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# Private speech among children with intellectual disabilities

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**Introduction:** Private speech has been shown to serve as a self-regulatory and planning tool for children during task-solving activities. While both typically developing children and those with neurodevelopmental disorders—such as attention-deficit/hyperactivity disorder and high-functioning autism spectrum disorder (ASD)—have been found to use private speech, the frequency and developmental trajectories vary across groups. However, little is known about private speech in children with intellectual disabilities.

**Methods:** This study examined private speech in children with intellectual disabilities ( $n = 20$ ) during a selective attention task. Verbalizations were recorded and categorized based on their relevance to the task.

**Results:** Seventy percent of the participants used private speech during the task, and 60% produced task-relevant utterances that appeared to assist in problem-solving. Notably, children with stronger ASD characteristics exhibited more frequent use of private speech than those with milder traits.

**Discussion:** These findings suggest that children with intellectual disabilities engage in private speech during cognitive tasks, and that this speech may function as a tool for behavioral regulation. The increased use among those with pronounced ASD tendencies may reflect differences in cognitive or social processing, underscoring the importance of considering individual variability in educational support.

## KEYWORDS

private speech, intellectual disability, language development, autism spectrum disorder, self-regulation, school-based research

## 1 Introduction

Private speech, which serves as a tool for thinking with functions such as behavioral regulation and planning, has been gaining attention in the study of children's language development (Lidstone et al., 2011; Aro et al., 2015; Mulvihill et al., 2020). During early childhood, when engaging in cognitive tasks, children think about, regulate, and direct their actions through (spoken) private speech. When entering school age, a transitional period in language development from private speech to (unspoken) inner speech emerges. During this time, the incidence of private speech gradually decreases and the volume of speech becomes quieter, eventually developing into inner speech (Winsler et al., 2000; Winsler and Naglieri, 2003; Manfra and Winsler, 2006).

## 2 Literature review

### 2.1 Private speech

Private speech is a concept in developmental psychology that is particularly associated with psychologist Vygotsky's (1934/1962, 1987) work. Private speech, also known as self-directed speech, refers to the internal verbalizations employed by individuals, particularly young children, to facilitate their cognitive processes and inform their actions. Private speech, in its typical form, is audible yet not directed at other individuals and serves a cognitive function rather than one of communication (e.g., Vygotsky and Luria, 1930/1993; Luria, 1961).

According to Lev Vygotsky, private speech can be conceptualized as an intermediate form of communication that lies between external communication and internalized thought. Over time, private speech becomes silent or "inner speech," a form of self-guided thought (Vygotsky, 1934/1962, 1987). Subsequent research has offered some empirical support for the notion that private speech is most prevalent during early childhood (ages 2–7), gradually diminishing as children progress through their developmental stages and evolve internalized thought processes (inner speech) (Kohlberg et al., 1968; Pellegrini, 1981; Duncan and Pratt, 1997). Additionally, research examining the development of private speech during the preschool and early school years has generally supported Vygotsky's theoretical predictions regarding age-related changes in its frequency and structure. Findings indicate that private speech typically follows a developmental progression, as outlined in Berk's levels of private speech, evolving from overt, task-irrelevant utterances (Level 1) to overt, task-relevant verbalizations, such as self-instructive comments (Level 2). Over time, these verbalizations become increasingly internalized, manifesting externally as whispering or inaudible muttering (Level 3), which represent transitional forms of inner speech (Berk, 1986; Berk and Garvin, 1984; Bivens and Berk, 1990).

### 2.2 Research on children with typical development

A substantial body of empirical evidence has emerged from studies on private speech subsequent to Vygotsky's seminal contributions. These studies have provided substantial empirical support for Vygotsky's (1934/1962) theory of the cognitive developmental function of private speech. According to this theoretical framework, private speech functions as an intermediate developmental stage, situated between externalized vocal speech and inner self-guiding verbal speech. Children use private speech as an externalized tool of thought to assist them in guiding and controlling their behaviors. With increasing cognitive maturity, private speech becomes internalized and transitions into internalized verbal thought or inner speech. Additionally, Vygotsky considered private speech vital in problem-solving when children encounter challenges in task-solving situations.

In uncovering the development of private speech during preschool and early school years, researchers have identified empirical evidence that aligns with Vygotsky's view of age-related

changes in the incidence and structure of this form of speech. Researchers have identified a predictable trajectory in the development of private speech, which initially evolves from overt task-irrelevant speech to overt task-relevant speech (e.g., self-guiding comments), subsequently transitioning to external manifestations of inner speech, such as whispering and inaudible muttering (Berk and Spuhl, 1995; Winsler et al., 1997; Patrick and Abravanel, 2000; Winsler and Naglieri, 2003).

To date, research investigating the performance-related benefits of private speech has primarily explored the relationship between task performance and either the frequency or developmental trajectory of private speech toward internalization (Behrend et al., 1989; Montero and De Dios, 2006). More recent studies have extended this line of inquiry by examining the role of specific content subtypes of private speech in task performance. Evidence indicates that these subtypes may differentially affect performance outcomes depending on their functional relevance. Specifically, greater use of task-irrelevant private speech has been associated with lower accuracy during construction tasks, whereas increased use of private speech involving planning and motivational content has been linked to improved task accuracy (Mulvihill et al., 2021). Additionally, researchers have indicated that the occurrence of private speech escalates in instances when juveniles encounter obstacles in task-solving scenarios (Kohlberg et al., 1968; Zivin, 1972; Deutsch and Stein, 1972; Dickie, 1973; Berk and Garvin, 1984; Duncan and Pratt, 1997; Fernyhough and Fradley, 2005), thereby corroborating Vygotsky's perspective on the adaptive function of private speech as a mechanism for self-regulation.

### 2.3 Research on children with neurodevelopmental disorders

Along with studies on the private speech of typically developing children that intensified after Vygotsky (1987) first documented the importance of private speech, research on children with neurodevelopmental disorders has also progressed in recent years. Despite utilizing comparable strategies when executing cognitive tasks, in comparison to their age-mates, children diagnosed with developmental language disorders exhibit a maturational delay in the onset and gradual internalization of private speech (Sturm and Johnston, 1999; Lidstone et al., 2012). Studies on children diagnosed with attention-deficit/hyperactivity disorder (ADHD) have observed that while these children employ private speech to complete tasks akin to those performed by typically developing children, they tend to produce a higher volume of private speech. Furthermore, the transition from private to inner speech is more protracted in children with ADHD compared to their typically developing peers (Winsler et al., 1999; Corkum et al., 2008).

Furthermore, Winsler et al. (2007) indicated that children diagnosed with high-functioning autism spectrum disorder (HFASD) demonstrate patterns of internal speech that resemble those observed in children diagnosed with ADHD. However, they also noted significant individual variations among children with HFASD. In summary, children with neurodevelopmental disorders may use private speech to solve tasks, despite delayed maturation in the developmental process of private speech. However, no previous studies have focused on this topic among children with intellectual disabilities.

