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# The relationship between speech perception, speech production, and vocabulary abilities in children: Insights from by-group and continuous analyses

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## Abstract

Purpose: To explore the relationship between speech perception, speech production, and vocabulary abilities in children with and without speech sound disorders (SSDs), analyzing the data both by group and continuously.

Method: Sixty-one Australian-English speaking children aged 48-69 months participated in this study. Children's speech production abilities ranged along the continuum from SSDs through to typical speech. Their vocabulary abilities ranged along the continuum from typical to above average ("lexically precocious"). Children completed routine speech and language assessments in addition to an experimental Australian-English lexical and phonetic judgment task.

Results: When analyzing data by group, there was no significant difference between the speech perception ability of children with versus without SSDs. Children with above average vocabularies had significantly better speech perception ability than children with average vocabularies. When analyzing data continuously, speech production and vocabulary were both significant positive predictors of variance in speech perception ability; both individually in simple linear regression and when combined in multiple linear regression. There was also a significant positive correlation between perception and production of two of the four target phonemes tested—/k/ and /ʃ/—among children in the SSD group.

Conclusion: Results from this study provide further insight into the complex relationship between speech perception, speech production, and vocabulary abilities in children. While there is a clinical and important need for categorical distinctions between SSDs and typically developing speech, findings further highlight the value of investigating speech production and vocabulary abilities continuously as well as categorically. By capturing the heterogeneity among children's speech production and vocabulary abilities, we can advance our understanding of SSDs in children.

While learning to talk, children develop their abilities to perceive, store, and say words. When perceiving speech, children create and process sound-based representations from acoustic input (Rvachew & Brosseau-Lapré, 2018). The creation of sound-based representations in infancy is thought to contribute to early speech production (Kuhl, 2004; Vihman, 2017) and the development of children's vocabulary knowledge (Werker & Gervain, 2013; Werker & Yeung, 2005). These abilities are believed to be interconnected (Massaro & Chen, 2008; Rvachew, 2007; Rvachew & Grawburg, 2006).

**The Relationship Between Speech Perception and Speech Production: What Do We Know?**

Our understanding of the relationship between speech perception, speech production, and vocabulary is incomplete, particularly when we consider children with speech sound disorders (SSDs). SSDs refer to "any combination of difficulties with the perception, articulation/motor production, and/or phonological representation of speech…that may impact speech intelligibility and acceptability" (International Expert Panel on Multilingual Children's Speech, 2012). The representation-based account of SSDs in children posits that children with SSDs have underspecified or poor quality underlying phonological representations for words (e.g., Edwards et al., 1999; Geronikou & Rees, 2016; Sutherland & Gillon, 2005). This means they may also be at risk for difficulties in other abilities that rely on underlying phonological representations—such as speech perception, phonological awareness (PA), and vocabulary (Benway et al., 2021). Speech perception is integral to forming robust underlying phonological representations of words (Edwards et al., 1999; Munson et al., 2010), and difficulties with speech perception are thought to underlie difficulties in speech production (Hearnshaw et al., 2019; Munson et al., 2011; Rvachew & Grawburg, 2006; Rvachew & Jamieson, 1989). However, only some, not all, children with

SSDs are reported to have poorer speech perception compared with their typically developing peers (Hearnshaw et al., 2019). It is unclear why this is the case.

This perspective of speech perception influencing speech production aligns with the psycholinguistic box-and-arrow model proposed by Stackhouse and Wells (1997) to illustrate the steps involved in speech processing. In this model, words are first perceived, then mapped onto a lexical representation which encompasses a range of information including phonological and semantic (Baker et al., 2001; Stackhouse & Wells, 1997). These representations are then accessed to produce a word. This unidirectional relationship of speech perception influencing speech production also aligns with the majority of research identified in a systematic review and meta-analysis conducted by Hearnshaw et al. (2019), where difficulties in speech perception appeared to lead to difficulties with speech production in children aged 3;0-7;11.

This hypothesis that a broad perceptual difficulty underlies SSDs in children drove early research in the field (e.g., Cohen & Diehl, 1963; Sommers et al., 1972; Travis & Rasmus, 1931). However, in Locke's (1980a, 1980b) landmark papers, he proposed instead that children with SSDs may have particular problems with perception of sounds or contrasts they produce incorrectly. Since Locke, the search for a specific perception difficulty among children with SSDs has dominated research efforts (e.g., Geronikou & Rees, 2016; Rvachew & Jamieson, 1989; Shuster, 1998). In most of these studies, researchers have recruited children with specific speech errors. For example, in a study of 7-year-old children with /s/ errors, Rvachew and Jamieson (1989) found that "children with articulation errors demonstrate speech perception difficulties that are specific to the misarticulated sound and/or its substitution rather than perceptual difficulties that are generalized to many speech sounds" (p. 205). They further stated that "the present results lend more support to the hypothesis that it is the speech perception deficit that causes, or contributes to, the articulation disorder." (p.

207). A relationship between perception and production of /ɹ/ errors in children aged 7 to 9 (Cabbage et al., 2016) and 7 to 13 (Shuster, 1998) has also been reported. However, not all studies have found evidence of phoneme-specific perceptual errors in children with SSDs. For example, although Edwards et al. (2002) found a significant difference between children with SSDs and children with typically developing speech in their performance on a speech perception task based on discrimination of final consonants, this difference "could not be attributed to a particular error pattern, because children with final consonant deletion did not perform more poorly than children without final consonant deletion." (Edwards et al., 2002, p. 240). Additionally, Brosseau-Lapré et al. (2020) summarized that while many children with SSDs present with phoneme-specific speech perception difficulties for phonemes they produce incorrectly, "most children with SSD present with broader perceptual difficulties … their underlying phonological representations of words may be generally poorer than their peers with TD" (p. 3608).

When considering the representation-based approach and evidence from previous research, speech perception appears to be integral to speech production (Edwards et al., 1999; Hearnshaw et al., 2019; Munson et al., 2010). If we are to better understand the nature of SSDs in children, we need to further consider the role of speech perception and how children build their underlying representations of words. Given that underlying representations of words include semantic and lexical knowledge, as well as phonological (Baker et al., 2001; Stackhouse & Wells, 1997), studying children's vocabulary knowledge might offer much needed insights into the nature of underlying representations in children with SSDs.

## The Relationship Between Speech Perception and Vocabulary: What Do We Know?

The presence of a relationship between speech perception and vocabulary is well supported (e.g., Benway et al., 2021; Edwards et al., 2002; Mills et al., 2004; Rvachew & Grawburg, 2006; Werker et al., 2002). However, the nature of this relationship is different from that between speech perception and speech production. Unlike speech production where 4- to 5-year-old children are expected to have acquired most of their speech sounds and have intelligible speech (McLeod & Crowe, 2018), children are not expected to have learnt all the words they will ever know by the age of four or five. Similarly, for speech perception, while 4- to 5-year-old children are expected to be able to perceive words and phonemic contrasts, researchers have found that speech perception abilities are not "adultlike" until after children are 12 years old (Hazan & Barrett, 2000; Rvachew & Brosseau-Lapré, 2018).

Although young children's early words are thought to be stored holistically (Gruenenfelder & Pisoni, 2009; Metsala, 1997; Storkel, 2002) and are influenced by their developing speech perception abilities (McAllister Byun & Tessier, 2016; Samuelson, 2021), vocabulary growth is also thought to influence the development of more detailed and segmented underlying representations of words (Gruenenfelder & Pisoni, 2009; Metsala, 1997; Storkel, 2002). This influence of vocabulary on speech perception has been described in the lexical restructuring hypothesis, which posits that underlying representations of words in the lexicon become more detailed and segmented to allow for storage and retrieval of similar words as children's vocabularies grow (Gruenenfelder & Pisoni, 2009; Metsala, 1997; Storkel, 2002). The lexical restructuring hypothesis aligns with research showing a positive relationship between the size of infants' vocabularies and the ability to perceive finer phonetic detail in speech (Mills et al., 2004; Werker et al., 2002). It also aligns with and explains the pattern of development of PA abilities—from awareness of larger segments such as words and syllables when the vocabulary is smaller, through to awareness of smaller segments such as phonemes as the vocabulary expands (Rvachew & Brosseau-Lapré, 2018; Rvachew & Grawburg, 2006; Sutherland & Gillon, 2005).

