQ scores increased, and as slope became steeper (more negative) EQ scores increased (higher EQ scores reflect better performance). Rate of change in efficiency across levels of mentalizing information on the RToM was positively associated with ADOS social + communication scores. RToM intercept for mentalizing information was negatively associated with ADOS social + communication and total scores. Due to the small sample size, none of these correlations survived false discovery rate correction.

Table 13

*Kendall’s tau correlation coefficients between performance efficiency across tasks and measures of ASD symptoms.*
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<td>-.07</td>
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Note: * = p < .05. None of the correlations survived false discovery rate correction

**Discussion**

We aimed to demonstrate that individuals with ASD would show deficits in affective cognitive control under uncertainty requiring processing of complex emotional information and recursive theory of mind inferences, and that the ASD group would be more susceptible to cognitive control interference from emotional information. Using an information theory approach, we designed several novel tasks to allow for systematic manipulations of uncertainty in emotional and social contexts. We predicted that individuals with ASD would be less efficient than typically developing controls in emotion processing and mentalizing under increasingly uncertain conditions, and that these deficits would be correlated with ASD symptom report.

Across the various tasks in this study, we did not find the expected interaction effect between group performance and uncertainty. Instead, we found that it was the TD group’s performance that decreased to a greater extent under conditions of increasing uncertainty.
uncertainty. Notably, the ASD group efficiency performance tracked the TD group performance very closely but slightly (not always significantly) lower across levels of uncertainty before converging with TD performance at the most demanding levels.

Furthermore, performance on these tasks was associated with social and communication deficits in the ASD group. While this pattern of results did not support our hypothesis, it closely resembled the pattern seen in the earlier cognitive control results (see General Discussion for elaboration on this), where there were slight differences at baseline that decreased as complexity increased (Mackie & Fan, 2015).

We found the cognitive control performance of the ASD group was less susceptible to interference by emotional information compared to the TD group. This is contrary to previous reports of increased interference in cognitive control performance by emotional information in ASD (Dichter & Belger, 2007). One possible explanation is that emotional stimuli do not hold the same information value for individuals with ASD as it does for neurotypical controls. Further supporting this idea, there appeared to be no difference in performance dependent on valence of information in the ASD group. For example, under the high load condition on the affective MFT, while TD performance decreased as frequency of fearful faces increased, ASD group performance was similar when the stimuli were all neutral compared to all fearful, and similar performance was also found when fear was low frequency compared to when neutral was low frequency. Nonetheless, the ASD group still used the emotional information to their advantage, as a facilitation effect of emotion was found in the 100% fearful condition. Compared to the
corresponding decrease in performance found in the TD group, this suggests differential effects of the presence of fearful information on cognitive control performance.

The ASD group performance relative to the TD group can again be considered in terms of the hypothetical efficiency performance models described in Chapter III (Figure 8). The results support Model B, in which there is a slight (but not always significant) group difference at baseline, and this difference decreases as a function of complexity. While unexpected, these patterns of results reliably demonstrate at the very least that cognitive control in the ASD group was not more susceptible to interference from emotional information than the TD group on these tasks.

These results are consistent with other studies that failed to find group differences in performance on tasks of emotion processing or emotion-cognition interactions (Adolphs et al., 2001; de Vries & Geurts, 2012; Fridenson-Hayo et al., 2016; Gedek, Pantelis, & Kennedy, 2016; Golan et al., 2006; Hubert, Wicker, Monfardini, & Deruelle, 2009; Louwerse et al., 2014). Overall, it appears that there is no clear evidence of a frank ASD deficit in affective cognitive control across a wider range of uncertainty values than is typically used to investigate this phenomenon.

**Limitations and alternative explanations**

The major limitation of this study was the limited sample size and associated power limitations. While within-subjects manipulations and associated power were quite strong, between-subjects effects were difficult to detect. In some cases it was clear that group differences would not be significant even with increased power (e.g., CERT), but on other tasks (e.g., MFT-E, RTom), it is likely that increased power would have resulted
in significant group differences and interactions. Due to limitations in our access to this population of high functioning adults with ASD with minimal comorbidities, increasing the sample size was not feasible.

Given that our sample was relatively high-functioning, these results may not generalize to the broader ASD population as a whole, particularly those with intellectual disability (Brown, Chouinard, & Crewther, 2017) and other neurodevelopmental disorders. It remains an open research question whether we would have found the expected group by uncertainty interaction effect with lower-functioning samples.

