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Executive function, motivation, and emotion recognition in high-functioning autism spectrum disorder

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ABSTRACT

Background: Several neurocognitive theories have been put forward to explain autism spectrum disorder (ASD). However, the specificity of executive cognitive, motivational (i.e., reward-related), and emotion-recognition impairments in ASD, and the role of early language delay in these impairments remain largely unclear.
Aim: This study aimed to examine executive cognitive, motivational, and emotion-recognition functions while considering the potential effect of language delay in ASD.
Methods: Twenty-two adolescents with high-functioning ASD (20 males) and 22 typically developing (TD) adolescents (16 males) aged 11–18 years were recruited. Each completed seven computerized tasks measuring executive cognitive (i.e., set-shifting, inhibition, updating, and access/generativity), motivational (i.e., flexible reinforcement learning and affective decision-making), and emotion-recognition functions (i.e., facial emotion recognition).
Results: We found that ASD participants with early language delay ($n = 10$) had poorer executive cognitive, motivational, and emotion-recognition functioning than TD controls, and had poorer executive cognitive and motivational functioning than ASD participants without language delay ($n = 12$). ASD participants without language delay only had poorer emotion recognition than TD controls.
Conclusion and implications: These preliminary findings suggest impairments in executive cognitive and motivational functions as well as emotion recognition in ASD with language delay, and impairment only in emotion recognition in ASD without language delay. They implicate a potential partial distinction in mental abilities between ASD with and without early language delay, highlighting the importance of considering language delay when evaluating executive cognitive and motivational functions in ASD.

What this paper adds?

In this study, we found that ASD with early language delay had impairments in executive cognitive, motivational, and emotion-recognition functions, whereas ASD without early language delay had impairment only in emotion recognition skills. Because ASD individuals with and without early language delay exhibited different levels of executive cognitive and motivational functioning, but

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comparable emotion recognition abilities, our findings argue for a partial distinction in mental abilities between ASD with and without early language delay. Our finding of a lower correlation between age and executive cognitive functioning in adolescents with ASD than in TD controls also suggests that executive dysfunction in adolescents with ASD may be partly attributable to an absence of age-related improvement. This finding highlights the importance of considering the developmental context when studying the executive cognitive function of ASD.

1. Introduction

Autism spectrum disorder (ASD) is a neurodevelopmental disorder characterized by "persistent deficits in social communication and social interaction" and by "restricted, repetitive patterns of behavior, interests, or activities" (American Psychiatric Association, 2013, p. 50). Several neurocognitive theories have been put forward to explain this disorder. The executive dysfunction theory posits that ASD is partly due to impairment in the higher-order cognitive processes that underlie goal-directed behavior, such as mental flexibility and inhibition (Hill, 2004). Supporting this hypothesis, recent meta-analyses have reported moderate impairments across different domains of executive cognitive function (Demetriou et al., 2018; Lai et al., 2017); we use the term "executive cognitive function" instead of "executive function" in this article because the executive dysfunction theory focuses on the cognitive aspects of executive function. In addition, the social motivation theory posits that ASD can be construed as an extreme case of diminished social motivation (Chevallier, Kohls, Troiani, Brodkin, & Schultz, 2012). In fact, recent systematic reviews and meta-analyses have shown diminished motivational (i.e., reward-related) behavior and neural responses to reward in both social and nonsocial domains, suggesting a general impairment in motivation and reward processing in ASD (Bottini, 2018; Clements et al., 2018). Furthermore, the amygdala theory (Baron-Cohen et al., 2000), and later the orbitofrontal-amygdala circuit theory (Bachevalier & Loveland, 2006), postulate that dysfunction of the amygdala or the orbitofrontal-amygdala circuit underlies socio-emotional impairment in ASD. Supporting these theories, recent meta-analyses have reported moderate-to-large impairments in emotion recognition in ASD across age and IQ, with a statistical trend toward poorer recognition of fear than for happiness (Uljarevic & Hamilton, 2013).

While these theories have received empirical support for capturing the impaired mental abilities (i.e., executive cognitive, motivational, and socio-emotional impairments) in ASD, they focus only on isolated aspects of this disorder. As such, the tendency has been to study executive cognitive, motivational, and socio-emotional functions separately; consequently, it is largely unclear whether the impaired task performance in ASD as reported by individual studies are pertinent to mental functions assumed to be measured by individual tasks or to processes that are recruited across tasks. For example, previous findings of impaired performance on executive functioning tasks in ASD may reflect impairment in executive function components, such as set-shifting and response inhibition, or in task-nonspecific functions, such as a lack of task engagement and attention over time. In fact, some studies have reported interrelationships between executive cognitive, motivational, and socio-emotional impairments in various psychiatric and neurological conditions, raising the possibility that impaired task performance in one specific domain could be the result of some general processing difficulties (Brand et al., 2005; Henry, Phillips, Crawford, Ietswaart, & Summers, 2006; Lee, Lee, Kweon, Lee, & Lee, 2009).

Several studies have examined multiple functional domains in ASD and have reported mixed findings. While some studies have reported impairments in flexible reinforcement learning and set-shifting (Ozonoff et al., 2004), or in affective mentalizing and set-shifting in ASD (Zimmerman, Ownsworth, O'Donovan, Roberts, & Gullo, 2016), others have reported impairment in flexible reinforcement learning and affective decision-making, but not in set-shifting or working memory in ASD (Yerys et al., 2009; Zhang et al., 2015). In addition, one study has reported impaired set-shifting and affective mentalizing, but intact affective decision-making in adults with Asperger's syndrome (AS; Gonzalez-Gadea et al., 2013). Despite these findings, no study to date has attempted to compare the various neurocognitive theories used to explain these executive cognitive, motivational, and socio-emotional impairments in ASD. In this study, we assessed each of these three functions in ASD to determine whether ASD impairs task performance in all of the three domains or only in some of the domains.

It is widely agreed that considerable variability exists within ASD. For example, while some individuals with ASD exhibit early language delay, others do not (Klin, Pauls, Schultz, & Volkmar, 2005). Although some studies have failed to report discernible differences in cognition and behavior between ASD with and without disrupted early language acquisition (i.e., high-functioning autism (HFA) and AS; Macintosh & Dissanayake, 2004), other studies have shown that these two ASD subtypes are differentiable on the basis of clinical characteristics and cognitive abilities. For example, according to a recent systematic review, three times as many studies report "significant or near significant level of differences" between AS and HFA as studies reporting "no differences" between them on many clinical variables (Tsai & Ghaziuddin, 2014). In addition, several empirical studies have reported (greater) impairment in set-shifting (Rinehart, Bradshaw, Moss, Brereton, & Tonge, 2001), mentalizing skills (Montgomery et al., 2016), and general intelligence (Manjiviona & Prior, 1999) in HFA than in AS. Some research with children/adolescents with ASD or typical development has shown that language, such as inner speech use, is associated with executive functioning (Russell, Saltmarsh, & Hill, 1999; Wallace, Silvers, Martin, & Kenworthy, 2009) and emotion recognition skills (Beck, Kumschick, Eid, & Klann-Delius, 2012). However, it remains largely unclear about the influence of disturbed language acquisition on later mental functioning in ASD.