## 2.4 Children with intellectual disabilities

Intellectual disability (ID) is a disorder that manifests during the developmental period, affecting intellectual and adaptive functioning. It is characterized by challenges in acquiring cognitive skills and adaptive social and communicative behaviors (American Psychiatric Association, 2013). Both preschoolers and school-age children with ID exhibit slow progress in language and learning skills, including reading and understanding concepts involving numbers and time, compared to typically developing children. Additionally, executive functions such as strategizing and cognitive flexibility are impaired (American Psychiatric Association, 2013), resulting in difficulties in planning, shifting, and regulating inappropriate language use and non-adaptive behaviors.

Intellectual disability is categorized into four severity levels based on standardized assessments of intellectual functioning and adaptive behavior. The Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) outlines the following classification criteria: individuals with mild intellectual disability typically exhibit full-scale IQ scores ranging from 50 to 69; those with moderate intellectual disability fall within the IQ range of 35–49; severe intellectual disability is defined by IQ scores between 20 and 34; and profound intellectual disability is characterized by IQ scores below 20 (American Psychiatric Association, 2013). These diagnostic categories are critical for determining the level of support required and for informing appropriate educational and clinical interventions.

While traditional diagnostic frameworks have emphasized intellectual functioning as a primary indicator of intellectual disability, the DSM-5 shifts the focus to adaptive functioning as the central criterion for determining severity levels (American Psychiatric Association, 2013). According to this model, classification is based on the amount of support an individual requires across three primary domains: the conceptual domain, involving skills related to academic learning and cognitive processing; the social domain, which includes interpersonal communication, social understanding, and judgment; and the practical domain, encompassing self-care, daily living skills, and occupational performance. Adaptive functioning reflects an individual's ability to manage everyday tasks and navigate social and practical challenges, offering a more ecologically valid measure of functioning than IQ alone (Schalock et al., 2010).

IQ scores continue to be recognized as indicators of cognitive potential, yet they are relatively stable over time and less responsive to intervention. In contrast, adaptive behavior can improve with targeted support and educational interventions, making it a more dynamic and functional measure for clinical decision-making and service planning. Standardized tools such as the Vineland Adaptive Behavior Scales are commonly used to evaluate these domains in clinical and educational contexts (Sparrow et al., 2016).

Private and inner speech have been conceived as keys to uncovering the mechanisms underlying the development of children's communicative competence (Feigenbaum, 2009). According to Vygotsky (1934/1962, 1987), children primarily begin to learn how to communicate through social interactions with adults. Then, they talk aloud to themselves, rather than to others, to practice, explore, and gradually comprehend their communicative skills. When children eventually develop an understanding of conversational norms, their private speech transforms from

being unconscious and unintended to conscious, purposeful, and communicatively competent (Feigenbaum, 2009). In this developmental process, language ability, particularly language acquisition, plays a critical role in the mastering of communication skills. If language ability does not develop to a certain level, children may struggle in the initial stage of interacting with adults, which could in turn affect the subsequent stages of communicative competence development.

Children with IDs often experience delays in language development. This raises the question of whether low language ability affects the development of private speech. Exploration of this possibility could offer significant value, as it would allow for the identification of potential disparities in private speech development among three distinct groups: children with IDs, typically developing children, and children with other developmental disorders. This identification of differences could provide novel insights into the domain of private speech research.

In the context of educational interventions for children diagnosed with IDs, there is a compelling need to implement teaching methodologies and specialized support that are meticulously customized to address the unique needs and characteristics of each child. For example, teachers in special support schools need evidence-based information regarding which aspects of a child's language behavior to observe to be able to respond effectively. This study aims to contribute to the body of knowledge surrounding the speech characteristics of children with IDs by providing special education teachers with actionable suggestions regarding the development of speech in this demographic, along with specific teaching methodologies and support.

In summary, research on children with typical development has demonstrated that private speech evolves in a predictable sequence from audible and externalized to more internalized, less audible, and abbreviated forms. Typically developing children utilize private speech as a means of self-regulation to assist them in overcoming challenges in tasks and regulating their behavior. Children with ADHD exhibit a speech pattern similar to that of their typically developing counterparts; however, they demonstrate a higher incidence of task-irrelevant private speech and a more protracted transition period between tasks. Research on the private speech of children with autism is quite limited, with the sole article finding that children with high-functioning autism show similar patterns of private speech to ADHD groups. To date, while discrepancies have been identified in the occurrence of private speech between children with IDs such as autism compared to their typically developing peers, no research has focused on the private speech of children with IDs. Therefore, the question regarding the characteristics of private speech among children with ID remains. To the best of our knowledge, this study is the first to examine private speech in children with IDs.

## 2.5 Purpose

The present study set the following research questions: (1) Do children with IDs exhibit private speech? (2) If so, what are the characteristics of their private speech?

Thus, we hypothesize:

- (a) Children with IDs have private speech.
- (b) The development of private speech in children with IDs shares the same pattern as that of typically developing children.
- (c) Although children with IDs strategically use private speech in problem-solving tasks, there are differences in frequency and content considering their age range, intellectual abilities, language level, other coexisting disorders (e.g., ASD), and social adaptability.

### 3 Methods

#### 3.1 Participants

Twenty children (seven girls) between the ages of 8 and 17 years ( $\bar{X}_{age} = 14.1$ ,  $SD = 2.4$ ), enrolled in a special needs school in Japan, participated in this study. All participants were clinically diagnosed with ID; eight participants were diagnosed with ASD ( $\bar{X}_{age} = 14.7$ ,  $SD = 2.2$ ), five participants (two girls) were diagnosed with Down syndrome ( $\bar{X}_{age} = 12.9$ ,  $SD = 3.3$ ), one (female) participant was diagnosed with a language disorder, one (female) participant was diagnosed with Soto syndrome, and one (female) participant was diagnosed with ataxic cerebral palsy

before they entered school. Based on the KABC-II results (for assessment profiles, see [Table 1](#)), only children with scores of 70 or below were included as participants in the study.

#### 3.2 Assessment

To assess participants' developmental conditions, a combination of standardized cognitive, language, social, and adaptive behavior measures were administered.

##### 3.2.1 Kaufman assessment battery for children—second edition (KABC-II, Japanese version)

The KABC-II ([Kaufman and Kaufman, 2018](#); [Japanese Version KABC-II Production Committee, 2013](#)) is a comprehensive cognitive assessment tool designed to measure problem-solving and processing abilities in children. The Japanese version includes both cognitive scales and an Achievement Scale to evaluate acquired academic skills. It is suitable for children aged 3–18.

TABLE 1 Basis profiles and assessment results of participants.