Although we attempted to increase ecological validity by incorporating facial picture stimuli that represented a wide range of actors displaying a wider range of emotions than is typically displayed in tasks that use emotional stimuli, the ecological validity of our tasks remained sub-optimal. The primary concern is that the stimuli were presented only to one sensory modality, whereas it has been suggested that difficulties with integration of information coming from multiple modalities may be responsible for social interaction deficits in naturalistic settings (Beaumont & Newcombe, 2006; Collignon et al., 2013), although there is other evidence that sensory modality does not impact group differences (Gedek et al., 2016). It has been argued that the social impairment in ASD may not be detectable on tasks that are not ecologically valid in the way that they simulate the experience of an autistic individual in a highly stimulating environment with need for rapid information processing (Barak & Feng, 2016; Wallace et al., 2016; Williams, Mazefsky, Walker, Minshew, & Goldstein, 2014). For the purpose of this study we chose to prioritize internal over ecological validity. Given that we did not
find frank deficits in processing of emotional information, using more ecologically valid tasks requiring multisensory integration remains a future direction for study.

An alternative explanation to the present results is that although group differences in performance were unclear, qualitative differences in the ways that the information was processed might still exist. That is, the groups processed the information differently, but arrived at comparable behavioral performance. Support for this possibility comes from previous studies that failed to show group differences on behavioral measures, but found qualitative (Adolphs et al., 2001; Dalton et al., 2005), physiological (Gu et al., 2015; Hubert et al., 2009), or neural processing (Duerden et al., 2013; Fan et al., 2012; Gu et al., 2015) differences between groups. These types of qualitative differences may be aided in part by the development of compensatory mechanisms in the course of development. Our sample was recruited in large part through the Seaver Autism Center, where participants had received an evaluation and/or services at some point in their development, such as social skills training. It is possible that exposure to these services may have contributed to a normalization of performance in adulthood (Adolphs et al., 2001). Consequently, it is unclear whether these results would generalize to others without exposure to such services.

As mentioned in Chapter II, successful social interaction relies on a series of several information processing steps that facilitate the selection of a suitable response, including encoding and interpretation of cues, setting goals for the situation, response construction and selection, and enactment of chosen response (Crick & Dodge, 1994;
Ziv, Hadad, & Khateeb, 2013). Each of these steps is guided by a mental database for social behavior that includes memories of past social situations, rules for behavior, etc. We did not capture explicit difficulty in the ASD group in encoding of social cues or interpretation of cues, and our data suggest that behavioral responses are overall generated just as efficiently as typically developing controls. However, examining the full range of processes involved in social interaction was beyond the scope of this study, and there is still the possibility of differential difficulty among the various steps even as development of some stages (i.e., encoding and interpretation) begin to approximate an age-appropriate level (Mazza et al., 2017). The presence of social deficits in ASD is well-documented, and a previous study has demonstrated deficits at every stage of these processes in preschoolers with ASD (Ziv et al., 2013), but differences in older children with ASD were less clear (Flood, Julian Hare, & Wallis, 2011), supporting the idea that social information processing development occurs at a slower rate in the ASD population.

**Conclusion**

This study aimed to investigate efficiency of cognitive control for emotional information and the relationship between emotional control deficits and the symptom presentation of ASD. We found that participants with ASD were not significantly less efficient than typically developing controls in employing cognitive control in the context of emotional information. Of three possible explanations of group differences in performance, the model in which the ASD group is less efficient than controls at baseline and group performances converge as they decline as a function of complexity. These findings suggest that there is not a frank deficit in affective cognitive control in adults
with ASD, especially when processing demands are high (DiCriscio et al., 2016). While this may appear counterintuitive, it is not at odds with an information theory approach to cognitive control, as outlined in Chapter V (General Discussion).
In this study, we aimed to investigate the efficiency and capacity of cognitive control in ASD relative to TD controls. We employed tasks that manipulated uncertainty in cognitive and affective domains, and examined the relationships between behavioral performance and ASD symptom report. We hypothesized that the ASD group would show reduced efficiency and capacity of cognitive control relative to TD controls, and have greater difficulty than TD controls with cognitive control as uncertainty increased. We expected that these deficits would be negatively correlated with ASD symptom report (i.e., lower performance associated with higher symptom report).