This study has two specific objectives. First, we asked whether executive cognitive, motivational, and emotion-recognition functions were all impaired in ASD. Second, we compared ASD with and without a history of language delay during early development; early language delay was operationalized as the absence of single words by age 2 or communicative phrases by age 3 (Noterdaeme, Wriedt, & Höhne, 2010; Takarae, Luna, Minshew, & Sweeney, 2008). If significant differences in any aspect of mental ability were to be found between ASD with and without early language delay, then this would constitute a support for the moderating role of early language acquisition in the later mental functioning of ASD.

2. Methods

2.1. Participants

Twenty-two adolescents with high-functioning ASD and 22 TD adolescents aged 11–18 years were recruited from secondary schools and via advertisements disseminated on the campuses and among service providers for children with special educational needs. All adolescents in the ASD group had a diagnosis of ASD, autism, AS, or pervasive developmental disorder not otherwise specified before participating in this study. Their diagnoses were confirmed by a clinical psychologist blind to the study's hypotheses. Diagnosis was confirmed based on the *DSM-5* criteria for ASD (American Psychiatric Association, 2013), and the Autism Diagnostic Interview-Revised (ADI-R; Lord, Rutter, & Le Couteur, 1994). None had a history of epilepsy disorder or concussion. In addition, none of the adolescents in the TD group had a history of any neurological or psychiatric disorders, and all scored below the cutoff on any of the ADI-R subscales. All of the TD adolescents were further screened using the second edition of the Social Responsiveness Scale (SRS-2) to ensure that they obtained a *T*-score < 60, which corresponds to the cutoff for clinically significant social impairment over the past six months (Constantino & Gruber, 2012).

Furthermore, the intelligence quotient (IQ) for each adolescent in the TD and ASD groups was estimated using the short form of the Hong Kong Version of the Wechsler Intelligence Scale for Children-Fourth Edition (WISC-IV-HK:SF; Wechsler, 2010). All adolescents obtained an IQ > 80 and self-reported normal or corrected-to-normal vision. We recruited participants using a variety of means and venues (e.g., online advertisement and service providers for ASD). In addition, for all the participants that we came into contact, we invited every adolescent who met the inclusion and exclusion criteria to take part in our study. Thus, the sample that we collected was a relatively unbiased representation of the population. All adolescents and parents provided written informed consent prior to the study. This study was approved by the Joint Chinese University of Hong Kong—New Territories East Cluster Clinical Research Ethics Review Committee. All procedures were conducted in accordance with the Declaration of Helsinki.

2.2. Procedure and materials

Each adolescent undertook an individual neuropsychological assessment while their parents participated in a semi-structured interview to collect data about the adolescent's developmental and medical history. During the neuropsychological assessment, adolescents were administered the WISC-IV-HK:SF (Wechsler, 2010), plus seven computerized tasks administered in a randomized order that was different for each participant. Fig. 1 illustrates an overview of the tasks. Four of these computerized tasks measured the core components of executive functions, including shifting, inhibition, updating, and access/generativity (Fisk & Sharp, 2004; Miyake et al., 2000). Two tasks measured reward-related functions, including flexible reinforcement learning and affective decision-making (Happaney, Zelazo, & Stuss, 2004; O'Doherty, 2004). One task measured emotion-recognition function, specifically facial emotion recognition. The battery took approximately 2 h to complete, including breaks.

We chose an unbalanced number of tasks because of time and fatigue factors as well as other considerations. First, executive function is a heterogeneous construct that is elusive to define and difficult to measure (Miyake & Friedman, 2012; Royall et al., 2002). For example, there have been inconsistencies in the number of components of executive function (Royall et al., 2002)—factor-analytic studies have shown that the number can vary from 3 (Miyake et al., 2000), 4 (Fisk & Sharp, 2004), to at least 18 (Packwood, Hodgetts, & Tremblay, 2011). In this study, we focused on executive function components that are consistently identified across studies, including shifting, inhibition, updating, and access to long-term memory or verbal fluency (Fisk & Sharp, 2004; Miyake et al., 2000; Packwood et al., 2011), and used one task for each component. Using this approach, the construct of executive function could then be maximally measured within a reasonable time period. In addition, many executive function tasks are complex, and poor performance on these tasks can be driven by deficits in non-executive processes, such as slow visual processing and motor speed (Miyake & Friedman, 2012). To ensure that our measures reflected executive functioning, most of the executive function tasks that we employed involved an executive demand condition and a matched control condition that had little executive demand. A contrast between these two conditions would allow us to isolate the executive process of interest.

We assessed motivational functioning using the two most representative tasks of reward-related functions in the field of neuropsychology (Happaney et al., 2004). In addition, we employed only one task for emotion recognition because facial emotion recognition has been the most widely studied aspect of emotion recognition in ASD research (Uljarevic & Hamilton, 2013). More importantly, this task involved the full range of basic emotions (i.e., happiness, sadness, anger, fear, disgust, and surprise) and neutral expressions. Thus, this task measured the ability to recognize emotions in general; its summary measure, the overall unbiased hit rate (see Section 2.2.3), also gave a relatively stable estimate of this ability.

2.2.1. Executive cognitive function tasks

A cued task-switching paradigm, involving two blocks of 49 trials each, was employed to measure shifting (Meiran, 1996). In each trial, a square grid was first presented for 1000 ms, after which a cue (i.e., "left/right? or "up/down?") appeared below the grid. After 100 or 1000s, a red circle appeared in one of the quadrants, and participants were required to judge the position of the circle in either the horizontal or vertical dimension. Trials were classified into repeat and switch trials, depending on whether the current task was the same or different from the previous task. The dependent variable (DV) was the RT switch cost, calculated by subtracting the mean RT on repeat trials from that of switch trials.

