

RESEARCH REPORT

Phonetic Intelligibility Testing in Developmental Motor Speech Disorders: a Preliminary Tool in Hebrew

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ABSTRACT

Background: Speech intelligibility is a core outcome in the assessment and treatment of individuals with developmental motor speech disorders. While open-set intelligibility testing is widely used, a closed-set phonetic intelligibility assessment, which evaluates listener perception of systematically varied speech contrasts, offers a focused approach to identifying segmental errors that impact intelligibility. However, such tools are unavailable in Hebrew.

Aims: This study introduces a novel, preliminary closed-set phonetic intelligibility tool designed for Hebrew speakers with development motor speech disorders, examining its utility in identifying phonetic contrasts produced in error by speakers with Down syndrome (DS), and determining overall error profiles of contrast categories.

Methods and Procedures: Recordings from 23 Hebrew-speaking adults with DS, between the ages of 21 and 37 years, were analyzed using a closed-set intelligibility paradigm, wherein naïve listeners selected perceived words from contrast-based minimal pairs. Error rates were calculated for individual phonetic contrasts and contrast categories (voicing, place, manner, vowels, and syllable structure). Closed-set intelligibility assessment scores were compared with those of open-set assessments, and phonetic profiles of individual contrasts and categories were formed across speakers.

Outcomes and Results: Closed-set intelligibility scores were higher than open-set transcription accuracy scores. Voicing contrasts, particularly in coda position, were most frequently impaired and significantly correlated with closed-set intelligibility scores. The overall contrast-category profile of the speakers with DS demonstrated voice, place, and manner difficulties across speakers, with only minimal vowel errors.

Conclusions and Implications: The Hebrew closed-set intelligibility tool successfully identified contrast-specific deficits relevant to speech intelligibility in speakers with DS. Its potential clinical value lies in targeting intelligibility-reducing features with increased diagnostic precision and language-specific relevance.

WHAT THIS PAPER ADDS

What is already known on this subject

- Closed-set phonetic intelligibility testing may facilitate the identification of errors that impact speech intelligibility among individuals with motor speech disorders. However, such testing is limited in languages other than English.

What this study adds to existing knowledge

- The preliminary closed-set intelligibility tool in Hebrew identified phonetic contrasts that were related to speech intelligibility scores among speakers with Down syndrome. Voicing errors were most consistently associated with reduced speech intelligibility among speakers.

What are the potential or actual clinical implications of this work?

- Language-specific tools are necessary for determining key factors affecting speech intelligibility among speakers with motor speech disorders. Furthermore, cross-linguistic factors may differentially affect phonetic contrasts that are associated with reduced speech intelligibility.

1 | Introduction

Speech intelligibility, the degree to which a listener recognizes the speaker's output and a measure of communicative efficiency (Dykstra et al. 2007), is often reduced in speakers with motor speech disorders, to varying degrees. Its assessment is a critical component in determining the severity of the motor speech disorder, measuring the efficacy of intervention, as well as identifying factors contributing to the reduced intelligibility (O'Leary et al. 2021). For developmental motor speech disorders, identifying contributing factors to intelligibility profiles has been addressed using phonetic intelligibility testing (Kent et al. 1989, Kent et al. 1994). This type of assessment is based on the identification of words differing by a single phonetic contrast. However, formal intelligibility assessments based on phonetic contrasts are limited in languages other than English. Differences in phonetic characteristics across languages highlight the need for language-specific contrasts within intelligibility assessment and may result in differing phonetic error profiles for speakers of these languages. The current study aimed to determine the feasibility of a preliminary phonetic-contrast intelligibility assessment in Hebrew and to identify phonetic profiles contributing to intelligibility difficulties for Hebrew speakers with developmental motor speech disorders secondary to Down syndrome (DS).

1.1 | Intelligibility Assessment

Individuals with developmental motor speech disorders, such as individuals with DS, demonstrate reduced speech intelligibility across their lifespan (Hustad et al. 2019; Kent and Vorperian 2013). Assessment of speech intelligibility in these populations has garnered much discussion in the research and clinical literature, specifically pertaining to methods of assessment as well as listener- and message-dependent factors. Transcription-based methods of assessment, in which listener transcriptions of word or sentence stimuli are compared and scored against the target words, are typically considered to be standard measures of speech intelligibility (e.g., Hustad 2006). These measures have demonstrated strong correlations with subjective rating measures of intelligibility, in which listener's rate the overall intelligibility of the stimulus based on a predetermined scale (Xue et al. 2023). As related to listener-dependent factors, speakers with motor speech disorders are judged to have increased speech intelligibility when the listener is experienced (O'Leary et al. 2021; see also Allison et al. 2025) or is familiar with the disorder or speaker (Hustad and Cahill 2003; Liss et al. 2002). Finally,

message-dependent factors include the type of stimulus, such as single-word or sentence stimuli, the latter of which may yield higher speech intelligibility scores (Higgins and Hodge 2002).