Participant	Gender	Diagnosis	Age (years-months)	KABC-II		PVT-R	SRS-II	VINELAND-II
				Cognitive composite score	Achievement composite score	Vocabulary age	Total score	Total score
A	M	ID, down syndrome	8–11	52	43	4–5	52	40
B	M	ID, down syndrome	10–2	49	51	<3–0	63	20
C	M	ID, autism	10–3	67	62	4–3	79	34
D	M	ID	12–4	60	54	7–5	55	38
E	M	ID	12–11	59	60	8–10	63	38
F	F	ID, language disorder	13–0	45	49	3–0	60	20
G	M	ID, autism	13–1	50	49	5–9	85	20
H	M	ID, autism	13–9	54	40	3–0	58	20
I	F	ID, down syndrome	14–0	44	47	3–2	69	20
J	F	ID, down syndrome	14–0	45	47	<3–0	74	20
K	F	ID, ataxic cerebral palsy	14–11	46	48	4–1	70	20
L	F	ID, sotos syndrome	14–11	43	47	3–4	67	20
M	F	ID, autism	15–1	56	47	<3–0	≥90	20
N	M	ID, autism	15–10	66	66	11–6	60	76
O	F	ID, autism	15–10	40	47	<3–0	≥90	20
P	M	ID	16–1	65	64	11–1	44	88
Q	M	ID, autism	16–3	41	47	<3–0	70	20
R	M	ID, autism	17–1	52	50	6–3	59	29
S	M	ID	17–1	60	52	9–0	60	23
T	M	ID, down syndrome	17–2	42	47	3–0	60	20

KABC-II: 85–100 = −1 SD to average; 70–85 = −2 SD to −1SD; 55–70 = −3 SD to −2 SD. SRS-II: normal range = 59 and below; mild = 60–65; moderate = 66–75; severe = 76 and above. Vineland-II: 85–115 = average; 70–85 = slightly low (−2 SD to −1 SD); <70 = low (−3 SD to −2 SD). ID, intellectual disability.



The KABC-II demonstrates high reliability, with Cronbach's alpha coefficients ranging from 0.88 to 0.97 across various scales (Kaufman and Kaufman, 2018). The Japanese version retains comparable reliability metrics, with Cronbach's alpha coefficients ranging from 0.88 to 0.97 across various scales (Japanese Version KABC-II Production Committee, 2013). Construct validity is supported through confirmatory factor analysis, affirming a five-factor structure (Sequential, Simultaneous, Learning, Planning, and Knowledge). Standard scores are reported with a mean of 100 and a standard deviation of 15, where higher scores indicate stronger cognitive performance.

### 3.2.2 Picture vocabulary test—revised (PVT-R)

The PVT-R (Ueno et al., 2008) is a brief, standardized measure of receptive vocabulary development for children aged 3–12.25 years. It evaluates a child's ability to comprehend spoken words by selecting the appropriate image from multiple choices.

The PVT-R is used to assess participants' receptive vocabulary because their language age is lower than their chronological age, a typical trait of children with intellectual disabilities. It is well-suited for this population as it provides a standardized, developmentally appropriate measure of language skills, essential for evaluating their use of private speech.

The instrument has high reliability ( $\alpha > 0.90$ ) and strong test-retest reliability ( $r > 0.85$ ). Its construct validity is supported by moderate to high correlations with other standardized language development assessments. While the PVT-R yields both standard scores and vocabulary age, this study adopts vocabulary age as the primary metric for evaluation.

### 3.2.3 Social responsiveness scale—second edition (SRS-2, Japanese version)

The SRS-2 (Kamikawa, 2017) is a norm-referenced questionnaire used to assess social impairments associated with autism spectrum disorder (ASD). It can be completed by parents or teachers and is applicable across a wide age range, from early childhood through adulthood.

The Japanese version of the SRS-2 demonstrates excellent reliability ( $\alpha = 0.95$ ) and strong test-retest reliability ( $r = 0.88$ ), with construct validity supported by significant correlations with established autism diagnostic tools such as the ADOS and SCQ. The scale yields T-scores ( $M = 50$ ,  $SD = 10$ ), where higher scores reflect greater severity of social impairment. Severity is classified into three categories: mild (T-score 60–74), moderate (75–88), and severe (89 and above).

In the present study, 15 participants were identified as having ASD according to the SRS-2: six at the mild level, five at the moderate level, and four at the severe level.

### 3.2.4 Vineland adaptive behavior scales—second edition (Vineland-II, Japanese version)

The Vineland-II (Tsuji and Murakami, 2014) is used to assess adaptive functioning across domains such as communication, daily living skills, socialization, and motor skills. It is widely used in clinical and educational contexts to evaluate individuals with developmental disabilities or other adaptive concerns.

The Japanese adaptation maintains high reliability ( $\alpha = 0.83$ – $0.94$ ) and robust inter-rater and test-retest reliability. Construct validity is demonstrated through factor analytic studies and correlations with developmental and intelligence tests. Standard scores ( $M = 100$ ,  $SD = 15$ ) are used, with higher scores reflecting better adaptive behavior. The scale assists in identifying both strengths and areas requiring intervention.

## 3.3 Procedure

### 3.3.1 Selective attention task

In a separate room at the school, the participants were video- and audio-recorded while performing a selective attention task. This task was developed to elicit children's private speech within an appropriate challenging range for typically developing preschoolers (Diaz, 1992; Winsler et al., 1997; Winsler, 1998; Winsler et al., 2003). Adjustments were made to accommodate the characteristics of children with IDs, including modifications in instructions, the number of tasks, and task procedures. For example, the selective task used in previous studies (Winsler et al., 2003) has two example items explained by the experimenter and 12 items for children to finish individually. However, in the current study, the experimenter provided three example items and 30 items for participants to finish by themselves. Further, instead of providing 18 answer cards for children to select from Winsler et al. (2003), the present study used three possible answer cards for each item to reduce the potential burden caused by variant stimuli for participants.

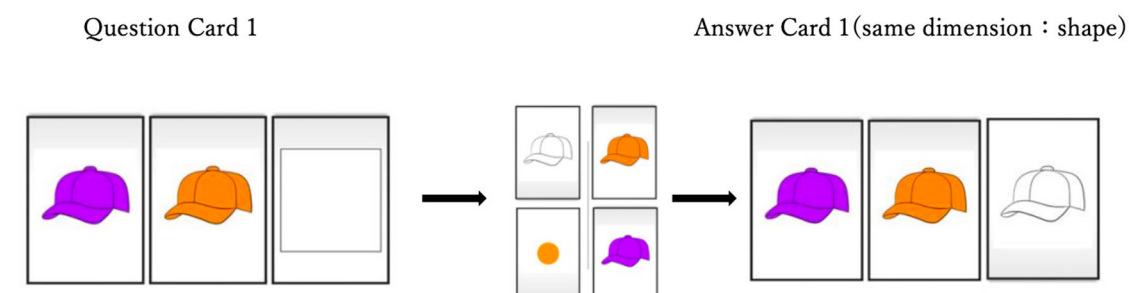
In the selective attention tasks, participants were instructed to decide first which dimension (either color or shape) was shared between two pictures on one card, then to select a new picture card with the same dimension as the other two, and finally to attach it as the third card in the set (see Figure 1). For instance, if the cards showed one "red car" and one "yellow car," the correct answer was a "car" of any color. The correct dimension varied randomly across the 30 items with three shapes (flower, car, or cat) and three colors (red, yellow, or green).