A go/no-go task, involving four blocks of 72 trials each, was employed to measure inhibition (Picton et al., 2006). Test stimuli comprised the letters *A*, *B*, *C*, and *D*. In each trial, a letter was presented for 300 ms, followed by a blank screen for 700 ms. In the

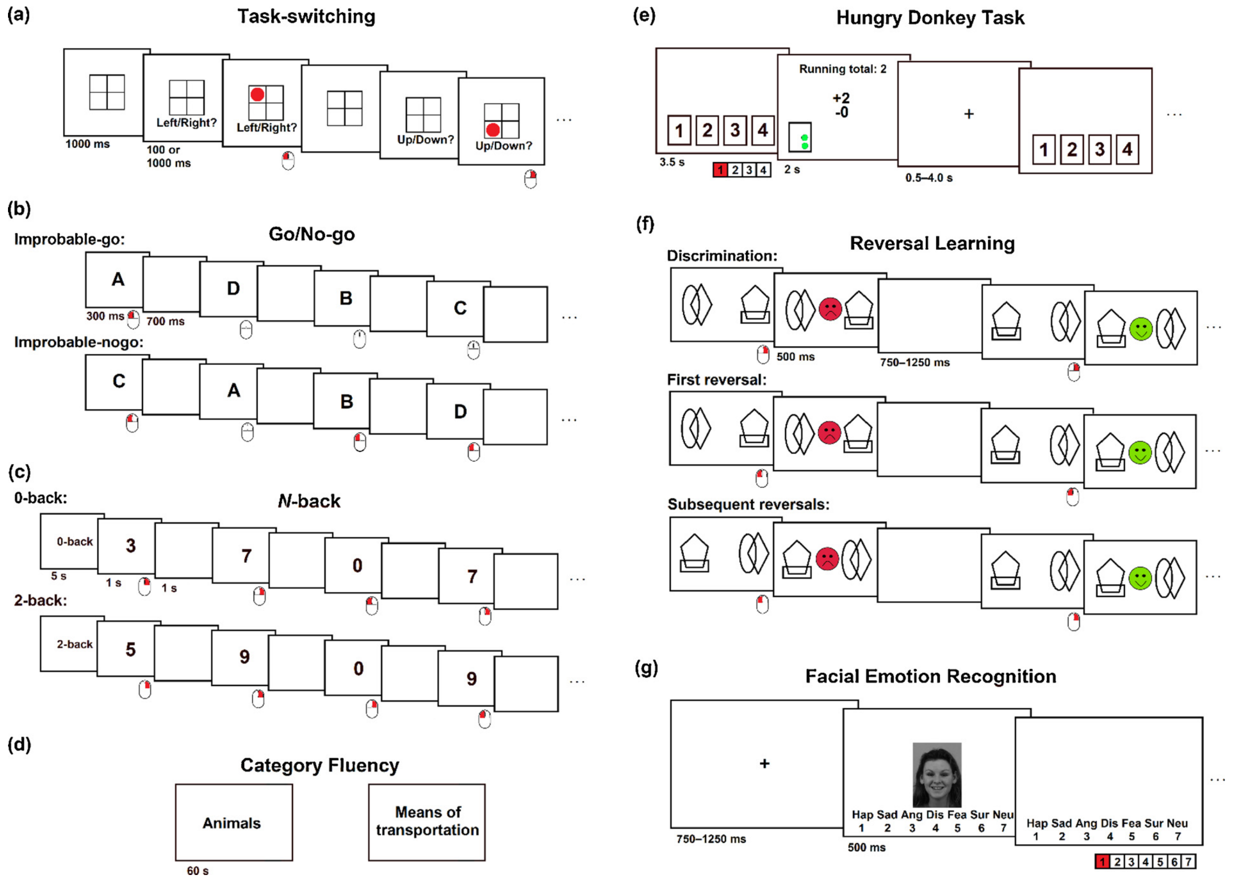

Fig. 1. Flow diagrams of the seven computerized tasks employed in this study. These tasks included the (a) task-switching paradigm, (b) go/no-go task, (c) *n*-back task, (d) category fluency task, (e) Hungry Donkey Task, (f) reversal learning task, and (g) facial emotion recognition task. The id of the sample image taken from the Karolinska Directed Emotional Faces stimulus set in (g) is AF09HAS.

improbable-go condition, participants had to press a mouse button only to the letter *A*; in the improbable-nogo condition, participants had to respond to all letters except for the letter *A*. Speed and accuracy were equally emphasized. The blocks were presented in either the *Go-Nogo-Nogo-Go* or *Nogo-Go-Go-Nogo* sequence, and the two sequences were counterbalanced across participants. The DV was the difference in RT-adjusted correct rejection rate between the two conditions.

The category fluency task was employed to measure access/generativity (Chan & Poon, 1999). Participants were required to produce as many words as they could belonging to animals or means of transportation, one minute per category. The DV was the total number of words produced.

A digit version of the *n*-back paradigm, with 0- and 2-back conditions, was employed to measure updating in working memory (Kirchner, 1958). The 0- and 2-back tasks were performed alternately in blocks (i.e., five target and 15 nontarget trials each), three times for each task. Each trial consisted of a single-digit shown for 1000 ms, followed by a blank interval of 1000 ms. Participants were required to press the left and right mouse buttons for targets and nontargets, respectively. In the 0-back condition, the target was the digit *0*; in the 2-back condition, the target was any digit that was identical to the digit that appeared two trials before. The DV was the difference in *A*', a performance index that considers both hit and false alarm rates between the two conditions (Snodgrass and Corwin, 1988). We used *A*' instead of accuracy because there was an unequal number of target and nontarget trials, and accuracy could be confounded by response bias. For example, classifying all digits as targets and nontargets would result in the same *A*' (i.e., 0.5) but different accuracies (i.e., 0.25 and 0.75, respectively). In addition, we analyzed *A*' rather than RT because the hit and false alarms, both of which are considered by *A*', are more sensitive in detecting cognitive impairment in patients (Tsuchida & Fellows, 2009).

2.2.2. Motivational or reward-related tasks

A reversal learning task was employed to measure flexible reinforcement learning (Cools, Clark, Owen, & Robbins, 2002). In this task, participants chose between two figural stimuli on a trial-by-trial basis. Participants were asked to learn and choose via button press the object that was rewarded most of the time. A green smiley face (i.e., positive feedback) or a red sad face (i.e., negative feedback) appeared for 500 ms after a response was made, and congruent feedback was provided 80 % of the time. There were three phases; in the discrimination phase, participants were required to reach the criterion of eight correct responses out of 10 consecutive responses in 50 trials (D'Cruz et al., 2013). After reaching the criterion, stimulus-reward contingencies reversed. When the criterion was met again in 50 trials, there would be 70 trials, during which the stimulus-reinforcement contingencies would reverse whenever the criterion was reached. Participants were asked to get as many smiley faces as possible. The DV was the total number of errors in all reversal phases.

The Hungry Donkey Test (HDT) was employed to measure affective decision making (Hooper, Luciana, Conklin, & Yarger, 2004). In this task, participants were asked to choose between four options (i.e., doors), each with a cost or reward in apples, on a trial-by-trial basis. Two options were advantageous in the long run, whereas the other two options were disadvantageous in the long run. The reward schedule was the same as that used in the Iowa Gambling Task (Bechara, Tranel, & Damasio, 2000), except that the magnitude of reward was reduced by 25 times. In each trial, participants had to select a door via button press on a keyboard. After a response was made, feedback conveying information about the running total, and the gain and loss of the current trial was shown for 2 s. Participants were asked to get as many apples as they could. The DV was the net score (i.e., difference between the number of advantageous and disadvantageous selections).