One advantage of transcription-based intelligibility measures judged by naïve listeners lies in the ability to construct a phonetically-balanced stimulus set that samples sounds or phonetic structures in a pre-determined manner (Kent et al. 1994). While subjective ratings of speech intelligibility provide an overall estimate of intelligibility skills, transcription-based measures allow for a precise analysis of phonetic structures perceived as errors (Ansel and Kent 1992; Hodge and Gotzke 2014; Kent et al. 1989). Furthermore, construction of such stimuli sets can be tailored to the population or type of speech disorder in question. For example, stimulus sets constructed for intelligibility assessment among individuals with motor speech disorders may differ substantially from those designed for individuals with other speech disorders, including cleft palate (Whitehill and Chau 2004) and secondary to hearing impairment (Monsen 1978). Speech intelligibility measures containing or targeting phonetic contrasts, namely words that differ by a single phonetic structure, can provide a precise determination of which phonetic structures are most impaired and thus contribute to the reduced intelligibility (Kent et al. 1989).

Several formal phonetic-intelligibility measures have been developed within the context of motor speech disorders for English speakers. Kent et al. (1989) first presented a phonetic contrast intelligibility assessment for speakers with acquired dysarthria; both phonetic and correlating acoustic contrasts were later investigated by Ansel and Kent (1992) among adults with cerebral palsy (CP). For children with motor speech disorders, Hodge and Gotzke (2014) developed the Test of Children's Speech (TOCS), with stimulus sets based on target phonetic contrasts. This assessment contains both single-word and sentence-level stimuli that can be presented to listeners in open-set or closed-set formats. This latter format typically presents the stimulus in a forced-choice task, in which the listener must choose the word that he heard from a choice of the target word and 1–2 foils (Kent et al. 1989).

The phonetic contrasts targeted in phonetic intelligibility assessment largely include phonetic structures that are difficult for speakers with motor speech disorders (Ansel and Kent 1992; Kent et al. 1989). These contrasts, as found in American English, typically comprise vowel contrasts (e.g., front vs. back, high vs. low), consonant contrasts relating to manner (e.g., stop vs.

TABLE 1 | Comparison of Hebrew and American-English consonant inventories. Consonants (listed as IPA symbols) are divided into columns according to their occurrence in only one (Hebrew/English -only) or both of the languages.

	Hebrew-only	Both	English-only
Stops		p, b t, d k, g ʔ	
Nasals		m, n	ŋ
Fricatives		f, v s, z, ʃ	θ, ð ʒ
	χ (uvular)	h	
Affricates	ʈʂ		tʃ, dʒ
Approximants	ʁ (uvular)	l, j	w, ɹ

fricative), place (e.g., alveolar vs. velar), and voicing (voiced vs. voiceless), as well as syllable structure contrasts (e.g., CVC vs. VC) (Ansel and Kent 1992; Hodge and Gotzke 2011). However, even among speakers with motor speech disorders, phonetic contrasts that elicit errors in a given language may not elicit the same errors in another language (e.g., Whitehill and Ciocca 2000). This may be attributed to differences in phonetic features, within both consonant and vowel systems (Carl and Icht 2021; Pinto et al. 2017), as well as the frequency of these structures (Macklin-Cordes and Round 2020; Tomaschek et al. 2014).