**General cognitive control deficits in ASD**

The present results support the hypothesis that high-functioning adults with ASD demonstrate lower efficiency and capacity for cognitive control under uncertainty. That is, the ASD group showed less efficient performance at baseline and had a lower capacity for rapid implementation of cognitive control. However, we did not find evidence that this deficit in cognitive control increased with increasing uncertainty. Rather, ASD performance either converged toward or stayed relatively parallel to the performance of the TD group. Performance on various tasks of cognitive control was negatively associated with ASD symptoms of social/communication deficits and restricted interest/repetitive behaviors.
Although counterintuitive, these results are not inconsistent with an information theory approach to cognitive control. It has been previously demonstrated that there is a linear increase in activation of the cognitive control network (notably in ACC and AI) and corresponding deactivation of the default mode network as a function of computational load measured in entropy (Fan et al., 2014). This increase in CCN activation is thought to reflect an increase in neural computation, while the deactivation in other regions represents the suppression of task-unrelated regions (e.g., DMN regions). Previous studies have shown deactivation of ACC and AI under lower entropy conditions, which suggests that activation of these regions is relative to state uncertainty (Fan et al., 2014). That is, if the uncertainty associated with the anticipation of the stimulus (e.g., during the fixation period) is higher than the task-related uncertainty, this will be reflected in a deactivation of these regions during task-related periods. Higher state uncertainty relative to task demands can occur when uncertainty is manipulated across a wide range of values, and participants learn to anticipate difficult trials.

Activation of ACC and AI is considered to be involved in dynamic switching between state uncertainty and task-related responses (Goulden et al., 2014). Participants with ASD have previously demonstrated an absence/hypoactivation of ACC under conditions of uncertainty that was associated with behavioral performance (Fan et al., 2012). Together with the present results, it appears that the initial separation of performance between the groups reflects higher state uncertainty at baseline in the ASD group and/or a higher threshold for activation of the CCN relative to state uncertainty. The activation threshold in healthy controls was previously estimated at 3.3 bits for
entropy. In our tasks, group performance converged on average at approximately 4 bits. Furthermore, while efficient switching between the cognitive control and default mode networks has been found to be related to efficient behavioral performance, failure to deactivate DMN under uncertainty has also been demonstrated in this population (Fan et al., 2012; Spencer et al., 2012). Converging evidence therefore supports the idea that the efficiency of implementation of cognitive control under conditions of uncertainty lags behind that of TD controls. However, once the difference between state- and task-related uncertainty becomes positive, implementation of cognitive control under uncertainty resembles that of TD, presumably via appropriate engagement of CCN and deactivation of DMN. A similar argument can be applied to our findings in the affective domain, as described below.

**Affective cognitive control deficits**

In the affective domain, we did not find support for the hypothesis that the ASD group would show greater deficits in affective cognitive control as uncertainty increased. Rather, the ASD group appeared to be less affected than the TD group by the presence/complexity of affective information, and emotional valence was non-contributory to performance in the ASD group. The pattern of results was remarkably similar to that in the cognitive domain, and therefore cannot be considered to be random “noise”.

Given the observed similar patterns of performance in the cognitive and affective domains, speculation about the possible neural mechanisms is warranted. In addition to their role in rapid information processing under uncertainty, the ACC and AI also have a
role in rapid processing and control of emotional information (Bush, Luu, & Posner, 2000; Carter et al., 1998; Craig, 2009; Critchley, Wiens, Rotshtein, Öhman, & Dolan, 2004; Fan et al., 2011). Furthermore, the ACC and AI have been demonstrated to have reciprocal connections with amygdala to regulate responses to emotional information (Bush et al., 2000; Ochsner & Gross, 2005; Wager, Davidson, Hughes, Lindquist, & Ochsner, 2008). Given these overlaps in neural circuitry for processing of cognitive and affective information, when both types of information are simultaneously present, they should compete for neural representation (Fan et al., 2011; Gu, Liu, Van Dam, Hof, & Fan, 2012; Padmala, Bauer, & Pessoa, 2011; L Pessoa, McKenna, Gutierrez, & Ungerleider, 2002; Luiz Pessoa, 2008). It has been demonstrated that stimulus valence interferes with cognitive control, and this may vary based on cognitive load with interference under high load and facilitation under low uncertainty (Gu et al., 2012). These results were replicated in our TD group, but the ASD group showed a different pattern of results, with no significant effect of emotional valence on cognitive control performance.