One experimenter introduced the task with three example items and asked the participants to complete three tests after each example to ensure that they understood the rules of the task. Subsequently, the participants were asked to complete the 30 items individually within 10 min. The experimenter remained silent and gave no reminders during the task unless the participant could not start or continue doing the task alone. Two video cameras mounted on a tripod were set at different corners of the room, and a digital voice recorder was placed on the table. Participants' speech was recorded by cameras and voice recorders during the task and later transcribed from videotapes and audio files by the author.

### 3.3.2 Ethics approval statement

The guardians of all participants were provided with a written explanation of the research overview, and written consent for participation in the study was obtained. This study was approved by the Institute of Human and Social Sciences Ethics Committee of Kanazawa University [approval number: [2021-15-4]] [20230412]. All procedures were performed in accordance with the ethical standards of the institution.

### Example 1.



### Example 2.

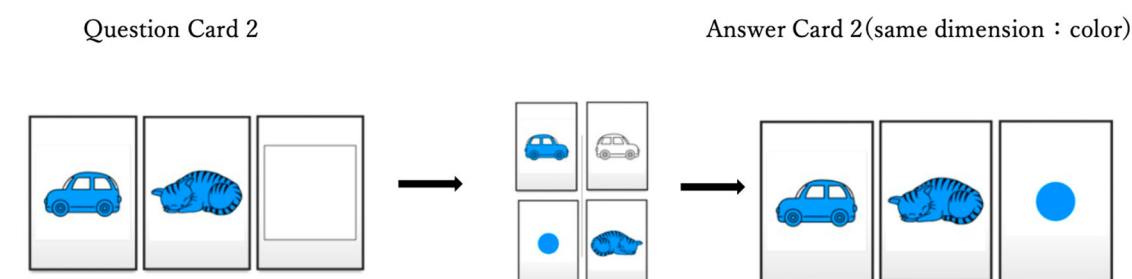


FIGURE 1  
Instructive examples of selective attention task.

## 3.4 Data processing

### 3.4.1 Coding

The coding process was meticulously executed in two stages. Initially, each utterance was assigned to a superordinate category, namely social or private. A single utterance's categorization as "social" was based on the following criteria (Ferryhough and Russell, 1997): (1) continuous or immediate eye contact with the experimenter during or within 2 s following an utterance; and (2) the child's behavior involving the experimenter through physical contact, gaze direction, or vocalization that reflected the same topic as the experimenter's previous utterance within 2 s of one utterance. Additionally, the content of social utterances included calling the experimenter by name or a vocative or asking the experimenter questions. Utterances occurring within 2 s of a prior social utterance were also coded as social if they met the aforementioned criteria.

Private utterances were further classified into three categories according to Berk's (1986) revised coding scheme. Level 1 private speech encompasses wordplay, repetition, task-irrelevant affect expressions, and comments directed toward absent, imaginary, and non-human entities. Level 2 private speech comprises self-directed comments, descriptions of one's own activity, and task-irrelevant self-questions without answers (added to the revised edition). Level 3 private speech encompasses task-relevant external manifestations of inner speech, including inaudible muttering—that is, remarks involving clear mouthing of words that cannot be heard—and lip

and tongue movement only, that is, no clear mouthing of words (for details, see Table 2).

Prior research (Winsler et al., 2007) has measured both social speech and private speech. Following this, the present study also assessed both forms of speech to enable potential comparisons (for details, see Tables 3a, b).

### 3.4.2 Inter-rater reliability

A subset (20%) of the transcripts was independently assessed by two graduate students studying special needs education. Cronbach's  $\alpha$  was 0.974 for the distinction between social and private speech and 0.984 for the three-level system in Berk's coding system.

## 4 Results

### 4.1 Participant profiles

Cognitive abilities were assessed using the Kaufman Assessment Battery for Children, Second Edition (KABC-II; Kaufman and Kaufman, 2004). Results indicated that most participants demonstrated significant cognitive impairments. Specifically, 7 participants scored between  $-3$  and  $-2$  standard deviations below the mean, and 13 participants scored between  $-4$  and  $-3$  standard deviations below the normative mean.

TABLE 2 Berk’s coding system (\*revised version).

Private speech categories	Subtypes within each category
Level 1, Self-stimulating task-irrelevant, private speech	(a) Word play and repetition Ex: “yellow, yellow, yellow...”/“red, reddish”/“b-l-u-e”
	(b) task-irrelevant affect expression Ex: “Nope!”
	(c) comments to absent, imaginary, or non-human others Ex: “It’s arriving!” (referring to a train)
Level 2, Task-relevant externalized, Private speech	(a) Describing one’s own activity and self-guiding comments Ex: “Alright, I got this!” (while reaching for an answer card)
	(b) *task-relevant self-questions without answer Ex: “Is it right?”/“What about this?”
	(c) task-relevant, self-answered questions Ex: “Which one is it?” “Ah, this one.”
	(d) reading aloud and sounding out words Ex: reading a picture book aloud
	(e) task-relevant affect expression Ex: “This is hard, isn’t it?”/“Hooray!”
Level 3, Task-relevant external manifestations of inner speech	(a) Inaudible muttering (remarks involving clear mouthing of words that cannot be heard)
	(b) lip and tongue movement only (no clear mouthing of words)

\* Besides Berk’s original category system, one new subtype was added [see (b)\*].  
(b)\* This subtype was found in the present study but not in Berk’s original category system.

Language abilities were evaluated using the Picture Vocabulary Test–Revised (PVT-R; Ueno et al., 1991). Performance varied substantially across the participants. Five participants demonstrated language functioning below the developmental level of a 3-year-old. Ten participants functioned at a level comparable to 3- to 6-year-old children, while 5 participants demonstrated language abilities within the developmental range of 7–11 years.

Autistic traits were assessed using the Social Responsiveness Scale, Second Edition (SRS-2). A total of 15 participants exhibited clinically significant levels of autistic traits. Of these, 4 participants scored in the severe range ( $T$ -score  $\geq 76$ ), 5 in the moderate range ( $T$ -score = 66–75), and 6 in the mild range ( $T$ -score = 60–65).

Adaptive functioning was assessed using the Vineland Adaptive Behavior Scales, Second Edition (Vineland-II). Most participants obtained scores below 70, indicating significant deficits in adaptive behavior. One participant scored in the moderately low range (ABC score = 71–85), and another scored within the average range (ABC score = 86–114).

4.2 Speech use

Participants’ use of private (see Table 3a) and social speech (see Table 3b) during the task was calculated. The values for the three

TABLE 3a Children’s overall private speech use during the tasks.

Children’s overall private speech use during the tasks			
$n = 20^*$			
Total private speech/min	Irrelevant private speech/min	Relevant private speech/min	Internalized private speech/min
Mean	Mean	Mean	Mean
1.67	0.18	1.2	0.3
SD	SD	SD	SD
1.54	0.26	1.22	1.1
% of children exhibiting	% of children exhibiting	% of children exhibiting	% of children exhibiting
70%	30%	60%	10%

TABLE 3b Children’s overall social speech use during the tasks.