Hebrew, a Semitic language, may differ from American English in terms of the contribution of phonetic contrasts to speech intelligibility. Notably, the Modern Hebrew language contains consonants that are not part of the American English consonant inventory (e.g., uvular fricatives and approximants /ʁ/, /χ/) and vice versa (e.g., interdental consonants /θ/, /ð/ and the alveolar rhotic /ɹ/ are not in the phonemic repertoire of Hebrew; Asherov and Cohen 2019). For a comparison of consonant inventories between the two languages see Table 1. Furthermore, the size of the vowel system in Modern Hebrew is significantly smaller in comparison to that of English, with only 5 monophthong vowels (/a/, /e/, /i/, /o/, /u/). This factor may impact the contribution of vowel contrasts to overall speech intelligibility, particularly among speakers with motor speech disorders (Asherov and Cohen 2019; Carl and Icht 2021). Various phonotactic conventions also distinguish Hebrew from English, including word stress patterns (typically final or penultimate stress; Silber-Varod et al. 2016) as well as a limited use of consonant clusters in both initial and final word positions (Schwarzwald 2005).

1.2 | Developmental Motor Speech Disorders

A high prevalence of motor speech disorders and reduced speech intelligibility are noted in speakers with DS (Rupela et al. 2016; Wilson et al. 2019). Individuals with DS demonstrate difficulties in speech production and related intelligibility that are reported throughout the lifespan (Kumin 1994; Wild et al. 2018). These difficulties are typically attributed to motor— (Rupela et al. 2016)

and/or phonological— (Diez-Itza et al. 2021) based impairment although there is no single consensus in the literature regarding the nature or source of reduced speech intelligibility in this population. Speakers with DS often exhibit speech characteristics associated with both dysarthria and childhood apraxia of speech (CAS), or features that are characteristic of both motor speech disorders (Rupela et al. 2016; Wilson et al. 2019). In fact, Wilson et al. (2019) reported that 98% of 45 adolescents with DS met criteria for a motor speech disorder. Characteristics of dysarthria in speakers with DS include articulatory distortions of speech sounds, reduced range of movement of oral structures, and abnormal pitch and/or voice quality, while characteristics of CAS include inconsistent production across word repetition, deletion of sounds, and a noticeable struggle to produce words (Rupela et al. 2016). Some evidence of further speech subsystem impairment has also been reported, including resonatory (Kent et al. 2021) and prosody (O' Leary et al. 2019) differences.

Articulatory subsystem difficulties among speakers with DS typically constitute the primary predictor of speech intelligibility in comparison to the remaining subsystems (Carl and Icht 2025; Chen et al. 2018; Kent et al. 2021), although voice characteristics have also been correlated with speech intelligibility in this population (Carl and Icht 2025). With respect to specific phonetic structures contributing to reduced intelligibility, English speakers with DS demonstrate greater difficulty with the production of the following contrasts, including consonant clusters (e.g., initial cluster vs. null), vowels (e.g., high vs. low vowel), and fricatives (e.g., fricative place) (Bunton et al. 2009). However, data regarding these contrasts among speakers of varying languages is limited. Application of language-specific phonetic intelligibility testing within developmental motor speech disorders is important in order to determine phonetic profiles and potential targets of intervention (Kim and Choi 2017; Levy and Moya-Galé 2024).

1.3 | The Current Study

In light of the importance of measures of speech intelligibility within the assessment and intervention of developmental motor speech disorders, the current study presents a preliminary tool for evaluating phonetic contrasts in Hebrew, with a focus on their contribution to speech intelligibility. Although such measures are available in English, used within assessment of both developmental dysarthria (Hodge and Gotzke 2014) and CAS (Dale and Hayden 2013), formal measures in other languages are lacking. The application of a closed-set measure of single-word speech intelligibility may facilitate the determination of contrasts that contribute towards reduced speech intelligibility in Hebrew speakers with motor speech disorders, and, ultimately, identify potential targets of intervention. Furthermore, phonetic profiles obtained for speakers with motor speech disorders in languages other than English provide a basis for cross-linguistic comparison and may provide insight into the effects of native language on characteristics of motor speech disorders. The following research questions were addressed in the current study:

1. Is the closed-set phonetic intelligibility assessment in Hebrew effective in identifying contrasts produced in error among speakers with developmental motor speech disorders?

2. Are individual contrasts and contrast categories associated with closed-set speech intelligibility scores?

2 | Methods

Ethical approval of the study was obtained from the University ethics review board (approval #AU-HEA-MI-20211008). As per legal guidelines regarding individuals with cognitive impairment (Ministry of Health 2020), informed consent was obtained from the speakers' parents or legal guardians, and all speakers provided verbal consent for participation within recording procedures.