But what do we know about the vocabulary knowledge of children with SSDs? Children who are hypothesized to have poorer underlying representations of words. Reports of vocabulary knowledge in children with SSDs are mixed. Munson et al. (2011) reported that "children with SSD typically have appropriately-sized vocabularies for their age. Though some studies do report that children with SSD have slightly smaller-sized vocabularies than their peers without SSD, they are typically well above conventional cutoffs for language impairment." (p. 26). By contrast, some research has shown that children with SSDs are at risk for concomitant language impairment (e.g., Eadie et al., 2015; Macrae & Tyler, 2014; Shriberg & Kwiatkowski, 1994). However, when the means, standard deviations, and ranges of vocabulary scores reported within the speech perception literature are closely inspected, there is also evidence of children with above average vocabulary abilities within SSD groups (e.g., Benway et al., 2021; Brosseau-Lapré & Schumaker, 2020; Edwards et al., 2002; Monnin & Huntington, 1974; Rvachew, 2007; Rvachew & Grawburg, 2006; Rvachew et al., 2003). Children with above average vocabulary abilities for their age may be referred to as "lexically precocious". In previous studies of 2-year-old children, lexically precocious talkers have been classified as those with an expressive vocabulary score above the 90th percentile (e.g., Kehoe et al., 2015; Kehoe et al., 2018), or those with expressive vocabulary scores at or above the 85th percentile (Smith et al., 2006). Smith et al. (2006) proposed that "children who can perceive and produce a greater number of phonemic contrasts should be more successful at comprehending input, more experienced at producing output, and thereby may more easily learn new words." (p. 370). Their proposition also supports a positive relationship between speech perception and vocabulary abilities. However, across the speech perception literature, as a group, children with SSDs and above average vocabulary have not been specifically examined or discussed.

To summarize, not all children with SSDs have problems with vocabulary. In fact, in some cases their vocabulary may be above average (e.g., Benway et al., 2021; Brosseau-Lapré & Schumaker, 2020; Edwards et al., 2002; Monnin & Huntington, 1974; Rvachew, 2007; Rvachew & Grawburg, 2006; Rvachew et al., 2003). Speech perception, speech production, and vocabulary are all connected and involved in building underlying representations (Benway et al., 2021; Massaro & Chen, 2008; Rvachew, 2007; Rvachew & Grawburg, 2006). To better understand the underlying nature of children with SSDs, we need to examine research that has considered all three abilities: speech perception, speech production, and vocabulary.

**The Relationship Between Speech Perception, Speech Production, and Vocabulary in Children With SSDs: What Do We Know?**

Few researchers have studied all three abilities in children with SSDs. In a study specifically focused on speech perception, speech production, and vocabulary, Edwards et al. (2002) found a significant difference in perception of final consonants between children with SSDs and typically developing speech. They also performed a multiple regression analysis examining the effects of age, receptive and expressive vocabulary, and speech production on perception of final consonants. Receptive vocabulary (accounting for 31% variance) and speech production raw score (accounting for 8.2% variance) were the two significant predictors of speech perception performance. Rvachew and Brosseau-Lapré (2015) also considered perception, production, and vocabulary in a randomized trial of different intervention approaches targeted at improving speech production in French-speaking 4-year-old children with SSDs. They found that targeting speech perception in therapy sessions alongside vocabulary at home (via dialogic reading) led to improvements in speech production (Rvachew & Brosseau-Lapré, 2015). Additionally, this improvement in speech production was comparable to that made by children who had targeted speech production in therapy and home practice (Rvachew & Brosseau-Lapré, 2015).

Other researchers have studied speech perception, speech production, and vocabulary abilities within the context of other related abilities that also depend on underlying representations. For example, Rvachew and Grawburg (2006) examined PA abilities of 4- to 5-year-old children with SSDs. They found that speech perception and receptive vocabulary were linked in children with SSDs. Speech perception and receptive vocabulary both influenced PA abilities—speech perception did so directly as well as indirectly mediated by receptive vocabulary (Rvachew & Grawburg, 2006). Benway et al. (2021) examined the relationship between PA, speech perception, and vocabulary in 7- to 17-year-old children with SSDs. They found that speech perception and vocabulary both significantly predicted PA ability, however, unlike in preschool-age children there did not appear to be an indirect effect of speech perception mediated by receptive vocabulary (Benway et al., 2021).

These studies provide insight into the relationship between speech perception, speech production, and vocabulary in children with SSDs. However, there is scope to expand on and add to this research. Specifically, these previous studies have included children with vocabulary scores that place them in the average to above average range. In previous studies that have analyzed vocabulary as a continuous measure, vocabulary has been considered across the full range of abilities included within each study—including advanced vocabulary—but in most cases, the role of advanced vocabulary on speech perception and production has not been explicitly discussed. One exception is Benway et al. (2021) who acknowledged that the overall high receptive vocabulary scores of their participants may have contributed to their findings that vocabulary did not mediate the relationship between speech perception and PA. Children with SSDs and precocious vocabularies present a conundrum regarding the quality of their phonological representations and speech perception abilities. Based on their SSD, we might expect these children to present with poor speech perception abilities. On the other hand, based on their larger vocabularies, we might expect them to present with robust speech perception abilities. Edwards et al.'s (2002) finding that vocabulary was the strongest predictor of speech perception ability in their model (accounting for 31% variance), would suggest that these children are more likely to present with robust speech perception abilities. However, this requires further investigation. Children with precocious vocabularies therefore provide a unique opportunity to study the complex relationship between speech perception, speech production, and vocabulary knowledge, and to understand the contribution of speech perception to both speech production and vocabulary knowledge. A valuable way to gain further insight would be by considering results from both by-group and continuous analyses.

## A Continuous Approach to Studying the Relationship Between Speech Perception, Speech Production, and Vocabulary

Children's speech perception, speech production, and vocabulary abilities can be studied in one of two ways—comparing abilities according to preassigned "impaired", "typical", or "above average" groups, or along a continuum from weaker to stronger abilities. When we allocate children to pre-defined groups based on their ability—using, for example, a percentile cut-off—we are placing an arbitrary distinction in an already continuous measure. Such cut-points are based on a potentially faulty assumption: that each group is categorically different from the other group. By-group comparisons have traditionally been used in clinical research as they offer clinically relevant insights. However, they also obscure within-group variability and heterogeneity between children's abilities (Perry & Kucker, 2019). Another option is to consider abilities as continuous measures along a spectrum. Analyzing as a continuous measure enables us to examine the true influence of raw ability and to examine individual differences between children (Iacobucci et al., 2015; Perry & Kucker, 2019). This also addresses potential issues with "median-splitting" data; such as less information about individual participants and performance; loss of power; and where multicollinearity is present, Type I errors (Iacobucci et al., 2015).

Perry and Kucker (2019) reflected that heterogeneity between children's abilities "highlights the importance of understanding both group differences and individual variation in characterizing atypical populations" (p. 556). Motivated by this idea, they conducted a study with late-talking children. They used both by-group (*t*-test, ANOVA) and continuous (mixed-effects regression) methods to analyze the same data. A *t*-test showed that both groups demonstrated an important word learning milestone (the shape bias); an ANOVA showed that while each group demonstrated the bias, late talkers lagged behind their peers with typical language; a continuous mixed-effects regression demonstrated qualitative differences between the groups in that the shape bias was related to vocabulary structure for children with typical language, but not late talkers (Perry & Kucker, 2019). Perry and Kucker (2019) highlighted the different conclusions that could be drawn from each analysis and acknowledged the value of continuous analysis; particularly with regards to understanding heterogeneity, individual abilities, and the range of abilities of children.

To date, different combinations of speech perception, speech production, and/or vocabulary have been considered as continuous measures in some studies with children with SSDs focused on underlying representations (e.g., Benway et al., 2021; Brosseau-Lapré & Roepke, 2019; Edwards et al., 2002; Preston & Edwards, 2010; Rvachew, 2007; Rvachew & Grawburg, 2006). The variable of interest for these continuous analyses was PA—with the exception of Edwards et al. (2002) where it was speech perception, and Rvachew (2007) where it was reading ability. Brosseau-Lapré and Roepke (2019), Edwards et al. (2002), and Rvachew (2007) used both by-group and continuous analyses. Edwards et al. (2002) performed ANOVA as their main analyses comparing speech perception performance between groups—age groups in Experiment 1 and SSD versus typically developing speech groups in Experiment 2. In their discussion they also reported results from a multiple regression analysis including speech perception, age, receptive and expressive vocabulary, and speech production as continuous variables (Edwards et al., 2002). Based on means and standard deviations reported in their paper, Experiment 2 included some children with above average vocabulary within the SSD group. However, above average vocabulary was not specifically discussed. Additionally, in their study, the SSD group presented with significantly lower receptive and expressive vocabulary scores than the typically developing speech group. In the studies by Brosseau-Lapré and Roepke (2019) and Rvachew (2007), the by-group and continuous analyses had different focuses. In Brosseau-Lapré and Roepke (2019), their by-group analysis examined different types of speech errors produced by children with SSDs versus typically developing speech, while their continuous analysis examined the relationship between different types of speech errors and PA abilities. In Rvachew (2007), their by-group analyses compared performance across a range of abilities in three groups of children—SSDs with low phonological processing abilities, SSDs with high phonological processing abilities, and typically developing speech. Their continuous analysis examined the predictive relationship between speech perception and PA abilities before starting kindergarten, and reading ability in grade one (Rvachew, 2007).