2.2.3. Emotion-recognition task

A forced-choice labeling task was employed to measure facial emotion recognition. Test stimuli consisted of photographs of faces selected from the Karolinska Directed Emotional Faces (KDEF; Lundqvist, Flykt, & Öhman, 1998). The facial expressions fell into the six basic emotions and the neutral expression. Ten photographs were selected for each emotion. In each trial, a photograph was shown, along with a horizontal array of seven options displayed underneath the photograph. The photograph disappeared after 500 ms, whereas the response options remained onscreen. Participants were asked to select the option that best matched the emotion depicted by the photograph via button press on a keyboard. The DV was the mean unbiased hit rate (Wagner, 1993), calculated by averaging the arcsine-transformed unbiased hit rates across all expressions. The unbiased hit rate is a performance index that controls for response bias and false alarms; the formula for calculating this index is [hit rate × (correct classification for an emotion category/ marginal frequency of using the respective emotion label)].

2.2.4. Psychometric properties of measures based on the existing literature

Based on the existing literature, the test-retest reliability (i.e., Pearson's r between two testing occasions that are several weeks apart) is 0.64 for the accuracy difference (i.e., high > low load) on the verbal n-back task, 0.68 for the RT switch cost on the task-switching paradigm, 0.65 for the commission rate on the go/no-go task, 0.68 for the number of words produced on the category fluency task, 0.35–0.65 for the total score on the Iowa Gambling Task (i.e., HDT), and 0.39–0.54 for the unbiased hit rate on the facial emotion recognition task (Cecilione et al., 2017; Harrison, Buxton, Husain, & Wise, 2000; Soveri et al., 2018; Weafer, Baggott, & de Wit, 2013; Xu, Korczykowski, Zhu, & Rao, 2013). The intraclass correlation coefficients are 0.03–0.74 for different error measures on the probabilistic reversal learning task (Freyer et al., 2009).

2.3. Data analysis

Three composite scores were generated to represent executive cognitive, motivational, and emotion-recognition abilities. The executive cognitive composite score was calculated by averaging the Z scores of the four executive cognitive tasks, the motivational composite score was calculated by averaging the Z scores of the two reward-related tasks, and the emotion-recognition composite score was based on the Z score of the facial emotion recognition task. The Z-transformation was based on the means and SDs of the TD group. One TD adolescent and two adolescents with ASD and early language delay failed to reach the criterion of the reversal learning task. These three people were excluded in all analyses involving this task.

For the go/no-go task, we used the RT-adjusted correct rejection rates as recommended by Seli, Jonker, Cheyne, and Smilek (2013) because of speed-accuracy tradeoffs in the improbable-nogo condition (i.e., Pearson's r between the mean RT and correct rejection rate in the whole sample = .56, $p < .001$). These indices were calculated based on the residuals of a linear regression line with the correct rejection rate as the DV and mean RT as covariate (Cohen & Cohen, 1983). Although there were no speed-accuracy tradeoffs in the improbable-go condition ($r = -0.06$, $p = .68$), the RT-adjusted correct rejection rate was also used for this condition so we could appropriately contrast the two conditions. Note, however, that the raw and RT-adjusted correct rejection rates in the improbable-go condition were almost equal because the correlation between the correct rejection rate and RT in this condition was close to zero. As a check for normality that is required by the linear regression model, we performed Kolmogorov-Smirnov tests with a Bonferroni-corrected p-value threshold of 0.0125. Results showed that all variables, $ps > .026$, except the correct rejection rate in the improbable-go condition, $p < .001$, met the normality assumption in the whole sample. However, using the difference in RT-adjusted correct rejection rates between the two go/no-go conditions or just the RT-adjusted correct rejection rate in the improbable-nogo condition yielded the same results. Thus, we report the results of analysis using the difference score because it reflected the inhibition process of interest.

We divided the ASD group into language delay (ASD-LD; $n = 10$) and no language delay (ASD-NLD; $n = 12$) groups to examine the potential moderating effects of early language delay on mental abilities in ASD. Participants were considered to have a history of language delay if they failed to produce their first single words by 24 months or to produce their first communicative phrases by 36 months (Takarae et al., 2008). We performed ANOVA and Fisher's exact tests (two-tailed) to compare the three groups on sample characteristics. Kolmogorov-Smirnov tests were subsequently conducted to check the normality assumption for the three composite Z scores, none of which were found to have violated the normality assumptions in the TD, ASD-NLD, or ASD-LD groups, $ps > .14$. Therefore, ANOVAs were conducted on the composite Z scores to compare the TD, ASD-NLD, ASD-LD groups. Post-hoc t-tests (one-

Table 1
Demographic, Intellectual, and Clinical Characteristics of Typically Developing (TD), Autism Spectrum Disorder with No Language Delay (ASD-NLD), and Autism Spectrum Disorder with Language Delay (ASD-LD) Groups.

	TD (n = 22)	ASD				
		ASD-NLD (n = 12)	ASD-LD (n = 10)			
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*F*	*p*	Post-hoc *t*-test
Age (year)	14.27 (1.75)	13.73 (2.25)	15.28 (1.99)	1.75	.19	–
Gender (male/female)[#]	16/6	12/0	8/2	–	.13	–
IQ	106.73 (12.92)	108.00 (15.52)	99.60 (15.25)	1.13	.33	–
ADI-R Social Interaction	2.73 (2.47)	14.58 (4.78)	22.00 (4.27)	107.56	< .001***	TD < ASD-NLD < ASD-LD
ADI-R Verbal Communication	1.41 (1.89)	10.92 (3.45)	16.40 (3.34)	116.86	< .001***	TD < ASD-NLD < ASD-LD
ADI-R Restricted and Stereotyped Behavior	0.05 (0.21)	4.42 (1.31)	4.40 (1.96)	79.12	< .001***	TD < ASD-NLD, ASD-LD
SRS-2 Total (*T*-score)	47.95 (3.85)	68.17 (12.93)	73.40 (8.28)	42.73	< .001***	TD < ASD-NLD, ASD-LD

Note. ADI-R = Autism Diagnostic Interview-Revised; IQ = Intelligence Quotient; SRS-2 = Social Responsiveness Scale-Second Edition. Post-hoc *t*-tests were qualified by $p < .017$ (i.e., Bonferroni correction). [#]Fisher's Exact Test was performed for group comparison. ***$p < .001$.

tailed) with Bonferroni correction were then conducted for pairwise comparison for (marginally) significant ANOVA results. One-tailed *t*-tests were used to compare task performance between groups because directional hypotheses were made—we hypothesized that adolescents with ASD, regardless of the presence of early language delay, performed worse than TD adolescents. We also expected that ASD participants with language delay performed worse than those without language delay.

Finally, we carried out Pearson's correlation analyses (two-tailed) to describe the relationships between age or IQ and mental abilities separately in TD and ASD adolescents (i.e., ASD with and without early language delay combined). If a correlation was significant within any group, a *Z* test would be performed to compare the correlation coefficients between the TD and ASD groups after Fisher's *r*-to-*z* transformation. The significance level was set at 0.05 for all statistical tests, unless otherwise specified. In addition, *p*-values that were larger than the *p*-value thresholds but at the same level as the *p*-value thresholds after rounding to the nearest 0.01 level were considered marginally significant.