2.1 | Participants

2.1.1 | Speakers

Recordings from 23 adults with DS (12 males, 11 females), between 21 and 37 years of age (mean age: 26.3, SD: 4.05) were used for the closed-set intelligibility assessment. These speakers are the same speakers as in Carl and Icht (2025), although the data of one speaker was removed (DSM08) from the current study due to a technical error with his closed-set assessment data. All speakers' primary language was Modern Hebrew, and no severe hearing impairment was reported for participants. All participants demonstrated sentence-level communication with the exception of one (DSM07), who demonstrated word-level productions, and all demonstrated a level of language understanding that was sufficient for participation in assessment procedures. It should be noted that the speakers' data were collected as part of a larger recording protocol. Further information regarding participants, including formal diagnoses of dysarthria and/or CAS as well as severity levels was not available during the current study.

2.1.2 | Listeners

A total of 138 participants (31 males) served as listeners for judgments of both open-set and closed-set intelligibility assessments, 69 listeners for each of the assessment types. Listeners were between 19 and 56 years of age (mean: 26 years, SD: 6.7), and all reported normal hearing, a lack of speech or language disorders, their native language to be Hebrew, and no extended experience with individuals with motor speech disorders. Listeners were recruited to the study by word of mouth and through the University. A total of three listeners judged each set of words in each of the open-set and closed-set assessments.

2.2 | Stimuli

A total of 15 phonetic contrasts were targeted in the closed-set listening task, presented in Table 2. These phonetic contrasts were taken from previous investigations of phonetic intelligibility testing for individuals with motor speech disorders (Ansel and Kent 1992; Bunton et al. 2009; Hodge and Gotzke 2011); they are grouped into the categories of Vowel contrasts (e.g., high vs. low vowels), Voicing contrasts (voiced vs. voiceless consonants), Place contrasts (e.g., for consonants of the same manner contrasting in place of articulation), Manner contrasts (e.g., plosives

vs. fricatives), and Syllable contrasts (e.g., contrasts relating to syllable shape or deletion). Certain contrasts that were sampled in previous studies were not included in the current analysis due to language characteristics and constraints. Notably, only two vowel contrasts were included due to the small vowel system in Hebrew (five monophthong vowels; no diphthongs). Consonant clusters were not included due to the relatively limited frequency of clusters in the Hebrew language, their frequent occurrence in morphologically inflected words (Asherov and Bat-El 2019; Yavaş et al. 2008), and difficulty finding meaningful words as contrasts. Finally, the liquid-glide contrast (/ɣ/-/w/) was not included, as the glide /w/ is not in the native phonemic repertoire of Modern Hebrew (Asherov and Cohen 2019). All target spoken words were simple in terms of lexical complexity (e.g., common, less sophisticated vocabulary items) and could be portrayed visually and realistically in an image. Furthermore, foils were chosen only if they were real words in Modern Hebrew. Certain contrasts were sampled in both initial and final word positions, although this was not controlled for across all contrasts.

A total of 34 words were presented in the closed-set intelligibility task, of which 5 words were repeated with different contrasting foils, for a total of 39 single-word stimuli. Of this word-list, 20 words overlapped with the stimuli from the Rosin and Yakir (2000) articulation and naming test, which was part of the larger recording protocol, while 14 words were added for the intelligibility testing and for previously reported acoustic analyses (see Carl and Icht 2025). Despite the overlap, the chosen words (common words in colloquial Hebrew) were intended primarily for use within a closed-set intelligibility assessment and were specifically chosen for the presence of the targeted phonetic contrasts.

For each auditory stimulus that was presented to the listener, four choices were presented: the target stimulus, two contrasting foils, and "Other." If "Other" was chosen, the listener was requested to type in the word that was heard. The option of "Other" was included primarily in light of previous findings of closed-set intelligibility assessment in this population (Bunton et al. 2009) in which listeners frequently reported that none of the given choices of the closed-set task matched the spoken auditory stimulus. The final list of target words and the contrasting foils are listed in Appendix A.

The full stimulus-set of the open-set assessment task is detailed in Carl and Icht (2025). The word list for the open-set assessment consisted of the same words included in the closed-set task, as well as several additional words that were part of the general recording protocol (e.g., Articulation testing). Due to the absence of formal materials for intelligibility testing in Hebrew that are appropriate for children or those with developmental disorders, assessment of speech intelligibility in this population has been typically conducted using informal and related materials.