Analyzing data by-group and continuously provides two ways of examining the same phenomenon. Each method can bring a different and valuable perspective to understanding children's abilities. Our study will expand on and add to previous research by using complementary by-group and continuous analyses with a sample of children with SSDs and typically developing speech, with vocabulary abilities ranging from average to precocious, focusing on speech perception as an outcome measure for both by-group and continuous analyses. With this approach we seek to advance our understanding of the relationship between speech perception, speech production, and vocabulary.

## Aim and Hypotheses

The aim of this study was to explore the relationship between speech perception, speech production, and vocabulary abilities in 4- to 5-year-old children with and without SSDs, with typical through to precocious vocabulary abilities. We were specifically interested in further understanding the relationship between a) speech perception and speech production, and b) speech perception and vocabulary, each from the perspective of the representation-based account. That is, we considered speech perception as the dependent variable. We investigated these children's speech perception abilities in two ways—by-group based on speech production and vocabulary ability, and then by considering both speech production and vocabulary abilities, each along a continuum.

1. In the by-group analysis, we classified children as either presenting with SSD or typical development in speech production. We also classified children as either having average or precocious vocabulary abilities. Our research question was:
   Is there a significant difference in speech perception ability between children with SSDs and those with typically developing speech, and children with average vocabulary and those with precocious vocabulary?
   We predicted poorer speech perception in the SSD speech production group than in the typical speech production group. We also predicted poorer speech perception in the average vocabulary group than in the precocious vocabulary group.
2. In the continuous analysis, we treated speech perception, speech production, and vocabulary scores as continuous variables. Our research question was:
   Do speech production and vocabulary abilities account for variance in speech perception ability?
   We predicted that both would account for variance in speech perception.

## Method

### Participants

We recruited 67 children aged 48-69 months (36 boys, 31 girls), from Canberra, Australian Capital Territory (ACT), Australia, and the surrounding region via advertisements on parenting group social media sites and in private speech pathology clinics. Inclusion criteria were: children speaking Australian-English; normal hearing (based on a hearing screening); and normal oral musculature structure and function (based on Robbins & Klee, 1987). Exclusion criteria were: children with childhood apraxia of speech (CAS) or childhood dysarthria; children with an identified cause for their speech difficulty including cleft palate or hearing loss; and children with a diagnosed developmental delay or autism.

We conducted a power analysis using the average effect size from studies included in Hearnshaw et al.'s (2019) systematic review. The average effect size was calculated based on 36 available effect sizes across 25 papers comparing differences in speech perception ability between children with SSDs and typically developing speech. The average Cohen's *d* was 1.50. Using this effect size, for 80% power the necessary total sample size would be 18 participants (nine per group). We also looked at a smaller subset of papers included in Hearnshaw et al.'s (2019) meta-analysis. These studies all used lexical and phonetic judgment tasks which is the type of speech perception assessment task used in the current study. The average Cohen's *d* based on eight available effect sizes from Hearnshaw et al.'s (2019) meta-analysis was 1.14. Using this effect size, for 80% power the necessary total sample size would be 28 participants (14 per group).

Of the 67 children recruited as participants, six were excluded from final analysis. Three children completed only one of the two required assessment sessions. Two children did not pass the hearing screening in either session. One other child was excluded due to non-compliance across multiple tasks. Hence, we included results from 61 participants (31 boys, 30 girls) in our analyses.

The children's socioeconomic status (SES) was quantified based on (i) mother's highest education level and (ii) residential postcode. The mean and median highest education level for children's mothers was a completed bachelor's degree. Highest education level ranged from completion of Year 10 in high school (11 years of formal schooling) through to completion of a postgraduate qualification. For residential postcode, The "Index of Relative Socioeconomic Advantage and Disadvantage" (IRSAD; Australian Bureau of Statistics, 2018) was used based on data collected in the 2016 Australian census. A decile of 1 represents the most disadvantaged areas, while a decile of 10 represents the most advantaged areas. For rank within Australia, the mean decile score was 9.5, the median was 10, and the range was 8–10.

For research question one, children were divided into two speech groups based on their performance on the *Diagnostic Evaluation of Articulation and Phonology (DEAP) – Phonology Assessment* (Dodd et al., 2002). The SSD group included 30 children (15 boys, 15 girls) with SSDs characterized by a range of phonological error patterns (e.g., stopping, cluster reduction, velar fronting, palatal fronting, deaffrication) and/or articulation-based errors (e.g., interdental lisp, lateral lisp). For phonological errors, children were allocated to the SSD group based on having at least five instances in the *DEAP–Phonology Assessment* (Dodd et al., 2002) of at least one phonological pattern-based error not appropriate for their age as per Appendix D from the *DEAP Manual* (Dodd et al., 2002). For articulation-based errors, both the *DEAP Manual* (Dodd et al., 2002) and extant literature were considered. Specifically, although Appendix A from the *DEAP Manual* (Dodd et al., 2002) stipulates that sibilants /s, z/ are in the consonant inventories of 90% of children by the age of 3;5, other researchers such as Smit (1993) suggest that some children's productions of these sibilants may be age-appropriate despite being "slightly distorted", while other distortions may be deemed "clinically significant". Therefore, the first two authors classified children with clinically significant distortions (e.g., lateralization or interdentalization of sibilants impacting intelligibility) on more than 50% of opportunities in the *DEAP–Phonology Assessment* (Dodd et al., 2002) as also presenting with SSDs. Regarding severity of SSD, based on the *Therapy Outcome Measures* (Enderby & John, 2019), 20/30 children presented with a mild SSD, 6/30 with a moderate SSD, 1/30 with a severe/moderate SSD, and 3/30 with a severe SSD. For children with a phonological-based SSD (*n* = 18), severity was determined by number of age-inappropriate phonological processes. For children with an articulation-based SSD (*n* = 12), severity was determined by the number and nature of articulation errors (Enderby & John, 2019). The TD group included 31 children (16 boys, 15 girls) with typically developing speech. These children presented with no age-inappropriate phonological pattern-based errors and no clinically significant sibilant distortions. For research question two, children's speech production abilities were considered continuously. Children's raw scores on the *DEAP–Phonology Assessment* (Dodd et al., 2002) ranged from 38-141 (out of a total of 141), with an average of 116. These raw scores were calculated based on percentage of consonants correct (PCC) from the 50-word sample as per the *DEAP–Phonology Assessment* form.

For research question one, children were also divided into two vocabulary groups following assessment: the lexically precocious group and the average vocabulary group. No children presented with below average vocabulary. We classed 28 children as having "lexically precocious" vocabulary as they scored at or above the 85$^{th}$ percentile on both the *Peabody Picture Vocabulary Test – 4* (*PPVT-4*; Dunn & Dunn, 2007) and the *Expressive One Word Picture Vocabulary Test – 4* (*EOWPVT-4*; Martin & Brownell, 2011). Of the 28 lexically precocious children, 12 were in the SSD group and 16 were in the TD group. We chose the criteria of receptive and expressive vocabulary scores at or above the 85$^{th}$ percentile because these scores are greater than one standard deviation above the mean and considered "moderately high" to "extremely high" scores according to the *PPVT-4* test form (Dunn & Dunn, 2007). This also aligns with the expressive vocabulary cut-off used by Smith et al. (2006) in their study of lexically precocious 2-year-olds. We included both receptive and expressive vocabulary in our criteria as we were interested in both receptive and expressive vocabulary in our analyses. For research question two, children's vocabulary abilities were considered continuously. Children's raw scores on the *PPVT-4* (Dunn & Dunn, 2007) ranged from 54-135, with an average of 99. Children's raw scores on the *EOWPVT-4* (Martin & Brownell, 2011) ranged from 37-108, with an average of 76.

Children also passed a pure tone audiometric hearing screening at 30dB for 500Hz, 1000 Hz, 2000 Hz, and 4000 Hz. This conservative approach of 30dB was taken to adjust for screening in homes which may be noisier environments compared with research labs or soundproof booths (see, for example, McLeod et al., 2017 who used a more conservative cut-off of 40dB). All children presented with age-appropriate oral structures and functions based on Robbins and Klee (1987), and no significant medical conditions or other developmental concerns as noted by parent report. Table 1 displays participant characteristics.

**Procedure**

Children were seen in their homes for two testing sessions, one week apart. Each session lasted 60 to 120 minutes. This research project was approved by the University of Sydney Human Research Ethics Committee (HREC; Project Number 2017/887). Sessions were audio and video recorded with parents' consent.

Children's speech production and receptive and expressive vocabulary abilities were assessed using standardized tests as reported in the *Participants* section. At the beginning of the first session, before completing the first module of the speech perception task, children were also asked to name picture cards depicting the eight target words used in the speech perception task: “cat, coat, chain, chin, rat, rope, sheet, shoe”. This task ensured children were familiar with the target words to be presented in the speech perception task.