3. Results

3.1. Sample characteristics

Table 1 presents the demographic, intellectual, and clinical characteristics of the TD, ASD-NLD, and ASD-LD groups. First, ANOVA and Fisher's exact tests were conducted to compare sample characteristics among these groups. We found no significant group differences in terms of age, gender, or IQ, $ps > .13$. In addition, we found significant group differences in all the ADI-R subscale scores and the SRS-2 total *T*-score, $Fs > 42.73$, $ps < .001$. Post-hoc *t*-tests showed that both the ASD-LD and ASD-NLD groups had significantly higher scores than the TD group for all variables, $ps < .001$. In addition, the ASD-LD group had significantly higher scores than the ASD-NLD group on the ADI-R social interaction and verbal communication subscales, $ps = .001$, but not on the ADI-R restricted and stereotyped behavior subscale or the SRS-2 total scale, $ps > .28$.

3.2. Executive cognitive, motivational, and emotion-recognition functions

A scatterplot of the composite *Z* scores with means and *SD*s in each group is shown in Fig. 2, and the raw scores that formed these composite scores are presented in Table 2. We first performed a mixed ANOVA with Group (TD, ASD-NLD, ASD-LD) as between-subjects factor and Domain (executive, motivational, emotional) as within-subjects factor on the composite scores. The main effect of Group was significant, $F(2, 38) = 10.65$, $p < .001$, $\eta_p^2 = .36$. Post-hoc Bonferroni tests showed that the ASD-LD group in general had a significantly poorer performance than the TD, $p < .001$, and ASD-NLD groups, $p = .036$. There was no significant difference between the TD and ASD-NLD groups, $p = .18$. No other main or interaction effects were significant, $Fs < 2.11$, $ps > .13$.

We then conducted planned ANOVA to compare the three groups on the executive cognitive, motivational, and emotion-recognition composite *Z* scores separately. There were significant group differences in the executive cognitive composite score, $F(2, 41) = 7.19$, $p = .002$, $\eta_p^2 = .26$, and the emotion-recognition composite score, $F(2, 41) = 5.60$, $p = .007$, $\eta_p^2 = .21$. In addition, there was a marginally significant group difference in the motivational composite score, $F(2, 38) = 3.20$, $p = .052$, $\eta_p^2 = .14$. For the executive cognitive composite score, post-hoc one-tailed *t*-tests (*p*-value threshold = .017) showed that the ASD-LD group had a (marginally) significantly lower score than both the TD, $p = .007$, and ASD-NLD groups, $p = .018$. There was no significant difference between the TD and ASD-NLD groups, $p = .21$. For the motivational composite score, post-hoc *t*-tests also showed that the ASD-LD group had a (marginally) significantly lower score than both the TD, $p = .013$, and ASD-NLD groups, $p = .019$. There was no significant difference between the TD and ASD-NLD groups, $p = .33$. For the emotion-recognition composite score, post-hoc *t*-tests showed that both the ASD-LD, $p = .003$, and ASD-NLD groups, $p = .001$, had a significantly lower score than the TD group. There was no significant difference between the two ASD groups, $p = .25$. In sum, early language delay moderated impairments in executive cognitive and motivational functions, but not in emotion recognition in ASD.

Because the sample size of this study was relatively small, it is possible that some of the nonsignificant results were due to

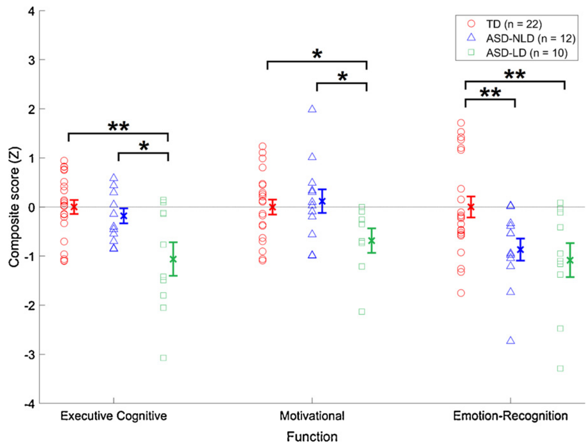

Fig. 2. Scatterplot showing the executive cognitive, motivational, and emotion-recognition composite *Z* scores in the typically developing (TD; red circles) and autism spectrum disorder with no language delay (ASD-NLD; blue triangles), and autism spectrum disorder with language delay (ASD-LD; green squares) groups. Means that are marked by "x" and error bars that denote one standard error ± the mean are also shown. Asterisks indicate the significance level of post-hoc one-tailed *t*-tests following (marginally) significant ANOVA results. $^*p < .05$, $^{**}p < .01$.

Table 2
Summary of Executive Cognitive, Motivational, and Emotion-Recognition Functioning for Typically Developing (TD) and Autism Spectrum Disorder (ASD) Groups.

	TD ($n = 22$)	ASD	
		ASD-NLD ($n = 12$)	ASD-LD ($n = 10$)
	M (*SD*)	*M* (*SD*)	*M* (*SD*)
Executive cognitive function			
Task-switching: mean RT (switch minus repeat; ms)	84.32 (105.43)	145.68 (92.33)	269.35 (183.21)
Go/no-go: RT-adjusted correct rejection rate (Improbable-nogo minus Improbable-go; a. u.)	4.29 (12.59)	0.72 (10.88)	−3.20 (13.61)
N-back: *A*' (2-back minus 0-back; a. u.)	−0.074 (0.060)	−0.057 (0.035)	−0.13 (0.15)
Category fluency: total number of words generated	30.32 (5.86)	29.58 (7.25)	25.10 (3.51)
Motivational function			
Reversal learning: total number of errors in the reversal phase[#]	26.05 (8.49)	26.08 (6.53)	30.00 (8.04)
Hungry Donkey Task: net score	−4.64 (20.36)	0.25 (27.38)	−18.20 (22.10)
Emotion recognition			
Facial emotion recognition: mean unbiased hit rate (a. u.)	0.69 (0.14)	0.57 (0.11)	0.53 (0.16)

Note. ASD-LD = autism spectrum disorder with language delay; ASD-NLD = autism spectrum disorder with no language delay; RT = reaction time.
[#] There were 1 and 2 missing values in the TD and ASD-LD groups, respectively, due to failures to reach the learning criteria of the reversal learning task.

insufficient power. Therefore, we carried out post-hoc sample size calculation for all nonsignificant results. For the executive cognitive composite score, we found that 138 individuals per group were needed to achieve enough power (power = .80; alpha = .05) to detect a significant difference between the TD and ASD-NLD groups, if any. In addition, for the emotional composite score, we found that 243 individuals per group were needed to achieve sufficient power to detect a significant difference between the two ASD groups, if any. Because the ASD-NLD group had a slightly higher motivational composite score than the TD group, post-hoc sample size calculation was not done for this comparison.