2.3 | Procedures

The recording procedures for the current data were part of a larger data collection protocol. Speakers sat in a quiet room, with one or two trained research assistants (SLP undergraduate students), who were instructed by the authors regarding recording

TABLE 2 | Phonetic contrasts used in the closed-set phonetic intelligibility assessment including example stimulus-foil pairs and frequency of contrast occurrence within the stimulus list.

Contrast	Example: word + foil (<i>translation</i>)	Number of contrasts
Vowel: Front-back	/guʁ/ (<i>puppy</i>)—/giʁ/ (<i>chalk</i>)	4
Vowel: High-low	/χatul/ (<i>cat</i>)—/χitul/ (<i>diaper</i>)	7
Voicing: Onset	/tuʃ/ (<i>marker</i>)—/duʃ/ (<i>shower head</i>)	6
Voicing: Coda	/dag/ (<i>fish</i>)—/dak/ (<i>thin</i>)	5
Place: Stop	/tik/ (<i>bag</i>)—/tit/ (<i>cement</i>)	10
Place: Fricative	/tuʃ/ (<i>marker</i>)—/tus/ ((<i>to</i>) <i>fly</i>)	7
Place: Nasal	/χalon/ (<i>window</i>)—/χalom/ (<i>dream</i>)	3
Manner: Plosive—Fricative	/sefeʁ/ (<i>book</i>)—/tefeʁ/ (<i>sewing stitch</i>)	6
Manner: Plosive—Affricate	/eʃs/ (<i>tree</i>)—/et/ (<i>pen</i>)	2
Manner: Plosive—Nasal	/jaʔon/ (<i>watch</i>)—/jaʔot/ (<i>hours</i>)	2
Manner: /ʁ/—/l/	/limon/ (<i>lemon</i>)—/ʁimon/ (<i>pomegranite</i>)	6
Manner: Fricative—Affricate	/ʃsipor/ (<i>bird</i>)—/sipuʁ/ (<i>story</i>)	4
Syllable: Onset—Null	/tof/ (<i>drum</i>)—/of/ (<i>chicken</i>)	4
Syllable: Coda—Null	/naʔal/ (<i>shoe</i>)—/naʔa/ (<i>moving</i>)	2
Syllable: Omission	/famajim/ (<i>sky</i>)—/majim/ (<i>water</i>)	3

procedures and stimulus presentation. Stimuli were presented on a laptop computer placed in front of the participant and consisted of clear photographs or animations of common objects within the language repertoire of children. Participants were asked to name the item that appeared on the screen. Participant responses were recorded with a high-quality digital recorder (Philips DVT4010/ DVT6110), at an approximate diagonal distance of 8 cm from the speaker's mouth. The entire recording procedure took approximately 20 min.

Listeners participated in the listening task via the Gorilla Experiment Builder (www.gorilla.sc), a web-based experimental platform (Anwyl-Irvine et al. 2020). Listeners completed a short demographic survey prior to the task and were instructed to sit in a quiet room. They were told that they would be hearing true words produced by people with speech disorders. All listeners, for both open-set and closed-set listening tasks, had the option to listen to the word twice; no further repetitions of the target word were possible. For the open-set task, listeners were instructed to write the word that they heard. For the closed-set task, listeners were presented with four choices on the screen (target word, two foils, and “Other”), from which they were instructed to choose one. If the listener chose “Other,” a text box appeared and the listener was asked to type in the word that was heard. Audio stimuli were presented randomly to the listeners within each of the tasks.

2.4 | Dependent Measures and Analysis

Intelligibility scores were calculated for both open-set and closed-set listening tasks, averaged across the three listeners for each task. Analysis of phonetic contrasts was conducted from the closed-set intelligibility assessment for both categories of contrasts as well as individual contrasts across all categories. In

order to determine the error rate of a specific contrast for each speaker, contrast errors were normalized across the number of occurrences of the target contrast, as conducted in Whitehill and Ciocca (2000). For example, if each of the three listeners chose three foils contrasting in initial voicing for a given speaker instead of the target word, the average of the number of errors (3) was divided by the total number of possible occurrences of the voicing contrast in onset position (e.g., 6). This yielded the proportion of errors for the voicing contrast in onset for this speaker. To determine phonetic profiles, error rates were averaged across speakers for each phonetic contrast. To calculate the rate of “Other” errors, the average number of times the listeners chose “Other” was divided by the number of trials, as “Other” was a choice for each trial. Error rates were also calculated, in an identical fashion to individual contrasts, for categories of phonetic contrasts, namely Vowels, Voicing, Place of Articulation, Manner of Articulation, and Syllable structure.