***Experimental Australian-English Speech Perception Task***

Speech perception abilities were assessed using an experimental computer-based Australian-English lexical and phonetic judgment task developed and used in prior research by Hearnshaw et al. (2018). The design and methodology of this task were based on Rvachew’s *Speech Assessment and Interactive Learning System* (*SAILS*) program (Rvachew, 2009); however, we developed our own guidelines for the number of stimuli and speakers included, as well as speaker characteristics as summarized below (Hearnshaw et al., 2018). Stimuli from Australian-English speakers were presented using E-prime® 2.0 (Psychological Software Tools Inc, 2014).

**Speech Recordings.** Speech samples were collected from 27 Australian-English speakers. Each speaker was recorded saying eight different words—“cat, coat, chain, chin, rat, rope, sheet, shoe”—across four different word-initial phonemes—/k, ʧ, ɹ, ʃ/. Twenty-four productions of each word were included in the task; spoken by three male and three female adults and three male and three female children with accurate speech productions, and six male and six female children with speech errors. A range of speech errors were included for each phoneme—for example, common phonological errors such as fronting, stopping, deaffrication, and gliding, as well as distortion errors such as interdentalization and lateralization. Some of these speech errors were similar to those made by children in the current study. The 24 samples of each target word were allocated evenly across two modules per word. Hence, the tool included a total of 192 speech samples across 16 modules. Lexical and phonetic accuracy of each sample was determined by 100% consensus of the first two authors. These codings were then assigned within E-prime®.

**Speech Perception Task Procedure.** Children listened to four blocks of 48 words across the two sessions; one at the beginning and end of each session. In session one, the first block was presented as the second activity; immediately following the familiarization production task, while in session two, the first block was presented as the first activity. The order of presentation of stimuli and modules was randomized for each child. Blocks contained four modules; one per phoneme. For example, a child may have listened to "sheet, cat, chain, rat" at the beginning of session one and end of session two and "shoe, coat, chin, rope" at the end of session one and beginning of session two. Wilcoxon signed-rank tests were used to compare speech perception performance in session one versus session two and at the beginning versus the end of each session. All comparisons were non-significant, $p > .05$.

Each module was presented on a laptop screen. Children listened to three practice items followed by 12 examples of a single target word, each spoken by a different speaker. Children used both lexical (i.e., target word) and phonetic (i.e., clear phoneme) judgment to decide whether each presentation was a correct or incorrect example of the target word. They indicated their decision by pressing either a happy face (for correct productions) or sad face (for incorrect productions) button located on a Psychological Software Tools Serial Response Box™. Children's response accuracy was recorded by E-prime® and listed against the codings allocated by the first two authors. Two pictures were shown on the laptop screen during each module—one depicting the target word and the other depicting the target word covered by a red cross—to facilitate judgment of accurate and inaccurate productions of the target word. The position of these pictures corresponded with the position of the happy and sad face buttons on the Serial Response Box™ (i.e., correct picture on the left, happy face button on the left; incorrect picture on the right, sad face button on the right). The end of each module was indicated by a brief animated picture on the computer screen, which also served as reinforcement. Children and the examiner wore headphones during administration of the speech perception task.

## Reliability

The first author performed the initial transcriptions and also re-transcribed a randomly selected 10% of the *DEAP–Phonology Assessments* (Dodd et al., 2002). Point-by-point intra-rater reliability was 97.8% based on 1320 points. The second author also transcribed the same randomly selected 10% of the *DEAP–Phonology Assessments* (Dodd et al., 2002). Point-by-point inter-rater reliability was 96.1% based on 1320 points. Cohen's κ was calculated to determine if there was agreement between the two authors' transcriptions. There was substantial agreement, $\kappa = .758$, $p < .001$.

## Data Analysis

Data were analyzed using independent-samples t-tests and ANOVA for by-group analyses, and simple and multiple linear regression for continuous analyses. The dependent variable was speech perception ability—the total number of items correct on the novel speech perception assessment task out of a total of 192 (range 88-182). A *p*-value less than .05 was considered statistically significant. Effect sizes were calculated using Pearson's $r$ and $R^2$, and partial eta squared (partial $\eta^2$). In line with Gaeta and Brydges (2020), $r$ of .25 represents a small effect, .40 a medium effect, and .65 a large effect. $R^2$ of .06 represents a small effect, .16 a medium effect, and .42 a large effect (based on Gaeta & Brydges, 2020). Partial $\eta^2$ of .01 represents a small effect, .06 a medium effect, and .14 a large effect (Cohen, 1977).

Analyses were completed using R (R Core Team, 2021; version 4.1.2) in Rstudio (Rstudio Team, 2021; version 2021.09.0). Data manipulation and plotting were completed using the tidyr (Wickham & Girlich, 2022; version 1.2.0) and ggplot2 (Wickham, 2016; version 3.3.5) packages.

# Results

## Speech Production, Vocabulary, and Speech Perception: By-Group Analyses

### *Speech Production Groups*

Figure 1 shows a violin plot displaying overall performance on the speech perception task for the SSD and TD groups. Speech perception performance was quantified as total number of items correct on the speech perception task out of a total of 192. An independent-samples *t*-test showed no significant difference in speech perception performance between the SSD ($M$ = 143.967, $SD$ = 22.716) and TD ($M$ = 153.484, $SD$ = 15.438) groups, $t(59)$ = 1.919, $p$ = .060, $r$ = .240.

Contrary to our first hypothesis, there was no significant difference in speech perception ability between SSD and TD groups. To investigate this unexpected finding, we conducted post-hoc exploration of the relationships between perception and production of the four target phonemes included in the speech perception task—/k, ʧ, ɹ, ʃ/—within each group. See Supplemental Material 1 for an overview of perception performance on each phoneme per group. In summary, there was no significant correlation between perception and production of any of the four phonemes for the TD group, and two of the four phonemes—/ʧ, ɹ/—for the SSD group. There was a significant moderate positive correlation between perception and production of the other two target phonemes for the SSD group: /k/ ($r$ = .416, $p$ = .022) and /ʃ/ ($r$ = .539, $p$ = .002).

### *Vocabulary Groups*

Figure 2 shows a violin plot displaying overall performance on the speech perception task for the average vocabulary and precocious vocabulary groups. An independent-samples *t*-test showed a significant difference in speech perception performance between the average vocabulary ($M$ = 144.09, $SD$ = 20.92) and precocious vocabulary ($M$ = 154.36, $SD$ = 17.11) groups, $t(59)$ = 2.074, $p$ = .042, $r$ = .259.

### *Speech Production and Vocabulary Groups*

When speech production and vocabulary were considered in the same model, a two-way ANOVA showed a significant main effect of vocabulary group on speech perception performance, $F(1, 58) = 4.079$, $p = .048$, partial $\eta^2 = .066$. There was not a significant effect of speech production group on speech perception performance, $F(1, 58) = 3.876$, $p = .054$, partial $\eta^2 = .063$.

Note the standard deviation of 22.716 in the SSD group reported in the *Speech Production Groups* section, which shows large variability in speech perception performance across children with SSDs (see also Figure 1). As per recommendations from Perry and Kucker (2019), next we analyzed the data continuously to further explore this heterogeneity and variability, and to further consider the role of vocabulary in this relationship.

## Speech Production, Vocabulary, and Speech Perception: Continuous Analyses

### *Speech Production and Speech Perception*

A simple linear regression analysis was run to examine whether speech production accuracy (*DEAP–Phonology Assessment* raw score) accounted for variance in overall speech perception performance. Figure 3 shows a scatterplot of this relationship, as well as showing individual children's scores on the speech production and speech perception tasks. Speech production accuracy was a significant predictor of variance in speech perception performance; accounting for 16.7% of variance, $F(1, 59) = 11.85$, $p = .001$, $R^2 = .167$ (see Table 2a for coefficients and confidence intervals).

### *Vocabulary and Speech Perception*

A simple linear regression analysis was run to examine whether receptive (*PPVT-4* raw score) and expressive vocabulary (*EOWPVT-4* raw score) accounted for variance in overall speech perception performance. Since multicollinearity was present between receptive and expressive vocabulary ($r = .816$, $p < .001$) and our categorical measure of lexically precocious was determined using both the receptive and expressive measures, we calculated a single composite vocabulary score averaging across *PPVT-4* and *EOWPVT-4* raw scores for each child. As the *PPVT-4* and *EOWPVT-4* tests are each scored on a different scale, we converted each measure to a z-score before averaging across receptive and expressive vocabulary. Figure 4 shows a scatterplot of the relationship between combined vocabulary z-score and overall speech perception accuracy. Vocabulary was a significant predictor of variance in speech perception performance; accounting for 20.3% of variance, $F(1, 59) = 15.02$, $p < .001$, $R^2 = .203$ (see Table 2b for coefficients and confidence intervals).