In addition, we checked whether the executive function results were biased by the increased number of measures used to represent this domain. Specifically, we calculated another executive composite score that was based only on the two most widely studied aspects of executive function in ASD: shifting and inhibition (Lai et al., 2017). The number of tasks or measures representing executive cognitive functioning (i.e., task-switching and go/nogo tasks) was thus identical to that representing motivational functioning (i.e., two). The ANOVA with Group (TD, ASD-NLD, ASD-LD) as between-subjects factor conducted on this new executive composite score remained significant, $F(2, 41) = 6.07$, $p = .005$, $\eta_p^2 = .14$. Post-hoc *t*-tests showed significant differences between the TD and ASD-LD groups, $p = .001$, and between the two ASD groups, $p = .049$, but no significant difference between the TD and ASD-NLD groups, $p = .064$. These results were comparable to those obtained with the composite score calculated based on four executive function tasks. Thus, the executive function findings were not biased by an unbalanced number of tasks.

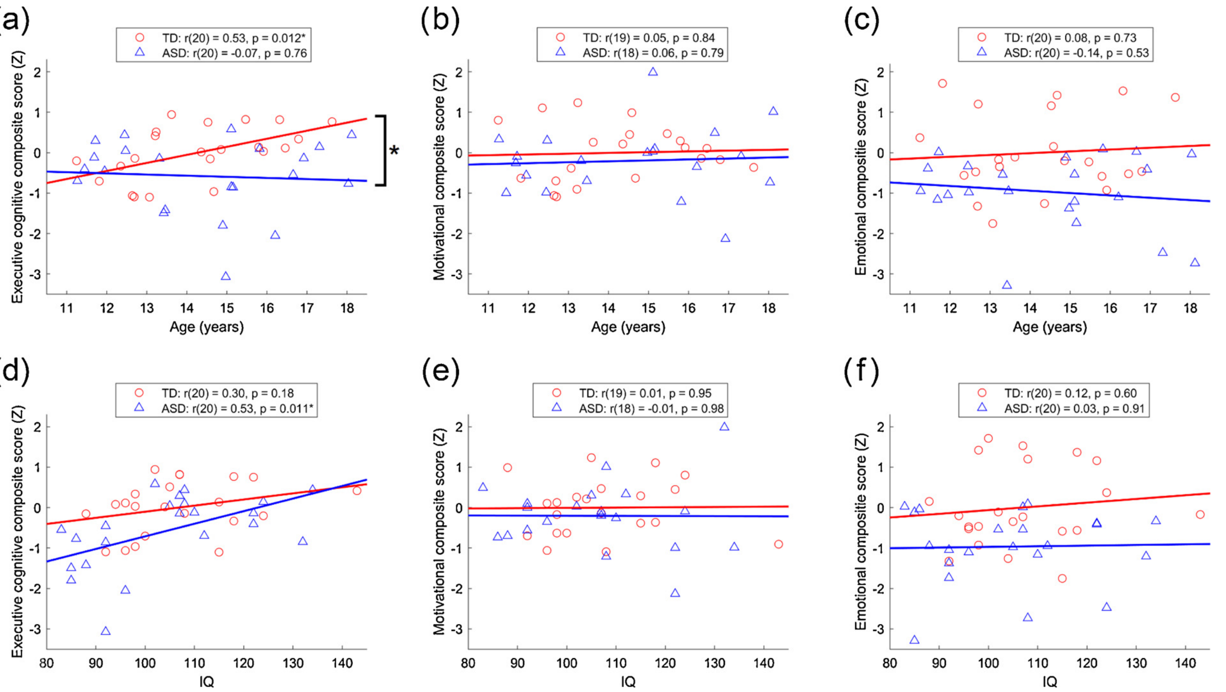

Fig. 3. Scatterplots showing the relationships between age and the (a) executive cognitive, (b) motivational, and (c) emotion-recognition composite Z scores, and between IQ and the d) executive cognitive, (d) motivational, and (e) emotion-recognition composite Z scores in the typically developing (TD; red circles) and autism spectrum disorder (ASD; blue triangles) groups. A regression line was fit for each group separately. Asterisks indicate the level of significance of two-tailed Pearson's correlation tests and Z tests. $^*p < .05$.

3.3. The moderating effects of demographic and intellectual variables in ASD

We performed additional analyses to determine whether demographic and intellectual factors might provide further explanation with respect to the variability in mental abilities in ASD. Pearson's correlation analyses (two-tailed) were carried out to quantify the relationships between age/IQ and the three composite Z scores in the TD ($n = 22$) and ASD ($n = 22$) groups. These relationships are illustrated in Fig. 3. In the TD group, we found that age was significantly correlated with the executive cognitive composite score, $r(20) = .53$, $p = .012$, but not with the other two composite scores, rs from 0.048 to 0.078, $ps > .73$; the positive result remained significant after applying the Bonferroni correction with an adjusted alpha level of 0.017. In the ASD group ($n = 22$), on the other hand, we failed to find a significant correlation between age and any of the three composite scores, rs from −0.14 to 0.062, $ps > .53$. We then carried out a Z test to compare the TD and ASD groups with respect to the correlation between age and the executive cognitive composite score. The group difference was significant, $Z = 2.02$, $p = .043$, such that the ASD group exhibited a significantly weaker correlation than the TD group.

We found no significant correlation between IQ and any of the composite scores in the TD group, rs from 0.014 to 0.30, $ps > .082$. In the ASD group, on the other hand, we found a significant correlation between IQ and the executive cognitive composite score, $r(20) = .53$, $p = .011$, but not for any other composite scores, rs from -0.006 to 0.027, $ps > .59$. The positive result survived the Bonferroni correction with an adjusted p-value threshold of 0.017. Unlike with age, a Z test revealed no significant difference in the correlation between IQ and the executive cognitive composite score between the TD and ASD groups, $Z = 0.87$, $p = .38$.

To determine whether age and IQ confounded our results, a mixed ANCOVA with Group (TD, ASD-NLD, ASD-LD) as between-subjects factor, Domain (executive, motivational, emotional) as within-subjects factor, and age and IQ as covariates, was performed on the composite Z scores. Same as before, the main effect of Group was significant, $F(2, 36) = 11.48$, $p < .001$, $\eta_p^2 = .39$. Post-hoc Bonferroni tests showed that the ASD-LD group in general had a significantly poorer performance than the TD, $p < .001$, and ASD-NLD groups, $p = .020$. There was no significant difference between the TD and ASD-NLD groups, $p = .23$. No other main or interaction effects were significant, $Fs < 2.52$, $ps > .10$.