Total social speech/min		
Mean	SD	% of children exhibiting
1.99	1.94	60%

specific categories of private speech were examined: irrelevant, task-relevant, and partially internalized whispers/mutterings. These categories were assessed in terms of frequency per minute and proportion of total private speech. The utterance per minute measures included all participants, while the proportional measures only included participants who engaged in at least some private speech. The total private speech per minute (total private speech/min) was calculated by dividing all private speech in the task by the total task completion time. The percentage of participants exhibiting (% of children exhibiting) refers to the number of participants who exhibited such private speech.

First, it should be noted that 70% of the participants used private speech during the task. Furthermore, 67% of the participants identified as having suspended ASD according to the SRS-2 used private speech during the task ( $ASD = 15$ ,  $\bar{X}_{age} = 14.1$ ,  $SD = 2.2$ ), whereas 80% of those without ASD used private speech during the task ( $ID = 5$ ,  $\bar{X}_{age} = 13.2$ ,  $SD = 3.7$ ). Second, the frequencies of the three subcategories of private speech (task-irrelevant, task-relevant, and partially internalized private speech) are summarized in Table 3a. Notably, ~60% of the participants used task-relevant private speech compared to only 30% of task-irrelevant private speech users and 10% of partially internalized private speech users.

4.3 Differences between groups

To investigate differences in private speech across groups, non-parametric statistical tests were employed. Specifically, the Mann–Whitney  $U$ -test was used to compare participants with and without comorbid autistic tendencies, while the Kruskal–Wallis test was applied to assess differences across three age groups: the elementary school group (aged 8 years 11 months to 12 years 4 months), the junior high school group (aged 12 years 11 months to 14 years 11 months), and the senior high school group (aged 15 years 1

months to 17 years 2 months). Results from the Mann–Whitney *U*-test indicated no significant differences between participants with

TABLE 4a Autistic tendencies and non-autistic tendencies groups.

Groups Mean, SD, result of statistical test	Autistic tendencies	Non-autistic tendencies
	<i>n</i> = 15	<i>n</i> = 5
Total private speech/min		
Mean	1.13	1.95
SD	1.47	1.78
<i>p</i> *	0.349	
Irrelevant private speech/min		
Mean	0.14	0.04
SD	0.30	0.09
<i>p</i> *	0.735	
Relevant private speech/min		
Mean	1.00	0.48
SD	1.30	0.87
<i>p</i> *	0.445	
Internalized private speech/min		
Mean	0	1.43
SD	–	2.03
<i>p</i> *	0.197	

\*Mann–Whitney *U*-test.

TABLE 4b Three age groups: elementary (8–11 to 12–4), junior high school (12–11 to 14–11), and senior high school (15–1 to 17–2) (mean, standard deviation, and non-parametric test score).

Groups, result of statistical test  Mean, SD	Elementary	Junior	Senior	Kruskal–Wallis test		
	<i>n</i> = 4	<i>n</i> = 8	<i>n</i> = 8	Kruskal–Wallis H (K)	Degrees of freedom	<i>p</i> -value
Total private speech/min						
Mean	1.80	0.86	1.58	1.677	2	0.432
SD	1.02	0.96	2.16			
Irrelevant private speech/min						
Mean	0.08	0.14	0.11	1.370	2	0.504
SD	0.02	0.30	0.30			
Relevant private speech/min						
Mean	1.03	0.72	0.94	1.261	2	0.532
SD	1.02	0.75	1.70			
Internalized private speech/min						
Mean	0.70	0	0.54	1.720	2	0.423
SD	1.40	–	1.53			

and without autistic tendencies in terms of total private speech per minute or any of the three private speech subcategories (see Table 4a). Similarly, the Kruskal–Wallis test revealed no significant age-related differences in total private speech per minute or in the three subcategories (see Table 4b).

A non-parametric analysis was conducted to investigate whether significant differences in private speech occurred across high- and low-scoring groups on various assessment measures. Results indicated that among children characterized as having autistic traits, those with more severe autism symptomatology, as measured by the SRS-2, exhibited significantly higher levels of both total and task-relevant private speech. Statistically significant group differences were observed among those classified with mild, moderate, and severe autism spectrum tendencies ( $p = 0.013$  for both comparisons; see Table 5d). In contrast, no significant differences were observed on the PVT-R, suggesting that verbal ability did not significantly affect the use of private speech (see Table 5c). Similarly, scores on the Cognitive Composite Scale and Achievement Composite Scale of the K-ABC did not show statistically significant differences, indicating that intellectual ability was not a significant factor in private speech occurrence (see Tables 5a, b). Due to the small sample size in the Vineland-II group, non-parametric analyses were not conducted for this measure; however, descriptive statistics are reported in Table 5e.

4.4 Correlation factor and multiple regression analysis

Spearman’s rho was calculated to test whether there were possible correlative factors, such as cognitive capacity, that influenced the output of private speech (see Table 6). SRS-II total



TABLE 5a High- and low-scoring groups across Cognitive Composite Scale of KABC-II (mean, standard deviation, and non-parametric test score).

Groups Mean, SD, result of statistical test	Below −3 SD	Between −3 SD and −2 SD
	<i>n</i> = 13	<i>n</i> = 7
Total private speech/min		
Mean	1.41	1.20
SD	1.58	1.60
<i>p</i> *	0.438	
Irrelevant private speech/min		
Mean	0.17	0
SD	0.31	–
<i>p</i> *	0.097	
Relevant private speech/min		
Mean	0.91	0.80
SD	1.09	1.48
<i>p</i> *	0.241	
Internalized private speech/min		
Mean	0.33	0.40
SD	1.20	1.06
<i>p</i> *	0.877	

\*Mann–Whitney U-test.

score were found to have a positive correlation with task-relevant private speech per minute ( $p = 0.018$ ), suggesting that participants with a higher tendency toward autism utilized more task-relevant private speech during the task.

Achievement Composite Scale of K-ABC, one of the key components of intellectual skills, showed a negative correlation with task-relevant private speech per minute ( $p = 0.035$ ), suggesting higher acquisitive skill led to less task-relevant private speech. Furthermore, participants' PVT-R vocabulary age was negatively correlated with task-relevant private speech per minute ( $p = 0.022$ ), suggesting that participants with more verb maturity used less task-relevant private speech in task-solving.

To further examine the relationship between autism spectrum tendencies (ASD) and task-relevant private speech, a multiple regression analysis was conducted using ASD, chronological age and vocabulary age (as measured by the PVT-R) as predictors. The full model was statistically significant,  $F_{(3,16)} = 7.515$   $p = 0.002$ , explaining ~60% of the variance in the use of task-relevant private speech (adjusted  $R^2 = 0.507$ ). ASD tendencies demonstrated a strong and statistically significant positive association with private speech (standardized  $\beta = 0.688$ ,  $p = 0.003$ ), indicating that higher levels of ASD traits were associated with increased use of self-directed speech during task performance. In contrast, neither chronological age ( $\beta = -0.217$ ,  $p = 0.208$ ) nor vocabulary age ( $\beta = -0.077$ ,  $p = 0.705$ ) were significant predictors (see

TABLE 5b High- and low-scoring groups across Achievement Composite Scale of KABC-II (mean, standard deviation, and non-parametric test score).