Two of our tasks of affective cognitive control (CERT and MFT-E) included distracting affective information that needed to be effectively filtered out for efficient task performance, while the other two tasks (MEPT and RToM) systematically increased the amount of affective to information to be processed, and placed increasing demands on the “cognitive” system of working memory. CERT performance confirmed that there is no explicit behavioral deficit in emotion recognition in ASD, consistent with other studies that failed to find group differences, even for other manipulations of complex
emotions (Fridenson-Hayo et al., 2016). However, on the tasks that manipulated amount of information to be processed a pattern similar to that on the cognitive tasks with a wide range of uncertainty was seen. Particularly for tasks with the widest range of affective uncertainty, the level of anticipatory state uncertainty is greatest, and performance efficiency looks closest to the TD group at the highest levels of uncertainty.

While previous studies have demonstrated a negative effect of emotional/social information on cognitive control in ASD (de Vries & Geurts, 2012; Dichter & Belger, 2007), we saw on the affective MFT that the ASD group was actually less susceptible to interference from emotional stimuli. Furthermore, the valence of the distracting emotional stimuli did not seem to matter to the ASD group, suggesting that they did not attend to negatively valenced stimuli (i.e., fear) in the same way as the TD group. In TD individuals, susceptibility to interference from distracting emotional information depends on the efficiency of cognitive control to prioritize task-relevant information over distractors (Mackie & Fan, 2015; Mackie et al., 2013; Mitchell et al., 2007; Mitchell, Richell, Leonard, & Blair, 2006). However, emotionally salient stimuli can capture attention resulting in stronger competition for representation (Davis, 2005; Fan et al., 2011; Gasquoine, 2014; Mitchell et al., 2007, 2006). This was not the case for the ASD group.

Many studies have described cognitive control, emotional processing, and mentalizing deficits in children and adolescents with ASD (review in Chapter II). However, the present results suggest that these deficits are not present in high-functioning adults with ASD. Their performance approaches normal, particularly as task
demands increase and cognitive control is engaged to a greater extent. This suggests either that individuals with ASD learn compensatory strategies over time that help to normalize their behavioral performance (even if achieved by alternate processing routes) (Hastings, 2003) or that there is simply a lag in the development of social and communication skills in ASD that begins to close in adolescence/early adulthood. Even in low-functioning groups, social behavior increases with social contact/imitation of others (Field, Sanders, & Nadel, 2001)

Conclusions

The present results support the idea that individuals with ASD have a lower capacity for cognitive control compared to TD individuals, but this does not necessarily mean impaired cognitive control performance across the board. There appears to be a lag in the implementation of cognitive control in the ASD group, such that a higher threshold of uncertainty is needed to trigger an adequate degree of control over information processing. The absence of frank deficits in affective cognitive control in this group stands in contrast with findings of clear patterns of deficits in children, suggesting that these processes are delayed in ASD, but come online later in development, at least in high functioning cohorts.

Overall, our data support a model of performance in which individuals with ASD are slightly less efficient in cognitive control at baseline, presumably due to inefficiency in engaging the CCN for processing of task-related uncertainty. However, as uncertainty increases, the CCN becomes more engaged and performance converges with that of TD controls. This information processing style is related (and likely contributes) to ASD
social/communication and restricted interests/repetitive behavior symptoms. Future studies may examine the processes that mediate the normalization of cognitive and affective control in high functioning adults with ASD.
Appendix A

Recursive Theory of Mind Task Sample Stimuli

MARK and LUKE

Mark and Luke are non-identical 13-year-old twins. Their mother has given them their allowance for the week. Every week they each receive a $5 note. However, this week their mother only has a $10 note and has left it up to them to split the money. Mark wants a CD that costs $9, and Luke needs to buy a book for his school project that costs $5. Mark wants to go into town and spend his half of the money. Luke wants to stay at home and work but is afraid that Mark will spend the money on the CD. Luke suggests that Mark should go into town to the bookshop first and buy the book for him, and then keep the change to spend on himself. Mark leaves for the town and Luke worries that Mark might not buy the book at all. After 20 minutes, Luke decides to call Mark on his cell phone to remind him. Mark tells Luke not to worry, he wrote the name of the book down so he won’t buy the wrong one.

Statements: Mark and Luke (T and F after statements indicate correct response. Number in parentheses indicates level of information; 'm' indicates 'memory' a.k.a. 'fact' statement, all others are theory of mind statements).