### *Speech Production, Vocabulary, and Speech Perception*

A multiple linear regression analysis was run to examine the influences of speech production accuracy (*DEAP–Phonology Assessment* raw score) and vocabulary (mean z-score calculated from *PPVT-4* and *EOWPVT-4* raw scores) on overall speech perception performance. Speech production accounted for 6.8% of unique variance in overall speech perception performance and was a significant predictor, $p = .024$. Vocabulary accounted for 10.3% of unique variance and was also a significant predictor, $p = .006$. These two variables combined contributed significantly to speech perception and accounted for 27.1% of variance in overall speech perception performance, $F(2, 58) = 10.76$, $p < .001$, $R^2 = .271$ (see Table 2c for coefficients and confidence intervals).

## Discussion

In this study we examined the relationship between speech perception, speech production, and vocabulary abilities in Australian-English speaking 4- to 5-year-old children along a continuum from SSDs through to typical speech production, and typical through to precocious vocabulary abilities. When analyzed by group, there was no significant difference in speech perception abilities between children with SSDs and children with typically developing speech. There was a significant difference in speech perception abilities such that children with precocious vocabularies performed better than children with average vocabulary abilities. When analyzed continuously, both speech production and vocabulary were significant predictors of variance in speech perception ability. We also found a significant positive correlation between perception and production of two of the four target phonemes—/k/ and /ʃ/—among children in the SSD group.

**No Difference in Speech Perception Ability of Children With Versus Without SSDs: Why?**

Unlike much of the previous literature and contrary to our first hypothesis, our results did not show a significant difference in overall speech perception performance between children in the SSD and TD groups. What are some possible reasons for this finding?

Based on a power analysis using an effect size from the previous literature, the sample size of this study should provide adequate power to find an effect. In both the by-group and continuous analyses examining the relationship between speech perception and speech production, the effect sizes were much smaller than the average of $d = 1.50$ and $d = 1.14$ from the previous literature. For our by-group analysis comparing speech groups, the effect size was $r = .240$ which converts to $d = 0.494$. For our continuous analysis including speech production raw scores, the effect size was $R^2 = .167$ which converts to $d = 0.896$. One possible reason for the smaller effect sizes is the high number of children in the SSD group with precocious vocabulary abilities. While we know that children with SSDs and precocious vocabulary abilities have been included in previous research, in many of these studies we do not know what number or proportion of children with SSDs have presented with precocious vocabularies. One exception is Rvachew and Grawburg (2006) who have presented individual results on their speech perception and receptive vocabulary assessments in Figure 2 of their paper. It is possible that our sample does not match many groups of children with SSDs who have participated in previous research.

Setting aside effect sizes, the precocious vocabulary abilities of nearly half the children in this study provide interesting insight into the relationship between speech perception and speech production. Our findings suggest it is difficult to examine the relationship between speech perception and speech production without also considering vocabulary.

Another possible reason for the finding of no significant difference in overall speech perception performance between children in the SSD and TD groups is because we did not set-out to specifically assess perception of phonemes produced in error by these children. Given the research supporting the presence of a phoneme-specific speech perception difficulty in children with SSDs (e.g., Monnin & Huntington, 1974; Rvachew & Jamieson, 1989), in assessing the same four phonemes across a mix of children, some who produced these phonemes in error and others who produced them correctly, we may have missed the presence of a phoneme-specific difficulty. However, based on other researchers such as Brosseau-Lapré et al. (2020), children with SSDs may also be expected to present with broader perceptual difficulties, and hence, we may still expect to see an effect in this study.

**The Relationship Between Speech Perception and Production of Specific Phonemes**

In this study, children who produced /k/ and /ʃ/ incorrectly were also more likely to perceive those phonemes incorrectly. This provides some support for a speech perception difficulty specific to phonemes produced in error. However, we found significant relationships between perception and production for only two out of four target phonemes: /k, ʃ/. Rvachew and Jamieson (1989) stated that “this relationship between speech production errors and speech perception ability may not exist for all phoneme contrasts because the role of auditory perception in the development of articulation skills may vary depending on the particular phoneme being learned” (p. 200). Development may be playing a role in this finding. /k/ and /ʃ/ are the two earliest-developing of the four target phonemes and are age-appropriate sounds in production for 4- and 5-year-old children. However, /ʧ/ and /ɹ/—especially /ɹ/—are phonemes that may be too perceptually and/or motorically complex for 4- and 5-year-old children to produce accurately (Cialdella et al., 2021; Preston et al., 2020). This finding suggests that there may be a relationship between perception and production of specific phonemes, however this may only be seen for phonemes that are within the expected phonemic repertoire for a child's age. This has implications for designing speech perception assessment tasks and which phonemes to assess in children at specific ages.

**Speech Production and Vocabulary Predict Unique Variance in Speech Perception Abilities**

Speech production and vocabulary were both significant predictors of variance in speech perception ability. For children with SSDs, the relationship between speech perception and speech production has been well established in the literature, however there has been less of a focus on the relationship between speech perception and vocabulary (Hearnshaw et al., 2019). Given the emphasis in the research literature on the relationship between speech perception and speech production in children with SSDs, it is interesting that in this study vocabulary predicted more variance in speech perception than that predicted by speech production. Although, we note that this finding is consistent with Edwards et al. (2002) who found that receptive vocabulary accounted for 31% variance in perception of final consonants, while speech production accounted for 8.2% variance. Once again, the greater range of vocabulary scores (in particular, high vocabulary scores) for children with SSDs in the current sample is a possible explanation for this finding.

We also observed that speech production and vocabulary accounted for variance in speech perception both separately and when combined. On its own, speech production accounted for 16.7% of the variance in children's speech perception ability; with the inclusion of vocabulary, we were able to determine that 6.8% of this variance was unique to speech production and 10.0% was shared with vocabulary (differences in decimal points due to rounding). Similarly, vocabulary accounted for 20.3% of the variance in speech perception ability, but only 10.3% of the variance was unique to vocabulary. The combined variance captures, in part, the other cognitive factors that affect children's performance on standardized assessments (e.g., general language ability, attention, cognition, processing speed, and memory). Thus, an advantage of linear regression is that the inclusion of multiple variables allows researchers to better isolate the unique effects of each construct on their outcome variable. Put another way, without the inclusion of vocabulary in the model, we would be unable to determine the extent to which the variance accounted for by our measure of speech production (16.7%) was truly the result of differences in children's speech production (6.8%) and not simply differences in general cognitive ability. The inclusion of additional variables in our model would potentially further improve our ability to isolate the effect of speech production and vocabulary.

While this study gives insight into the relationship between speech perception, speech production, and vocabulary abilities, as explained by Edwards et al. (2002), the directionality of these relationships cannot be determined or confirmed by these results. Regarding speech perception and speech production, while much research supports the perspective that speech perception influences speech production, researchers have also suggested other possible directionalities (Hearnshaw et al., 2019). For example, speech production may influence speech perception (e.g., Attoni et al., 2010; Monnin & Huntington, 1974); or there may be a bidirectional relationship between speech perception and speech production, with each influencing the other (e.g., McAllister Byun, 2012; Shuster, 1998). Regarding speech perception and vocabulary, the lexical restructuring hypothesis provides evidence that vocabulary growth influences development of speech perception (Gruenenfelder & Pisoni, 2009; Metsala, 1997; Storkel, 2002). However, other research supports the influence of speech perception on the development of vocabulary knowledge (e.g., McAllister Byun & Tessier, 2016; Samuelson, 2021). This study adds to the body of research showing that speech perception, speech production, and vocabulary abilities appear to be related and are worth considering in children with SSDs.

**What Did We Learn From By-Group Versus Continuous Analyses?**

The complementary by-group and continuous analyses yielded results that provided different insights into our data. Looking at the *t*-test in isolation, we found no significant difference between the speech perception abilities of children with SSDs versus typically developing speech. This is in contrast with the majority of the previous literature that does show a difference between these groups (Hearnshaw et al., 2019). However, the continuous analyses showed that speech production did predict variance in speech perception abilities.

The lack of significant difference between the speech perception abilities of SSD versus TD groups may align with conclusions from previous studies that some, but not all, children with SSDs have speech perception difficulties (Hearnshaw et al., 2019). Heterogeneity between children may prevent group differences from being seen in the results. There are many possible sources of heterogeneity; for example, general language ability, attention, cognition, processing speed, and memory. By including children with SSDs along the continuum from average to precocious vocabulary abilities, we know there are differences between children within the SSD group. This was accounted for in the continuous analyses but not in the *t*-tests. Despite this, by-group analyses also contribute important information, and diagnosis and grouping can be important in clinical and research settings. However, we should remember that these cut-points are arbitrary and not assume that all children in a particular group are the same.