Mean, SD, result of statistical test	Groups	Below −3 SD	Between −3 SD and −2 SD
		<i>n</i> = 16	<i>n</i> = 4
Total private speech/min			
Mean		1.56	0.45
SD		1.62	0.90
<i>p</i> *		0.099	
Irrelevant private speech/min			
Mean		0.14	0
SD		0.29	–
<i>p</i> *		0.290	
Relevant private speech/min			
Mean		0.97	0.45
SD		1.27	0.90
<i>p</i> *		0.249	
Internalized private speech/min			
Mean		0.45	0
SD		1.25	–
<i>p</i> *		0.750	

\*Mann–Whitney U-test.

Table 7). These results suggest that the observed relationship between ASD tendencies and private speech is not confounded by developmental or linguistic factors. Instead, ASD tendencies appear to independently influence the emergence or persistence of private speech in cognitive tasks, consistent with prior findings highlighting the distinct cognitive and self-regulatory strategies observed in individuals with higher autistic traits (Winsler et al., 2007; Lidstone et al., 2012). Although, conducting a multiple regression analysis with 20 participants and three predictors results in a low participant-to-predictor ratio, which compromises the reliability and stability of the findings. Additionally, the small sample size limits the ability to adequately assess and validate the assumptions underlying the regression model. Therefore, this analysis is primarily exploratory in nature and is complemented by visualizations that illustrate the relationships among variables and highlight any potential outliers (see Figures 2–4).

## 5 Discussion

### 5.1 Private speech of children with IDs

This study aimed to examine whether children with intellectual disabilities (IDs) engage in private speech during task performance. Findings revealed that 70% of participants used private speech,

TABLE 5c Low, Medium, and High-scoring groups across PVT-R (mean, standard deviation, and non-parametric test score).

Mean, SD, result of statistical test	Groups	Under 3 years old, ≤3 years old	Over 3 years old, >3 years old
		<i>n</i> = 8	<i>n</i> = 12
Total private speech/min			
Mean		1.51	1.22
SD		1.72	1.49
<i>p</i> *		0.521	
Irrelevant private speech/min			
Mean		0.13	0.10
SD		0.30	0.25
<i>p</i> *		0.792	
Relevant private speech/min			
Mean		1.38	0.53
SD		1.53	0.83
<i>p</i> *		0.115	
Internalized private speech/min			
Mean		0	0.59
SD		–	1.43
<i>p</i> *		0.571	

\*Mann–Whitney U-test.  
Children’s vocabulary age younger than 3 years and 0 months (<3–0) were coded as 0 due to unavailable exact age information.

indicating its prevalence as a self-regulatory tool within this population. Exploratory multiple regression analysis showed that neither chronological age nor vocabulary age significantly predicted private speech use, suggesting that its development may occur independently of general developmental indicators.

Moreover, intellectual functioning—as measured by the Cognitive Composite Scale and Achievement Composite Scale of the K-ABC—did not significantly affect private speech usage, as determined by the Mann–Whitney *U*-test. These results support the view that private speech may represent a developmentally robust self-regulatory mechanism that emerges regardless of cognitive ability. It may remain accessible to children with varying levels of intellectual functioning, underscoring its potential role in supporting learning and task engagement.

Additionally, 67% of participants identified as having ASD according to the SRS-2 used private speech during the task, a figure comparable to the 70% reported in Winsler et al.’s (2007) study of children with high-functioning ASD. This suggests that ~70% of children with ASD—regardless of the presence of an intellectual disability—engage in private speech during problem-solving tasks.

The second purpose was to uncover the characteristics of the private speech of children with ID. Participant’s language development was found to negatively correlate with task-relevant private speech in the selective attention task, as well as with the Achievement Composite Scale of K-ABC. If higher verbal skills can

help children better understand the task and lead them to solve it more easily, the use of private speech as a verbal tool to deal with difficulties can be relatively reduced. Further, participants with higher acquisitive skills could comprehend the essence of the task more effortlessly, so they could complete the task smoothly without or with less help from the verbal tool.

Additionally, according to Berk’s categories of private speech, the level 2 task-relevant externalized private speech and task-relevant self-answered questions subtype is used by typically developing children during tasks (Kohlberg, 1968; Berk and Garvin, 1984; Berk, 1986). However, this subtype was not observed in the present study. Instead, some participants used task-relevant self-questions without providing vocalized answers. It remains unclear if this pattern constitutes a special form of private speech unique to children with IDs, as there are no previous studies for comparison. Given that private speech is for internal purposes, it is quite possible that children raised one question vocally and then did not say the answer out loud, as they already knew it in their minds. Future studies could explore the subtypes of private speech in children with IDs to determine the potential differences compared to populations.

### 5.2 Comparisons with research on typical developing children

Studies on the private speech of typically developing children have found that private speech peaks during the preschool years and is gradually replaced by partially internalized private speech, such as inaudible muttering, as children move to early primary school (Kohlberg et al., 1968; Berk, 1986; Winsler et al., 2003). However, for the participants with IDs in this study, the developmental process of private speech appears slower and extends across a wider age range, spanning from primary school to senior high school (from 8 to 17 years old).

From the perspective of Berk’s three levels of private speech internalization, typically developing children initially use immature level 1 task-irrelevant private speech, such as word play and repetition; task-irrelevant affect expressions; and comments to absent, imaginary, or non-human entities. As they develop, children use more mature and task-relevant level 2 private speech, including describing one’s own activities, task-relevant self-answered questions, self-guiding comments, reading aloud and sounding out words, and task-relevant affect expressions. Ultimately, private speech turns into level 3 partially internalized speech, consisting of inaudible muttering and silent lip and tongue movement.

For children with IDs in this study, all three types of level 1 task-irrelevant private speech were observed in the junior high school group (12–11 to 14–11 years old). For level 2 private speech, the task-relevant self-answered questions subtype was not observed. Instead, task-relevant self-answered questions without answers were noted in both the elementary (8–11 to 12–4 years old) and junior high school groups (12–11 to 14–11 years old). For level 3 partially internalized private speech, only two participants (one in elementary school and one in senior high school) produced inaudible muttering during the task. Considering the small sample

TABLE 5d Mild, moderate, and severe-scoring groups across SRS-II (mean, standard deviation, and non-parametric test score).