We found that age and IQ specifically correlated with executive cognitive functioning in either the TD or ASD group, and t-tests revealed significant differences between the TD or ASD-NLD group and the ASD-LD group in executive cognitive functioning. Thus, we then carried out two separate ANCOVA, with both age and IQ as covariates, to confirm whether these two group differences still existed after controlling for these two factors. An ANCOVA with Group (TD, ASD-LD) as factor, and age and IQ as covariates, showed that the difference between the TD and ASD-LD groups remained significant, $F(1, 28) = 14.50$, $p = .001$, $\eta_p^2 = .34$. In addition, another ANCOVA with Group (ASD-NLD, ASD-LD) as factor, and age and IQ as covariates, showed that the difference between the two ASD groups also remained significant, $F(1, 18) = 4.60$, $p = .046$, $\eta_p^2 = .20$.

3.4. Role of cognitive abilities other than executive, motivational, and emotional functioning

We performed additional analyses on the four IQ subtest scaled scores to check whether the differences in composite scores among the TD, ASD-NLD, and ASD-LD groups were driven by differences in cognitive abilities other than executive, motivational, and emotional functioning among groups. Like before, we used one-way ANOVA and *t*-tests to compare the groups; however, two-tailed *t*-tests were used because individuals with ASD have been shown to demonstrate strengths on some IQ subtests but weaknesses on others (e.g., Oliveras-Rentas, Kenworthy, Roberson, Martin, & Wallace, 2012). Supplementary Table 1 presents the means and standard deviations of the subtest scaled scores in each group. We found that the three groups did not significantly differ in the scaled scores of the Digit Span, Coding, or Matrix Reasoning subtests, $F\text{s} < 2.44$, $ps > .10$. However, there was a significant difference among the three groups in the scaled score of the Similarities subtest, $F(2, 41) = 4.04$, $p = .025$. Post-hoc *t*-tests showed no significant differences between the two ASD groups, $p = .10$, or between the TD and ASD-NLD groups, $p = .50$. In contrast, the ASD-LD group had a significantly lower score than the TD group, $p = .003$.

Nonetheless, Pearson's correlation analyses with Bonferroni correction (i.e., *p*-value threshold = .0125) showed that the Similarities scaled score, as well as the three other scaled scores, significantly correlated with none of the composite *Z* scores in either the TD, *r*s from −0.23 and 0.37, $ps > .093$, or ASD group, *r*s from −0.33 to 0.52, $ps > .014$. The results of ANCOVA with Group (TD, ASD-LD) as factor, and the Similarities scaled score as covariate, conducted on each composite score separately also showed that all the differences between the TD and ASD-LD groups remained significant, $F\text{s} > 5.80$, $ps < .022$.

4. Discussion

This study examined the executive cognitive, motivational (i.e., reward-related), and emotion-recognition functions of adolescents with high-functioning ASD. We found that early language delay exerted a moderating effect on some of the impairments seen in ASD. Specifically, while ASD with early language delay led to impairment in all three domains of mental abilities, ASD without language delay led to impairment only in emotion recognition as compared to TD controls. More importantly, ASD with language delay had poorer executive cognitive and motivational functioning than ASD without language delay. Finally, we found a lack of age-related improvement in executive cognitive function within ASD relative to typical development. Altogether, our findings suggest that early language delay and age play specific moderating roles in the executive cognitive and/or motivational functions of ASD.

The findings of this study are consistent with recent meta-analytic findings of impaired executive cognitive function (Demetriou et al., 2018; Lai et al., 2017) and emotion recognition (Uljarevic & Hamilton, 2013) in ASD. More importantly, these findings imply that while ASD without language delay leads to impairments in executive cognitive and motivational functions and emotion recognition, ASD with language delay results in impairment only in emotion recognition. It should be noted that the impairment in multiple domains in the language delay group was not simply a result of the decrease in global cognitive functioning, because the ASD-LD group had a comparable IQ with other groups. Therefore, the deficits seen in ASD individuals with language delay were likely attributable to impaired goal-directed behavior, or reduced capacities to flexibly adapt behavior to the current demands and evaluate the consequences of actions, and social-emotional perception. A lack of task engagement and attention over time may also explain the impaired performance across the computerized tasks, which were more demanding than the IQ test in general. On the other hand, our findings suggest that ASD without early language delay might be associated with impaired emotion perception, but relatively intact goal-directed behavior, as measured by the computerized tests. Nevertheless, it should be emphasized that although our findings support relatively intact goal-directed behavior in laboratory settings in ASD with typical language development, they do not inform goal-directed behavior in the real world.

Our findings of differential executive cognitive and motivational deficits between ASD with and without a history of language delay suggest that early language acquisition plays a moderating role in the later cognitive functioning of ASD. These findings are consistent with those of previous studies in terms of set-shifting impairment in HFA, but not in AS (Rinehart et al., 2001). Some studies have reported no significant differences among the various aspects of executive function between AS and HFA (e.g., Verte, Geurts, Roeyers, Oosterlaan, & Sergeant, 2006). These findings, however, are based on individual aspects of executive function, whereas the current study is concerned with the overarching concept of executive function, which seems appropriate because of moderate intercorrelations among various facets of EF (Miyake et al., 2000). In addition, our findings of impaired reward-related processes in ASD with language delay, but not in ASD without language delay, are quite consistent with previous findings of relatively intact value-based decision-making in AS (Gonzalez-Gadea et al., 2013; Johnson, Yechiam, Murphy, Queller, & Stout, 2006), but not in ASD (i.e., AS and HFA combined; Mussey, Travers, Klinger, & Klinger, 2015; Zhang et al., 2015).

Several mechanisms possibly underlie the moderating effect of early language delay on the later cognitive functioning of ASD. First, some studies have shown that inner speech plays a mediating role in executive control (Cinan & Tanör, 2002), and that impairment in the internalization of language can result in cognitive and behavioral impairments (Winsler & Naglieri, 2003). Therefore, early language delay might negatively affect the development of the use of inner speech or phonological resources during executive cognitive and motivational tasks in ASD. In addition, people with AS may have better language skills than HFA (Noterdaeme et al., 2010). Thus, it is possible that people with ASD with typical early language development can devise effective verbal strategies to compensate for their impairment, whereas people with ASD with language delay have difficulty in employing compensatory strategies during executive cognitive and motivational tasks. Furthermore, some magnetic resonance imaging studies directly comparing HFA and AS have shown that children with HFA but not children with AS had smaller grey matter (McAlonan et al., 2008) and white matter (McAlonan et al., 2009) volume in the left frontal lobe than TD children. Because the frontal lobe has been implicated in various aspects of goal-directed behavior (Miller & Cohen, 2001), differential abnormalities in frontal lobe structures may underlie the differences in executive cognitive and motivational functioning between ASD with and without a history of language delay. Nevertheless, our study was based only on neuropsychological assessments. Thus, further studies examining both brain structure and task performance are needed to clarify the neural basis of the differences in these abilities between these two ASD groups.