1) Luke wants to spend $5 on a book. T (2m) T/F
2) Mark believes that Luke thinks he has bought a CD. F (2) T/F
3) Luke needs a CD. F (1m) T/F
4) Luke thinks that Mark understands that Luke believes that Mark thinks that Luke knows he has spent the money. F (5)

5) Mark goes to town to buy a book that costs $5. T (3m)

6) Luke phones Mark to see if he has spent the $5 note on a book. F (3m)

7) They have a $10 note to take to town to buy a book for $5. T (4m)

8) Mark thinks Luke might keep the money. F (1)

9) Luke phones to see if the $5 note has been spent, in town, in a bookshop, on a book for his school project. F (5m)

10) Mark has gone to town, to go to a bookshop, to buy a book for Luke and his School Project. T (5m)


12) Mark has a $5 note and wants to go to town. F (2m)

13) Mark believes that Luke thinks that Mark does not know that Luke believes that they should share the money. F (4)

14) Luke thinks that Mark wants to keep the money. T (2)

15) They have a $10 note to buy a CD, in town that costs $5. F (4m)


17) Mark understands that Luke believes that Mark thinks the money should be spent on a CD. F (3)

18) Mark believes that Luke thinks that Mark knows that Luke believes that he cannot remember the name of the book. T (4)
19) Mark thinks that Luke believes that Mark knows that Luke thinks that Mark does not know the name of the book. T (5)   T/F
20) Mark goes to town. T (1m)   T/F
Appendix B

Response Time and Accuracy Results

Sequential information processing: Results of EVT

RT

Entropy. For RT, the main effect of Group was significant \((F(1,27) = 4.58, p < .05, \eta_p^2 = .15)\), and revealed that the ASD group \((M = 485\pm 75 \text{ ms})\) was slower to respond than the TD group \((M = 442\pm 43 \text{ ms})\) (Figure 17a). The assumption of sphericity was violated for \(entropy\), \(\chi^2(2) = 32.43, p < .05, \varepsilon = .58\), and with Greenhouse-Geisser correction there was a significant main effect of \(entropy\) \((F(1.17, 31.53) = 17.69, p < 0.001, \eta_p^2 = .40)\). Pairwise comparisons with Bonferroni correction revealed that RTs for \(H = 1\) \((M = 497\pm 64 \text{ ms})\) were significantly longer than for the \(H = 0.54\) \((M = 466\pm 62 \text{ ms})\) and \(H = 0\) \((M = 429\pm 70 \text{ ms})\) conditions \((ps < .01\), respectively). There was no significant difference between the \(H = 0\) and \(H = 0.54\) conditions \((p = .29)\). The Group by \(entropy\) interaction was not significant for RT \((F < 1)\). RT intercept was significantly higher ASD group \((M= 452\pm 80 \text{ ms}, R^2 = .87)\) than for the TD group \((M = 404\pm 43 \text{ ms}, R^2 = .96, t(27) = 1.99, p < .05, \text{one-tailed})\). There was no significant difference in RT slope between groups \((t(27) = -1.08, p = .29)\).

Surprise. The main effect of Group was trending toward significance \((F(1,27) = 3.91, p = .06, \eta_p^2 = .13)\), with slower performance in the ASD group \((M = 501\pm 88 \text{ ms})\) than the TD group \((M = 455\pm 57 \text{ ms})\) (Figure 17b). For \(surprise\), sphericity had been violated, \(\chi^2(5) = 32.23, p < .001, \varepsilon = .56\), and with correction there was a significant main
effect \((F(1.67, 45.17) = 119.35, p < .001, \eta_p^2 = .82)\). Pairwise comparisons with Bonferroni corrections revealed significant increases in RT for each increasing value of surprise \((429 \pm 70\, \text{ms}, 457 \pm 61\, \text{ms}, 497 \pm 64\, \text{ms}, \text{and } 532 \pm 77\, \text{ms for } I = 0, 0.19, 1, \text{and } 3, \text{respectively, all } ps < .001)\). The Group by surprise interaction was not significant for RT \((F<1)\). There was a higher accuracy intercept for the TD group \((M = 100 \pm 1\%, R^2 = .88)\) than the ASD group \((M = 99 \pm 2\%, R^2 = .83, t(27) = -1.79, p < .05, \text{one-tailed})\). There were no significant group differences in RT slope \((t(27) = 0.84, p = .41)\).