Groups, result of statistical test  Mean, SD	Mild	Moderate	Severe	Kruskal–Wallis test		
	<i>n</i> = 6	<i>n</i> = 5	<i>n</i> = 4	Kruskal–Wallis H (K)	Degrees of freedom	<i>p</i> -value
Total private speech/min						
Mean	0.29	0.51	3.18	8.727	2	0.013*
SD	0.48	0.73	1.17			
Irrelevant private speech/min						
Mean	0.04	0.03	0.43	1.599	2	0.450
SD	0.05	0.06	0.50			
Relevant private speech/min						
Mean	0.25	0.48	2.76	8.727	2	0.013*
SD	0.44	0.72	1.08			
Internalized private speech/min						
Mean	0	0	0	0.000	2	1.000
SD	–	–	–			

\*Indicates a statistically significant difference (*p* < 0.05).

size and diverse diagnostic backgrounds of participants, it is hard to draw definitive conclusions about whether children with IDs use the same subtypes of private speech as typically developing children. Nevertheless, the participants with IDs in this study indeed showed similar usage of private speech to that of typically developing children.

### 5.3 Comparisons with research on other developmental disorders

The current findings revealed a positive correlation between SRS-2 scores and task-related private speech during the selective attention task, suggesting that participants with intellectual disabilities (IDs) who exhibited stronger ASD tendencies engaged in more private speech than those with milder ASD characteristics. While this might initially appear to contradict existing literature, it may be better understood in the context of how individuals with ASD utilize verbal strategies for cognitive regulation. Previous research has consistently demonstrated that individuals with ASD tend to rely less on inner speech during complex cognitive tasks. For example, Williams et al. (2012) reported a reduced use of inner speech for planning among individuals with ASD, while Joseph et al. (2005) found that individuals on the spectrum did not spontaneously engage in inner speech even when processing nameable stimuli. These findings suggest that the verbal mediation of working memory is often impaired or underutilized in this population.

From a Vygotskian perspective, private speech emerges in early childhood as a tool for self-regulation and gradually internalizes

TABLE 5e Significantly below average, below average, and average-scoring groups across VINELAND-II (mean, standard deviation).

Groups  Mean, SD, result of statistical test	Significantly below average  <i>n</i> = 1	Below average  <i>n</i> = 1	Average  <i>n</i> = 18
Total private speech/min			
Mean	0	0	1.49
SD	–	–	1.56
Irrelevant private speech/min			
Mean	0	0	0.13
SD	–	–	0.27
Relevant private speech/min			
Mean	0	0	0.97
SD	–	–	1.23
Internalized private speech/min			
Mean	0	0	0.40
SD	–	–	1.18

into inner speech as cognitive functions mature. In typically developing children, this progression allows for increasingly efficient internal verbal mediation. However, for individuals with ASD, this developmental transition may be delayed or disrupted,

TABLE 6 Spearman's rank correlation coefficient on KABC-II, PVT-R, SRS-II, and Vineland-II.

Assessment tools		Spearman's $\rho$			
		Total and categories of private speech	Total private speech/min	Irrelevant private speech/min	Relevant private speech/min
KABC-II	Cognitive composite scale	−0.087 ( $\rho = 0.717$ )	−0.402 ( $\rho = 0.079$ )	−0.219 ( $\rho = 0.354$ )	−0.219 ( $\rho = 0.354$ )
	Achievement composite scale	−0.242 ( $\rho = 0.305$ )	−0.264 ( $\rho = 0.261$ )	−0.474* ( $\rho = 0.035$ )	0.232 ( $\rho = 0.326$ )
PVT-R vocabulary age		−0.278 ( $\rho = 0.235$ )	−0.211 ( $\rho = 0.373$ )	−0.524* ( $\rho = 0.018$ )	0.290 ( $\rho = 0.215$ )
SRS-II total score		0.250 ( $\rho = 0.288$ )	0.182 ( $\rho = 0.443$ )	0.508* ( $\rho = 0.022$ )	−0.374 ( $\rho = 0.104$ )
Vineland-II total score		−0.150 ( $\rho = 0.527$ )	−0.150 ( $\rho = 0.527$ )	−0.398 ( $\rho = 0.082$ )	0.306 ( $\rho = 0.190$ )

Children's vocabulary age younger than 3 years and 0 months (<3–0) were coded as 0 due to unavailable exact age information. \*Indicates a statistically significant difference ( $p < 0.05$ ).

TABLE 7 Multiple regression analysis of task-relevant private speech.

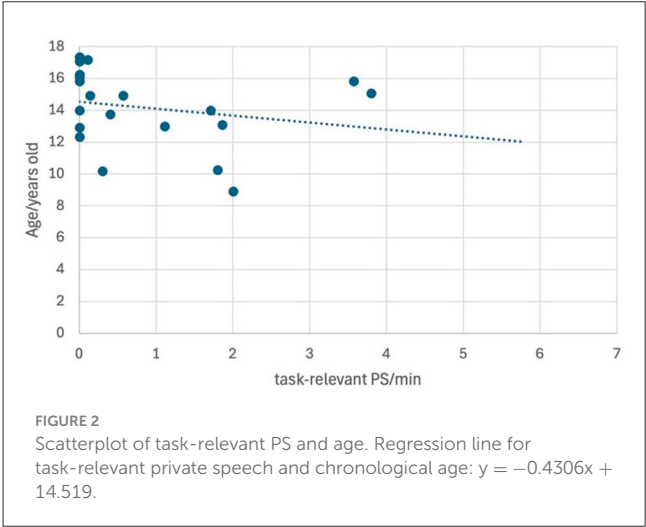
Independent variable, statistic	Independent variable			$F$	Adjusted $R^2$
	ASD tendency (SRS-II)	Age	Vocabulary age (PVT-R)		
Task-relevant PS	0.688**	−0.217	−0.077	7.515*	0.507

\* $p = 0.002$ , \*\* $p = 0.003$ . All coefficients are standardized.  
The model derived through forced entry regression.  
Children's vocabulary age younger than 3 years and 0 months (<3–0) were coded as 0 due to unavailable exact age information.

leading to continued reliance on overt private speech into later developmental stages. In this context, the increased frequency of private speech observed in individuals with stronger ASD traits may reflect a compensatory mechanism, wherein private speech serves as an external scaffold to support attention and task performance due to the inefficacy of inner speech.

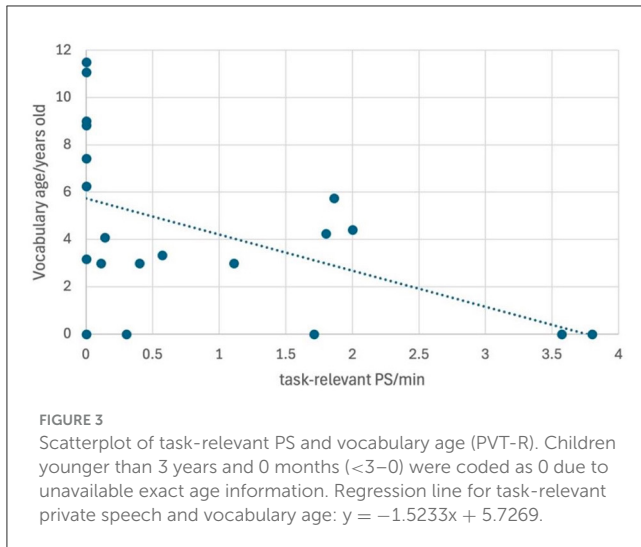
The implications of this interpretation are both theoretical and practical. From a theoretical standpoint, it underscores the necessity of revisiting assumptions about the normative trajectory of private-to-inner speech development, particularly in neurodiverse populations. Practically, the findings suggest that encouraging private speech in educational and therapeutic contexts may benefit children with ASD and IDs by enhancing cognitive regulation and task performance. Interventions that validate and support the use of externalized verbal strategies could serve as an effective scaffold for executive functioning. Future research should explore the integration of private speech-based strategies into individualized education plans and therapeutic protocols for children with developmental disorders.