**Theoretical Implications**

Findings from this study have theoretical implications regarding the relationship between speech perception, speech production, and vocabulary abilities. Based on the representation-based account of SSDs, children with SSDs are thought to have underspecified or poorer quality underlying phonological representations for words (e.g., Edwards et al., 1999; Geronikou & Rees, 2016; Sutherland & Gillon, 2005). Difficulties with speech perception and the formation of robust acoustic-auditory representations for words have been reported to underlie speech production errors in children with SSDs (e.g., Anthony et al., 2010; Brosseau-Lapré & Schumaker, 2020; Edwards et al., 1999; Munson et al., 2010). However, the findings from our study align with other research in suggesting we need to better consider the heterogeneity among children, with the knowledge that not all children with SSDs have difficulties with speech perception. For example, in our study, participant 43 presented with good speech perception, above average vocabulary, and poor speech production. Participant 36 presented with good speech perception, average vocabulary, and poor speech production. By contrast, Participant 29 presented with poor speech perception, average vocabulary, and poor speech production. What is the difference between these children with SSDs who do and do not struggle with speech perception?

One consideration is motor ability. McAllister Byun and Tessier (2016) posited that motor performance and underlying representations work together as children learn to speak. Some children with SSDs may have difficulty perceiving a word, which may in turn lead to poorly specified underlying phonological representations, and an inability to create an appropriate motor plan to produce speech. By contrast, some children with SSDs may have adequate perception and well-specified underlying phonological representations, but perhaps a reduced ability to create or access a suitable motor plan for speech production. This aligns with the understanding that children's motor speech abilities and control improve with age throughout childhood and even into adulthood (McAllister Byun & Tessier, 2016; Munson et al., 2010). As discussed regarding the finding of shared variance between speech production and vocabulary measures in this study, other abilities may contribute to speech perception (as well as speech production and vocabulary) performance, for example, general language ability, attention, cognition, processing speed, and memory. In summary, there does not appear to be a one-size-fits-all theoretical explanation for the relationship between speech perception, speech production, and vocabulary in children with SSDs.

### *Lessons Learned From Studying Children With Precocious Vocabularies*

We know from previous research that children with poorer vocabulary abilities and SSDs may have poorer speech perception than children with SSD-only or typically developing speech (e.g., Brosseau-Lapré et al., 2020; Nathan et al., 2004). Here we found that children with higher scores on receptive-expressive vocabulary measures tended to have stronger perceptual abilities. This aligns with previous research and supports the hypothesis that knowing many words may be a protective factor for speech perception in children with SSDs. With better specified underlying representations, children can potentially quickly retrieve the motor plans for previously produced speech, which in turn may help speech production (McAllister Byun & Tessier, 2016). This suggests that building a child's vocabulary might improve the quality and robustness of their underlying representations enough to support other areas such as speech perception or speech production. This aligns with Rvachew and Brosseau-Lapré (2015)'s finding that building vocabulary at home via dialogic reading, paired with speech perception training in therapy sessions led to improvements in speech production abilities of French-speaking 4-year-old children with SSDs. The clinical implications of this suggestion warrant further investigation.

## Clinical Implications

Findings from this study add to the literature supporting the need for Speech-Language Pathologists (SLPs) to assess the speech perception abilities of children presenting with speech concerns. Our findings about the potentially important role of vocabulary in SSDs add to findings from other research and support a need to re-consider the areas of assessment on a routine assessment battery for these children. Historically, vocabulary has not been consistently included (McLeod & Baker, 2014). Our findings raise questions over this practice, suggesting vocabulary assessment may be a valuable inclusion as part of routine care. By conducting a comprehensive assessment, SLPs may be able to better profile individual children's strengths and needs and make evidence-informed decisions to optimize management. As Perry and Kucker (2019) suggest, "by capturing heterogeneity, we can better conceptualize and understand individual abilities (especially within at-risk and disordered populations) and make more informed conclusions about children, their abilities, outcomes, and interventions" (p. 556). If we better understand the nature of the problem, we can better plan and optimize management of SSDs for children.

**Limitations and Future Directions**

One limitation of this study is that most children with SSDs presented with a mild or moderate speech difficulty. Moreover, children presented with average to above average vocabulary abilities. Future research could include children with a more even spread of abilities along the whole continuum from low to typical speech and low to high vocabulary. We also included children with phonological and/or articulation errors. Future research could focus on the speech perception abilities of children with phonological or articulation errors only. Additionally, recruiting children with speech production errors on the phonemes assessed in the speech perception task would allow for further investigation of speech perception errors specific to phonemes produced in error. Future research could also further investigate the language abilities of children with SSDs—examining language abilities beyond vocabulary, using, for example, a language sample and/or other comprehensive language assessment measures.

Although speech production and vocabulary were each significant predictors of variance in speech perception ability, together they predicted 27.1% variance in speech perception. There is a need for future research to explore what other variables and abilities are predictors of speech perception. Another limitation of this study is that all assessments used in this study were static. Future research could also include dynamic assessments—such as word learning assessments—to provide additional insight into children's learning (Camilleri & Law, 2014). Furthermore, although the overall high SES across participants is a product of the recruitment location, this may reduce the generalizability of findings to other populations; especially considering that high maternal education is a potential protective factor for speech and language ability (Harrison & McLeod, 2010). Finally, future research could investigate the value of profiling not only speech perception and production abilities of children with SSDs, but also vocabulary, and then providing tailored intervention to optimize outcomes.

## Conclusion

This study provides further insight into the complex relationship between speech perception, speech production, and vocabulary abilities in children, as well as the value of by-group alongside continuous analyses. There was no significant difference in speech perception ability between children with and without SSDs, however both speech production and vocabulary significantly predicted variance in speech perception ability. This research has further highlighted the heterogeneity among children, and different profiles of strengths and needs across speech perception, speech production, and vocabulary. Future research is needed to investigate the value of tailoring management according to children's individual profiles of abilities.

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## Data Availability Statement

The datasets generated and analyzed during the current study are not publicly available due to ethical restrictions.

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**Table 1**

*Participant Characteristics*

| | SSD[a] group | | TD[b] group | |
|---|---|---|---|---|
| | *M*[c] (range) | *SD*[d] | *M*[c] (range) | *SD*[d] |
| Age (months) | 56.03 (48-69) | 5.92 | 57.58 (48-68) | 5.50 |
| *DEAP*[e] (PCC[f]) | 73.78 (27-90) | 13.37 | 91.03 (80.9-100) | 5.25 |
| *PPVT-4*[g] (raw score) | 97.93 (54-135) | 22.61 | 99.90 (64-134) | 17.30 |
| *PPVT-4*[g] (standard score) | 116.63 (87-139) | 14.03 | 116.29 (92-141) | 12.43 |
| *EOWPVT-4*[h] (raw score) | 75.33 (37-108) | 16.28 | 77.52 (53-96) | 11.19 |
| *EOWPVT-4*[h] (standard score) | 119.53 (85-146) | 13.79 | 120.23 (86-140) | 13.43 |
| SES[i] (mother's highest education level) | Bachelor's degree (Vocational training – Postgraduate qualification) | n/a | Bachelor's degree (High school – Postgraduate qualification) | n/a |

[a]SSD = speech sound disorder. [b]TD = typically developing. [c]*M* = mean. [d]*SD* = standard deviation. [e]*DEAP = Diagnostic Evaluation of Articulation and Phonology – Phonology Assessment.* [f]PCC = percentage of consonants correct. [g]*PPVT-4 = Peabody Picture Vocabulary Test–4.* [h]*EOWPVT-4 = Expressive One Word Picture Vocabulary Test–4.* [i]SES = socioeconomic status.