**Accuracy**

**Entropy.** The main effect of Group was significant \((F(1,27) = 4.10, p = .05, \eta_p^2 = .13)\), with TD group \((M = 96 \pm 3\%)\) performing more accurately overall than those in the ASD group \((M = 95 \pm 3\%)\) (Figure 17c). For entropy, sphericity was not violated \((\varepsilon = .93)\), and there was a significant main effect \((F(2,54) = 24.32, p < .001, \eta_p^2 = .47)\). Pairwise comparisons with Bonferroni correction demonstrated that accuracy was significantly higher for \(H = 0 \,(M = 99 \pm 1\%)\) compared to \(H = 0.54 \,(M = 97 \pm 2\%, p < .01)\), and \(H = 1, \,(M = 96 \pm 3\%, p < .01)\). There was no significant difference between the \(H = 0.54\) and \(H = 1\) conditions \((p = .13)\). The Group by entropy interaction was not significant \((F < 1)\). Accuracy intercept was significantly lower for the ASD group \((M = 98 \pm 1\%, R^2 = .71)\) than for the TD group \((M = 99 \pm 1\%, R^2 = .67, t(27) = -2.47, p < .01 \text{ one-tailed})\). There was no significant difference in accuracy slope between groups \((t(27) = -0.85, p = .40)\).
Surprise. There was no significant group difference for overall accuracy ($F(1, 27) = 1.30, p = .26$; Figure 17d). For surprise, the assumption of sphericity was violated, $\chi^2(5) = 112.05, p < .001$, $\varepsilon = .37$, and with correction there was a significant main effect ($F(1.17, 30.12) = 32.53, p < .001, \eta^2_p = .55$). Pairwise comparisons with Bonferroni corrections revealed significant decreases in accuracy for each increasing value of surprise from $I = 0.19$ up (Means: $98 \pm 2\%$, $96 \pm 3\%$, and $86 \pm 11\%$ for $I = 0.19$, $1$, and $3$ respectively, $ps < .05$, respectively) but not from $I = 0$ to $I = 0.19$ ($p = .87$). The Group by surprise interaction was not significant ($F < 1$). The TD group had a significantly
higher accuracy intercept \((M = 100\pm1\%, R^2 = .88)\) than the ASD group \((M = 99\pm2\%, R^2 = .83, t(27) = -1.85, p < .05, \text{one-tailed})\). There were no significant group differences in accuracy slope \((t(27) = -0.15, p = .88)\).

**Cognitive control for non-sequential stimuli: Results of the MFT**

**RT.** There was a significant main effect of Group (see Figure 18a), \(F(1,28) = 8.87, p < .01, \eta^2_p = .24\), indicating that the ASD group \((M = 1172\pm106 \text{ ms})\) had longer RTs than the TD group \((M = 1066\pm88 \text{ ms})\). For entropy, the assumption of sphericity had been violated, \(\chi^2(14) = 54.53, p < .001, \varepsilon = .56\), and with correction, there was a significant main effect of entropy, \(F(2.8, 78.9) = 683.88, p < .001\), such that RT increased with increasing information. There was no significant Group by entropy interaction \((F(2.8, 78.9) = 1.40, p = .25)\). There was no significant difference between the groups in RT slope \((t(28) = -0.41, p = .68)\), but RT intercept was significantly higher for the ASD group \((M = 650\pm126 \text{ ms}, R^2 = .95)\) than for the TD group \((M = 533\pm98 \text{ ms}, R^2 = .94, t(28) = 2.85, p < .01, \text{one-tailed})\).

**Accuracy.** There was a significant main effect of Group (see Figure 18b), \(F(1,28) = 8.11, p < 0.01, \eta^2_p = .23\), indicating that the ASD group \((M = 90\pm5\%)\) was significantly less accurate than the TD group \((M = 94\pm3\%)\). The assumption of sphericity had been violated for the entropy factor, \(\chi^2(14) = 148.60, p < 0.001\), therefore univariate ANOVA with Greenhouse-Geisser corrections are reported \((\varepsilon = .32)\). There was a significant main effect of the entropy on accuracy, \((F(1.6, 45.1) = 173.90, p < 0.001, \eta^2_p = .86)\), such that accuracy decreased with increasing information. The Group by entropy interaction was marginally significant, \(F(1.6, 45.1) = 3.32, p = .06, \eta^2_p = .11\). There was a significant
difference in accuracy slope between the groups ($t(28) = -2.01, p < .05$, one-tailed), indicating that accuracy decreased to a greater extent for the ASD group ($M = -.06 ± .02, R^2 = .76$) than for the TD group ($M = -.05 ± .02, R^2 = .65$), with increasing information load. There was no significant group difference for accuracy intercept ($t(28) = -0.971, p = .34$).