Additionally, this study found a negative correlation between language development and task-relevant private speech. This contrasts with findings in ADHD populations, where private speech usage appears independent of verbal ability. For example, Andreou et al. (2005) noted diminished language skills in children with ADHD, yet Corkum et al. (2008) reported similar problem-solving performance to typically developing peers. In ADHD populations, private speech—particularly task-relevant and task-irrelevant external private speech—is more frequent than in typically developing children (e.g., Copeland, 1979; Zentall et al.,



1983; Berk and Potts, 1991; Berk and Landau, 1993; Winsler, 1998; Kopecky et al., 2005; Corkum et al., 2008). Benedetto-Nasho (2001), for instance, found that 87% of children with ADHD used both forms of private speech during a math task, compared to only 30–40% in the control group.

In the present study, 60% of the participants produced task-relevant external private speech and 30% used task-irrelevant private speech in the problem-solving task (see Table 3a). These results suggest that children with IDs also use private speech as a regulatory tool, particularly during problem-solving. However,



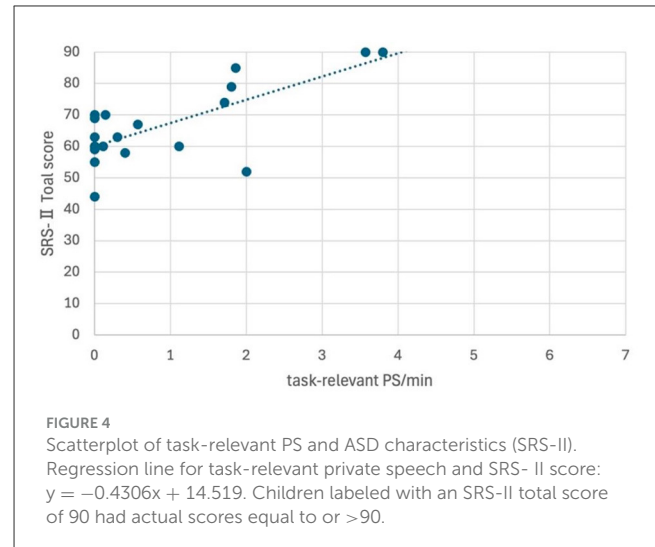
the relatively lower frequency of task-irrelevant speech compared to ADHD populations may reflect differing attentional profiles. Children with ADHD are more prone to distraction, potentially resulting in more off-task verbalizations. In contrast, children with IDs may demonstrate greater task persistence or task-irrelevant speech may be less detectable due to methodological limitations.

Collectively, these findings highlight the importance of understanding private speech as a dynamic and context-dependent cognitive tool, rather than as a uniform developmental marker. The patterns observed in this study underscore the need for population-specific frameworks that account for the diverse functions and developmental trajectories of private speech across neurodevelopmental conditions. Continued investigation is warranted to delineate the mechanisms underlying private speech use further and to inform the design of targeted interventions that leverage its regulatory potential in children with developmental disabilities.

## 5.4 Practical applications in educational settings

In special needs schools, a lack of understanding regarding children's private speech remains a concern. It is frequently observed that teachers interrupt students' private speech during class or discourage it by telling them that such behavior is inappropriate. As a result, children may refrain from using private speech spontaneously or come to perceive it negatively. Moreover, although many teachers are familiar with echolalia, private speech is often misunderstood as being synonymous with echolalia—merely meaningless repetition of sounds. Consequently, when teachers hear private speech that resembles echolalia, they may respond by asking the child to stop.

To address these issues, it is essential to distinguish clearly between echolalia and private speech and to inform teachers about the functions and significance of private speech. Children with intellectual disabilities also engage in private speech, which plays an important role in self-regulation and serves as a cognitive tool for



problem-solving. By enhancing teachers' accurate understanding of both echolalia and private speech, it is expected that they will be better equipped to interpret children's verbal behavior appropriately and to provide more effective and supportive educational guidance.

## 5.5 Limitations

Considering the characteristics of IDs, particularly the delayed development of language acquisition, this study was conducted across a wide age range, from elementary to high school, to examine the relationship between language ability and private speech. Although the number of participants was small, valuable data were obtained. In future research, it would be beneficial to increase the number of participants and explore more potential characteristics of private speech in children with IDs.

Moreover, considering that many children with IDs have co-occurring conditions, such as ASD, this study investigated the impact of ASD tendencies on private speech. It is possible that as a coexisting factor, autistic tendencies influence the cognitive capability and receptive language ability of children, leading to different outputs of private speech in problem-solving tasks among these children compared with those who only have IDs. This study did not compare the differences between the pure ID group and the group that also had autistic tendencies. Further studies could focus on this challenging point by collecting two sample groups (pure ID group and group with both ID and ASD) and exploring whether there are different outputs of private speech during problem-solving tasks, such as selective attention tasks in the present study.

Third, future studies should consider the influence of tasks on private speech. Problem-solving tasks, such as the selective attention task used in the present study, may more easily elicit private speech, whereas other tasks (e.g., behavioral inhibition tasks) may not (Diaz, 1992; Winsler et al., 1997; Winsler, 1998; Winsler et al., 2003). Additionally, different task types may stimulate different subcategories of private speech. Corkum



et al. (2008) indicated that individuals diagnosed with ADHD demonstrated distinct behavioral manifestations corresponding to varying stages of curvilinear progression from overt to internalized forms of private speech when performing problem-solving or behavioral inhibition tasks. The study's findings revealed that problem-solving tasks prompted more overt, task-irrelevant forms of internalized speech, while behavioral inhibition tasks elicited more task-relevant, partially internalized speech. Therefore, future studies should utilize two different types of tasks within the Zone of Proximal Development in children with IDs and/or ADHD/ASD to explore whether there are distinct outcomes.

Fourth, one key limitation of this study is the small sample size, which resulted in a low participant-to-predictor ratio in the multiple regression analysis (20 participants and three predictors). This compromises the reliability and stability of the regression coefficients and limits the statistical power to detect meaningful effects. Additionally, the limited sample size restricts the ability to thoroughly assess and validate the assumptions of the regression model. As such, the regression analysis should be interpreted as exploratory, and its findings are best understood in conjunction with visual representations that depict the relationships among variables and identify potential outliers.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

## Ethics statement

The studies involving humans were approved by Institute of Human and Social Sciences Ethics Committee of Kanazawa University. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## Author contributions

YN: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. YY: Conceptualization, Methodology, Project administration, Writing – review & editing.

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- The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.
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