**Table 2**

*Coefficients Tables for: (a) Simple Linear Regression of Speech Production Accuracy (DEAP–Phonology Assessment Raw Score) on Overall Speech Perception Performance, (b) Simple Linear Regression of Vocabulary (Vocabulary Z-Score Calculated from PPVT-4 and EOWPVT-4 Raw Scores) on Overall Speech Perception Performance, and (c) Multiple Linear Regression of Speech Production Accuracy (DEAP–Phonology Assessment Raw Score) and Vocabulary (Vocabulary Z-Score) on Overall Speech Perception Performance*

**a**

| | Coefficients | Standard Error | *t*-statistic | *p*-value | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| (Constant) | 98.498 | 14.797 | 6.657 | .000 | 68.889 | 128.106 |
| DEAP Raw Score | .432 | .126 | 3.443 | .001 | .181 | .684 |

**b**

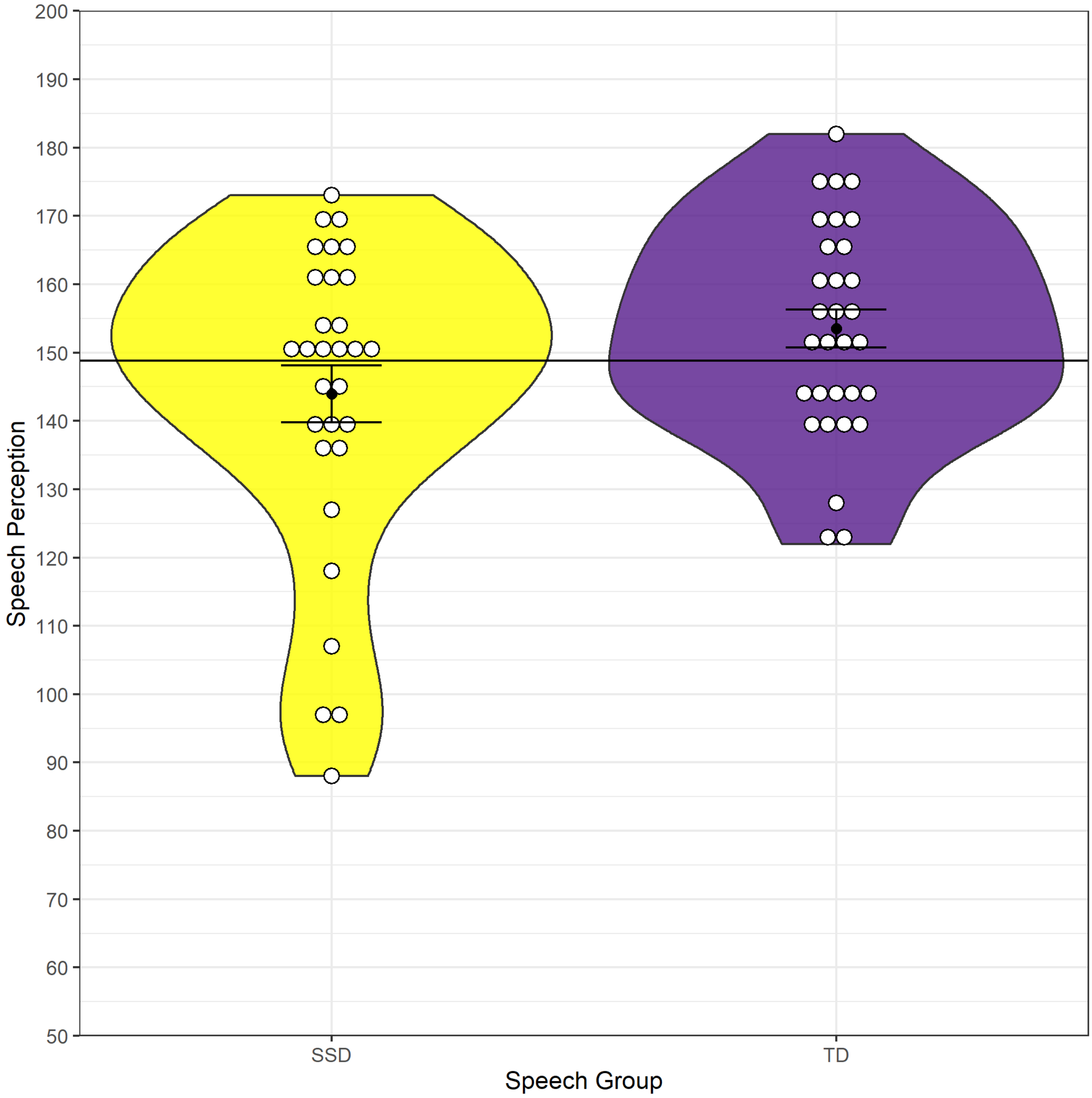
| | Coefficients | Standard Error | *t*-statistic | *p*-value | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| (Constant) | 148.803 | 2.281 | 65.234 | .000 | 144.239 | 153.368 |
| Vocabulary Z-Score | 9.355 | 2.413 | 3.876 | .000 | 4.526 | 14.184 |

**c**

| | Coefficients | Standard Error | *t*-statistic | *p*-value | Lower 95% | Upper 95% |
|---|---|---|---|---|---|---|
| (Constant) | 114.330 | 15.018 | 7.613 | .000 | 84.267 | 144.392 |
| DEAP Raw Score | .296 | .128 | 2.320 | .024 | .041 | .552 |
| Vocabulary Z-Score | 7.192 | 2.508 | 2.868 | .006 | 2.172 | 12.213 |

**Figure 1**

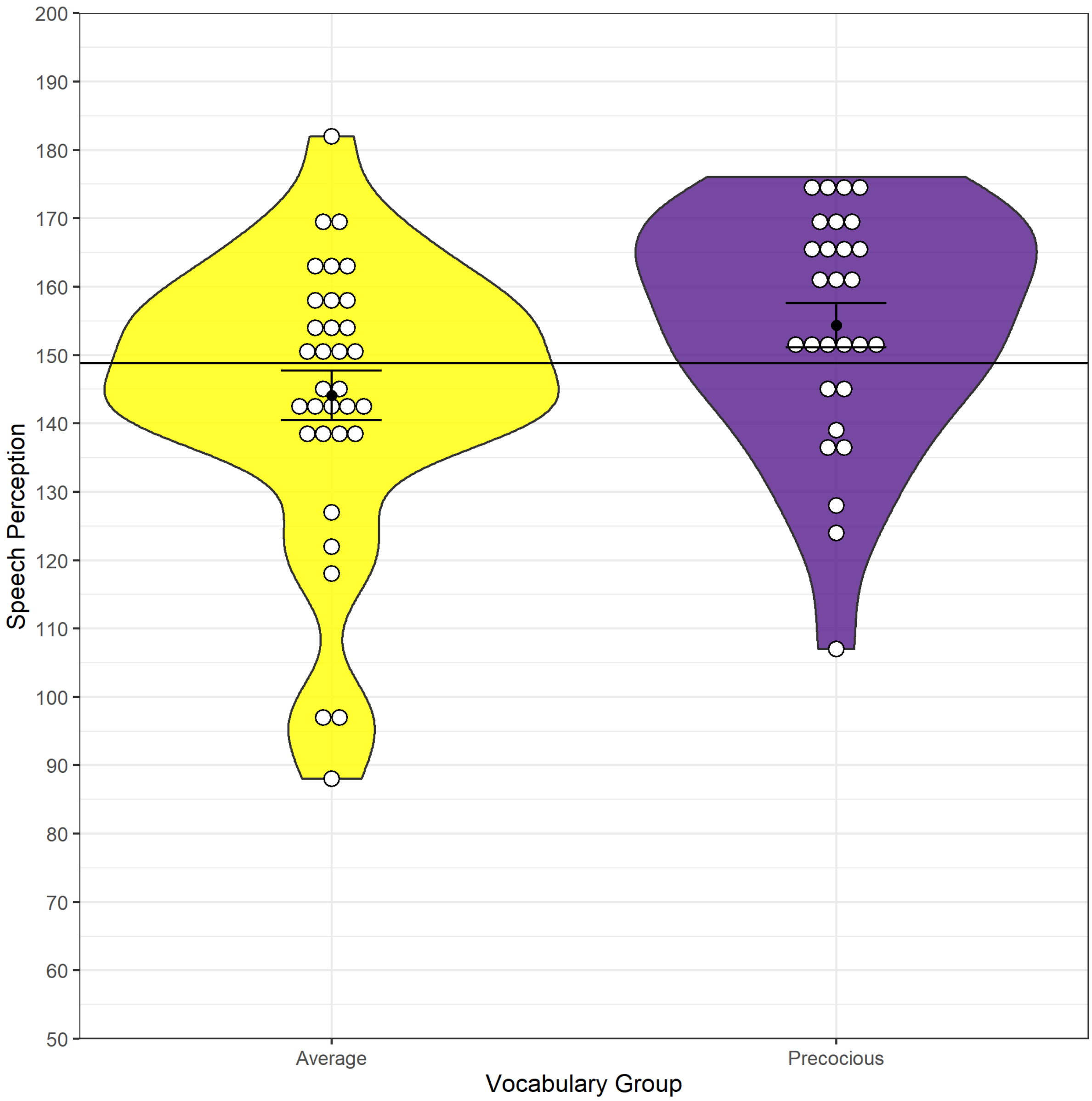
*Violin Plot Displaying Overall Speech Perception Performance for the Speech Sound Disorder (SSD) and Typically Developing (TD) Groups*




Note: Line at 149 on the y-axis shows the mean *Speech Perception* score across all children combined

**Figure 2**

*Violin Plot Displaying Overall Speech Perception Performance for the Average Vocabulary and Precocious Vocabulary Groups*




Note: Line at 149 on the y-axis shows the mean *Speech Perception* score across all children combined

**Figure 3**

*Scatterplot Showing the Relationship Between Speech Production Accuracy (DEAP–Phonology Assessment Raw Score) and Overall Speech Perception Performance*