Cognitive control capacity under time constraints: Results of the DCT and MFT-M

**DCT**

**RT.** Figure 19a shows RT performance as a function of computational load. The main effect of Group was not significant ($F < 1$). Sphericity was violated for *entropy* $\chi^2(9) = 81.47, p < .001, \varepsilon = .50$, and with Greenhouse-Geisser correction there was a significant main effect ($F(2.01,56.22) = 233.17, p < .001, \eta_p^2 = .89$). Pairwise comparisons with Bonferroni correction indicated significant increases in RT with each increasing value of *entropy* (all $ps < .001$). The interaction between Group and Load was
not significant ($F(2.01,56.22) = 1.96, p = .15, \eta^2_p = .07$). There were no significant group differences for slope ($t(28) = -0.29, p = 0.39$) or intercept ($t(28) = 0.37, p = 0.36$).

**Accuracy.** Figure 19b shows accuracy performance as a function of computational load (entropy). The main effect of Group was significant ($F(1,28) = 11.81, p < .01, \eta^2_p = .30$), with less accurate performance from the ASD group ($M = 81\pm11\%$) than the TD group ($M = 95\pm11\%$). Sphericity was violated for entropy $\chi^2(9) = 79.44, p < .001, \varepsilon = .52$, and with Greenhouse-Geisser correction there was a significant main effect ($F(2.07,57.84) = 26.32, p < .001, \eta^2_p = .49$). Pairwise comparisons with Bonferroni correction indicated that there were significant decreases in accuracy from the 2-bit to 3-bit condition ($p < .01$), the 4-bit to 5-bit condition ($p < .01$), and the 5-bit to 6-bit conditions ($p < .001$), but not from 3 bits to 4 bits ($p = .37$). The interaction between Group and entropy was significant ($F(2.07,57.84) = 7.01, p < .01, \eta^2_p = .20$), with a greater decrease in accuracy in the ASD group compared to the TD group, as

![Figure 19. DCT RT and ACC on Task 2]
computational load increased. The ASD group ($M = -0.07 \pm 0.06$) had a significantly greater accuracy slope than the TD group ($M = -0.03 \pm 0.02$), $t(28) = -2.75, p < .01$. There were no significant group differences in intercept ($t(28) = 0.93, p = .18$).

**MFT-M. RT.** Results are presented in Figure 20. For ET, the assumption of sphericity was violated ($\chi^2(5) = 16.68, p < .01, \varepsilon = .67$), and with correction the main effect on RT was significant ($F(2.01, 48.12) = 67.12, p < .001, \eta_p^2 = .74$). Pairwise comparisons revealed significant increases in RT with each increase in ET (all $p_s < .001$). Sphericity was violated for Entropy ($\chi^2(2) = 18.41, p < .001, \varepsilon = .65$), and with correction the main effect on RT was significant ($F(1.29, 30.95) = 184.36, p < .001, \eta_p^2 = .88$).

![Figure 20. MFT-M RT Results](image)

Pairwise comparisons revealed significant increases in RT with each increase in entropy (all $p_s < .001$). Sphericity was violated for the ET by Entropy interaction ($\chi^2(20) = 63.20, p < .001, \varepsilon = .55$), and it was significant with correction ($F(3.32, 79.96) = 47.06, p < .001, \eta_p^2 = .66$), such that the extent to which RTs increased with entropy was greater with each increase in ET. The main effect of Group was not significant ($F < 1$). The ET
by Group ($F(3,72) = 1.32, p = .14, \eta_p^2 = .05$), Entropy by Group ($F < 1$), and ET by Entropy by Group ($F < 1$) interactions were not significant.

**CERT**

For RT (See Figure 21 a & b), there was a main effect of Complexity ($F(1,28) = 24.15, p < .001, \eta_p^2 = .46$), such that response times were longer on average in the compound emotion condition ($M \pm SEM = 1441 \pm 42$ ms) compared to the basic emotion condition ($M = 1365 \pm 42$ ms). The main effect of Group was not significant ($F < 1$).

For accuracy (Figure 21c & d) the main effect of Complexity was significant ($F(1,28) = 151.88, p < .001, \eta_p^2 = .84$), with significantly lower accuracy in the compound emotion condition ($M \pm SEM = 67 \pm 1\%$) compared to the basic emotion condition ($M = 79 \pm 1\%$). The main effect of Group ($F < 1$) was not significant. The Complexity by Group interaction trended toward significance ($F(1,28) = 2.42, p = .09, \eta_p^2 = .10$).

**Figure 21. CERT RT and accuracy results**
MEPT

In terms of RT (Figure 22a), for the main effect of Level, the assumption of sphericity was violated ($\chi^2(14) = 97.81, p < .001, \varepsilon = .48$), and Greenhouse-Geisser correction was applied ($F(2.4,68.1) = 18.06, p < .001, \eta^2_p = .39$), with longer RTs at higher levels of emotional information processing. The main effect of Group was not significant ($F<1$). The Level by Group interaction was not significant ($F<1$).