We also found a lack of age-related improvement in executive cognitive function in ASD. Some meta-analyses have reported a negative relationship between age and the extent of impairment in specific aspects of executive function, including flexibility (Lai et al., 2017), and working memory (Demetriou et al., 2017), in ASD across studies. In contrast, some cross-sectional studies of children and adolescents with ASD have reported an increasing magnitude of impairment in working memory (Luna, Doll, Hegedus, Minshew, & Sweeney, 2007), attention and planning (Kouklari, Tsermentseli, & Monks, 2018), and behavioral aspects of executive function (Rosenthal et al., 2013) in ASD with advancing age. Our findings are thus consistent with those of previous cross-sectional studies. In cross-sectional studies, a sample is represented by an individual, and all samples complete the same set of experimental tasks. In meta-analyses, on the other hand, a sample is represented by a single study, and all samples undergo different tasks. Thus, the discrepancy in these findings is possibly due to differences in sample type between cross-sectional and meta-analytic studies. Nevertheless, the sample size of this study was relatively small, and further studies recruiting a larger longitudinal sample are therefore needed to verify the present correlation findings.

Altogether, our findings of the specific moderating roles of language delay and age in the mental functioning of ASD may help to explain some of the discrepant findings reported by studies examining at least two aspects of executive cognitive, motivational, and socio-emotional functions in ASD. Ozonoff et al. (2004) reported impairments in both flexible reinforcement learning and set-shifting in individuals with HFA who had a mean age of 16 years, whereas Yerys et al. (2009) reported impaired flexible reinforcement learning but relatively intact set-shifting in children with ASD (83 % HFA) who had a mean age of only 10 years. Our findings of a greater deficit in executive cognitive function in older adolescents than in younger adolescents with ASD may explain this discrepancy in findings. In addition, our findings of impaired emotion recognition but not motivational functioning in ASD individuals with typical language development are congruent with the findings of impaired affective mentalizing but intact affective decision-making in adults with AS (Gonzalez-Gadea et al., 2013). Furthermore, two studies have reported impaired set-shifting and affective mentalizing (Zimmerman et al., 2016) or affective decision-making (Zhang et al., 2015) in ASD individuals with a mean age of more than 18 years. These studies recruited individuals with either HFA or AS and did not consider language delay—if the ASD samples consisted primarily of individuals with HFA, then the findings would be compatible with our findings of impairment in executive cognitive and motivational functions as well as emotion recognition in ASD with language delay.

Our study is one of the first to compare various neurocognitive theories of ASD using a combination of multifunctional neuropsychological testing and a within-subject design. The findings of this study provide some evidence with which to support the executive dysfunction theory (Hill, 2004), (social) motivation theory (Bottini, 2018; Chevallier et al., 2012; Clements et al., 2018), and the amygdala or the orbitofrontal-amygdala circuit theories of ASD (Bachevalier & Loveland, 2006; Baron-Cohen et al., 2000). More importantly, our study emphasizes the importance of considering early language delay in these theories because we found that the presence of language delay during early development moderated the impairments in executive cognitive and motivational functions within ASD. Accordingly, early language delay may be a factor that helps to explain the large heterogeneity of executive functioning within ASD as reported by recent meta-analyses (Demetriou et al., 2018; Lai et al., 2017). In addition, few studies have examined the role of early language development in the later socio-emotional functioning of ASD, although language and emotion recognition skills have been found to be related in school-age children (Beck et al., 2012). Our findings suggest that, insofar as language delay is concerned, emotion-recognition deficit may be common among different ASD subtypes.

There is some evidence that executive control over verbal and spatial information can be dissociable (Geddes, Tsuchida, Ashley, Swick, & Fellows, 2014). In addition, some studies have shown that individuals with ASD exhibit greater impairment in spatial than verbal working memory (Williams, Goldstein, Carpenter, & Minshew, 2005; see Kercood, Grskovic, Banda, & Begeske, 2014, for review). However, it is uncertain whether material has a moderating effect on the executive functioning of ASD. In this study, we have provided some preliminary evidence that ASD individuals with early language delay performed more poorly on executive function tasks, which were mostly verbal, than those without early language delay. Nevertheless, it is unclear whether these two groups also had different levels of performance on executive function tasks with spatial materials. Thus, future studies comparing tasks with verbal and spatial materials are needed to determinewhether there is an interaction between material and early language delay in the executive cognitive functioning of ASD.

Apart from behavioral measures, we found significant differences in the ADI-R social interaction and verbal communication scores but not in the SRS-2 *T*-scores between the ASD-NLD and ASD-LD groups. These results suggest greater social communication abnormalities in ASD with language delay than in ASD without language delay during early development, but comparable current social communication characteristics between the two ASD groups. Note that the two ADI-R items that formed the basis of group classification (i.e., age of first single words and age of first communicative phrases) were included in neither the ADI-R social interaction nor the verbal communication subscale. Thus, the differences in the ADI-R social interaction and communication subscale scores (i.e., early social communication skills) between the two ASD groups could not be solely attributable to the use of these two items for group classification. These findings are consistent with the findings of a recent systematic review suggesting that three times as many studies report "significant or near significant level of differences" between AS and HFA as studies reporting "no differences" between them on many clinical variables (Tsai & Ghaziuddin, 2014).

This study had a relatively small sample size. While studies with a small sample size may have a higher chance of reporting false positive and false negative results, we undertook several measures to ensure that this is not likely the case for our subgroup analysis. First, the Bonferroni correction, which is a conservative method to control for Type I error, was applied in our subgroup analyses.

Thus, our significant results were unlikely to have resulted from inflated Type I error due to multiple comparisons. Second, the effect sizes for the nonsignificant results regarding pairwise comparisons between the TD, ASD-NLD, and ASD-LD groups were all small (i.e., Cohen's $d \leq 0.30$). Post-hoc sample size calculation done for the nonsignificant results also showed that a very large sample including at least 138 individuals per group (e.g., 138 TD and 138 ASD-NLD participants) was required to achieve enough power to detect significant group differences, if any. Thus, it is unlikely that the nonsignificant results reported were due to insufficient power. Furthermore, we have shown that differences in the computer task performances among the three groups could not be possibly confounded by age, IQ, or other cognitive abilities such as verbal concept formation and reasoning. Because the sample size was relatively small, however, readers should exercise caution when interpreting our subgroup results. Further studies recruiting a larger sample are needed to confirm the role of language delay in executive cognitive and motivational functioning in ASD.

In summary, we found differential impairments in executive cognitive, motivational, and emotion-recognition functions that were moderated by a history of language delay in ASD. Based on these preliminary findings, we conclude that impaired executive cognitive and motivational functions are specific to ASD with early language delay, whereas impaired emotion perception is central to ASD, regardless of the presence of early language delay. Although limited by a relatively small sample, our findings argue for a potential partial distinction in mental abilities between ASD with and without early language delay, emphasizing the importance of combining multifunctional neuropsychological testing and a within-subject design to understand the heterogeneity of ASD.

CRediT authorship contribution statement

Michael K. Yeung: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing - original draft. **Agnes S. Chan:** Conceptualization, Funding acquisition, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ridd.2020.103730.

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