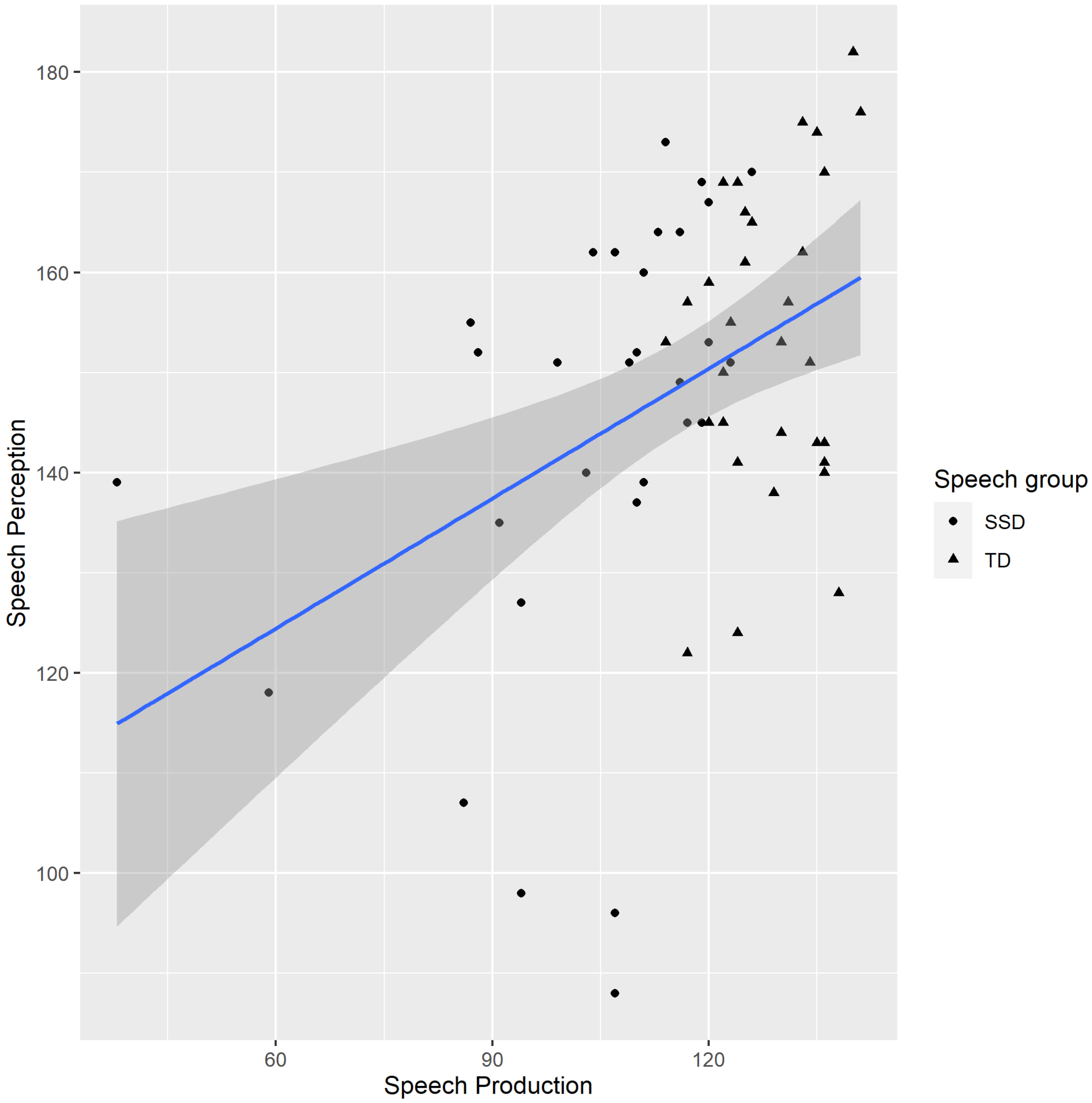
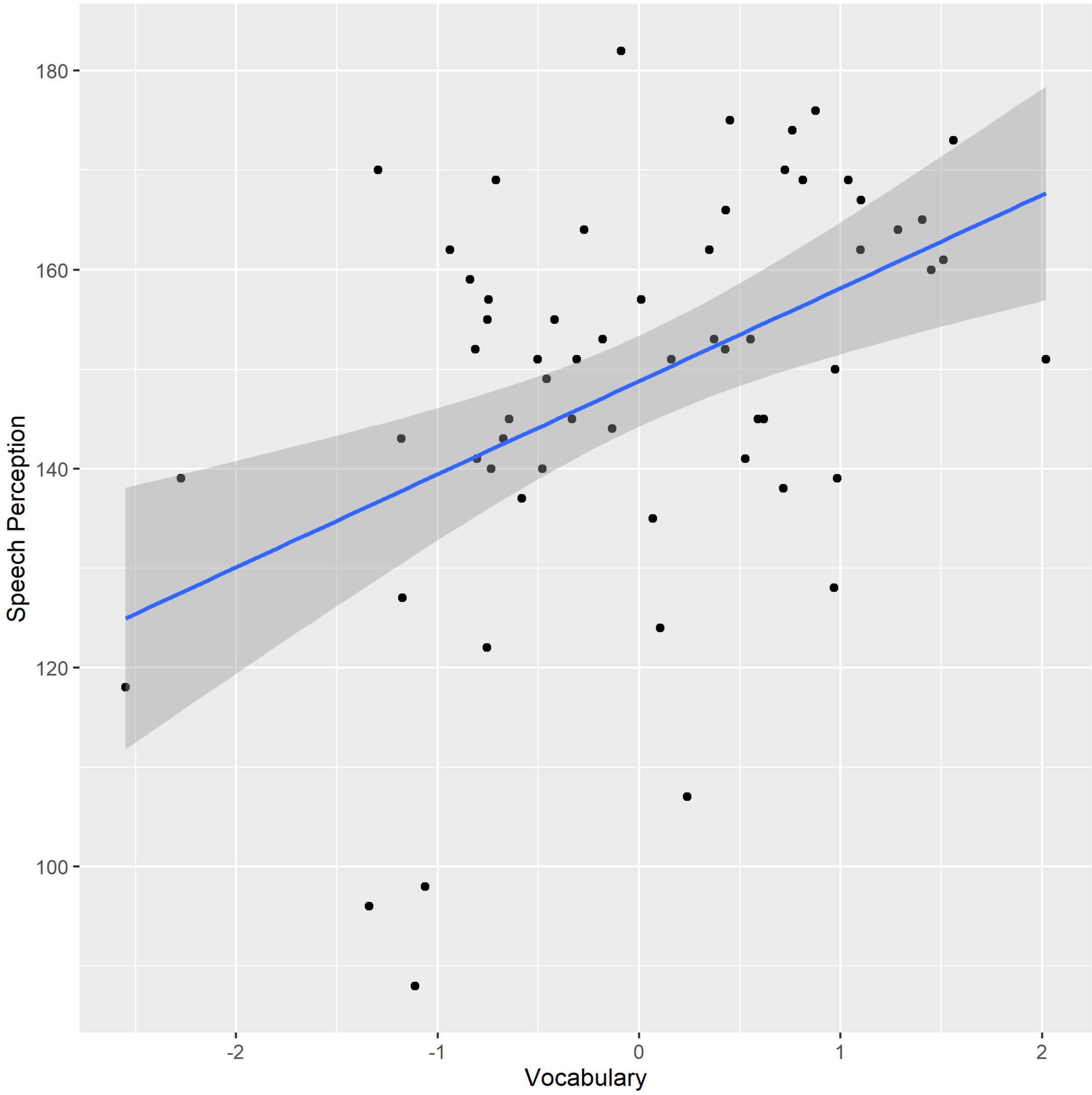


**Figure 4**

*Scatterplot Showing the Relationship Between Combined Vocabulary Z-Score and Overall Speech Perception Performance*



## Supplemental Material

*Supplement 1:* Overview of Speech Perception Performance on Each Phoneme Per Speech Group (Overall Number Correct out of a Maximum of 48)

Group (Overall Number Correct out of a Maximum of 48)

| | SSD[a] group | | TD[b] group | |
|---|---|---|---|---|
| | *M*[c] (range) | *SD*[d] | *M*[c] (range) | *SD*[d] |
| /k/ | 37.90 (21-46) | 7.30 | 41.48 (27-48) | 5.21 |
| /ʧ/ | 36.27 (16-44) | 6.35 | 38.48 (26-46) | 4.96 |
| /ɹ/ | 33.53 (23-43) | 5.60 | 35.10 (26-45) | 4.98 |
| /ʃ/ | 36.27 (23-44) | 5.67 | 38.42 (30-46) | 4.38 |

[a]SSD = speech sound disorder. [b]TD = typically developing. [c]*M* = mean. [d]*SD* = standard deviation.