For accuracy (Figure 22b), the assumption of sphericity was violated for Level ($\chi^2(14) = 31.83, p < .01, \varepsilon = .69$); with correction the main effect was significant ($F(3.4,96.2) = 18.01, p < .001, \eta^2_p = .39$), with lower accuracy at higher levels of emotional information processing. The main effect of Group trended toward significance ($F(1,28) = 2.51, p = .06, \eta^2_p = .08$, one-tailed). The Level by Group interaction was not significant ($F<1$).

RTToM
In terms of RT, sphericity was violated for Level ($\chi^2(5) = 47.29, p < .001, \epsilon = .49$), and with correction the main effect was significant ($F(1.5, 41.4) = 46.36, p < .001, \eta_p^2 = .63$). Pairwise comparisons revealed significant increases in RT with each increase in Level (all $p$s < .001, see Figure 23a). The main effect of Type of information was significant ($F(1, 28) = 74.80, p < .001, \eta_p^2 = .72$), with significantly longer RT for theory of mind questions ($M = 8244 \pm 648$ ms) compared to fact questions ($M = 4669 \pm 321$ ms). The main effect of Group was not significant ($F<1$). Sphericity was also violated for Level by Type of information ($\chi^2(5) = 48.77, p < .001, \epsilon = .51$), and with correction the interaction effect was significant ($F(1.5, 41.4) = 21.12, p < .001, \eta_p^2 = .44$), such that as Level increased, the RT difference between the two information types also increased. The Level by Group, Type by Group, and the three-way interaction were not significant (all $F$s < 1).

![Figure 23. RToM RT and accuracy results](image_url)
For accuracy, the main effect of Level was significant \( (F(3, 84) = 29.30, p < .001, \eta^2_p = .50) \), such that accuracy decreased as information increased (Figure 23b). Accuracy decreased significantly for each increasing level of information (all ps < .05). The main effect of Type was significant \( (F(1, 28) = 3.40, p = .04, \eta^2_p = .26, \text{one-tailed}) \), with lower accuracy for theory of mind questions \( (M = 75 \pm 2\%) \) compared to factual questions \( (M = 81 \pm 2\%) \). The main effect of Group trended toward significance \( (F(1, 28) = 2.50, p = .07, \eta^2_p = .08) \), with lower accuracy in the ASD group \( (M = 75 \pm 2\%) \) compared to the TD group \( (M = 81 \pm 2\%) \). The Level by Type interaction was significant \( (F(1, 28) = 3.33, p = .02, \eta^2_p = .10) \), with lower accuracy for theory of mind questions as the amount of information increased. The Level by Group \( (F(3,84) = 2.38, p = .08, \eta^2_p = .08) \) and Level by Type by Group \( (F(3,84) = 2.77, p = .06, \eta^2_p = .09) \) interactions trended toward significance. The Type x Group \( (F<1) \) interaction was not significant.

**MFT-E**

For RT (Figure 24), The main effect of Frequency was significant \( (F(4,112) = 3.46, p = .01, \eta^2_p = .11) \), with longer response times associated with higher frequency of fearful faces. The main effect of Uncertainty was also significant \( (F(4,28) = 155.45, p < .001, \eta^2_p = .85) \) with longer response times with higher uncertainty. The main effect of Group was not significant \( (F(1,28) = 1.15, p = .29, \eta^2_p = .04) \). The Group by Frequency \( (F<1) \), Group by Uncertainty \( (F<1) \), Frequency by Uncertainty \( (F<1) \), and the Frequency by Uncertainty by Group \( (F(4,112) = 1.15, p = .26, \eta^2_p = .05) \) interactions were not significant.
In terms of accuracy, the main effect of Frequency was not significant \((F(4,112) = 1.44, p = .23, \eta^2_p = .05)\). The main effect of Uncertainty was significant \((F(1,28) = 16.71, p < .001, \eta^2_p = .39)\), with lower accuracy in the high uncertainty compared to the low uncertainty condition. The main effect of Group was not significant \((F<1)\). The Frequency by Uncertainty interaction was significant \((F(4,104) = 4.48, p = .001, \eta^2_p = .15)\), such that the effect of uncertainty increased as frequency of fearful faces increased. The Frequency by Group \((F<1)\), Uncertainty by Group \((F<1)\), and three-way \((F<1)\) interactions were not significant.

![Graph showing MFT-E results](image)
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