2.5 | Statistical Analysis

All statistical analyses were conducted in R (R Core Team 2020), unless otherwise noted. Differentiation of scores across type of intelligibility assessment was conducted using a one-way ANOVA, with Assessment type (Closed vs. Open) as the dependent variable and intelligibility score as the independent variable. The normality of the data was tested prior to the ANOVA calculations, as determined by measures of skewness and kurtosis for each of the two assessment types. Results revealed skewness values within the range of $-/+2$, and kurtosis values within the range of $-/+7$, for each of the Closed and Open assessment types, indicating that the data are normally distributed (Demir 2022).

In order to determine possible differences between contrast categories across speakers, a linear mixed-effects model was

applied to the categories of contrasts (Vowel, Voice, Manner, Place, Syllable), with error proportion as the dependent variable, Contrast category as the independent variable, and Speaker as the error variable. Post-hoc analysis was conducted across Categories to detail the significance of comparisons between contrast categories. The linear mixed-effects model was chosen due to its robustness despite missing data or unbalanced data sets (Baayen 2008), as well as its robustness to non-normally distributed data (Knief and Forstmeier 2021; Schielzeth et al. 2020). Nonetheless, measures of skewness and kurtosis of the Contrast category error rate variable revealed skewness values within the range of $-/+2$, and kurtosis values within the range of $-/+7$, indicating distribution of the data to be within normal limits (Demir 2022).

Analysis of individual contrasts was conducted with relation to those with the highest proportion of errors (as in Bunton et al. 2009; Whitehill and Ciocca 2000), as well as correlations between these contrasts and averaged closed-set intelligibility scores. Due to the relatively small number of contrasts within each category, predictive linear regression was not utilized within the analyses; instead, the current study relied on correlational analysis. Spearman's rho-rank correlation was applied to both contrast categories and highest proportion of individual contrasts, to determine their relationship with closed-set intelligibility scores.

A power analysis of the closed-set data was calculated to ensure sufficient power given the number of speakers and stimuli. A post-hoc power analysis of contrast category comparisons was conducted using the web-based program WebPower (Zhang and Yuan 2018), using the multi-level analyses. The effect size was calculated from previously conducted studies of phonetic contrasts (e.g., Whitehill and Chau 2004), for which the average effect size was noted to be 0.58 for differences between phonetic contrasts. For the target significance level of $\alpha = 0.05$, a sample size of 23 speakers, and 39 single-word stimuli, the calculated power was 0.945, indicating sufficient power of the contrast category analysis.

2.6 | Interrater Reliability

Interrater reliability between the listeners on the closed-set intelligibility assessment was calculated in R. The intraclass correlation analysis (ICC) was applied using the one-way random effects model and absolute agreement (Koo and Li 2016). Results revealed an ICC of 0.69, $F(22, 44) = 3.2$, $p < 0.001$, similar to related intelligibility studies (e.g., Landa et al. 2014).

3 | Results

3.1 | Comparison of Closed- and Open-Set Intelligibility Scores

The average score for closed-set intelligibility assessment was 0.88 (SD: 0.07, range: 0.74 – 0.99), while the average score for open-set intelligibility assessment was 0.80 (SD: 0.1, range: 0.57 – 0.96). Results of the one-way ANOVA revealed significant differences

between the types of intelligibility assessment (Closed-set vs. Open-set), $F(1, 44) = 8.01$, $p = 0.007$.

3.2 | Phonetic Profiles: Contrast Categories

Mean error proportions for both individual contrasts and contrast categories are listed in Table 3. A visual depiction of contrast categories is presented in Figure 1. Results of the linear mixed-effects model are detailed in Table 4. Post-hoc analyses, using the Tukey adjustment for comparing multiple estimates, demonstrated significant differences for several between-category contrasts: The Voicing contrast category was differentiated from each of the other categories, namely Manner, $t(88) = -4.49$, $p < 0.001$, Place, $t(88) = -3.02$, $p = 0.03$, Syllable, $t(88) = -6.081$, $p < 0.001$, and Vowel, $t(88) = 6.87$, $p < 0.001$. The Place contrast category was also differentiated from the Vowel category, $t(88) = -3.86$, $p = 0.002$, and the Syllable category, $t(88) = 3.07$, $p = 0.02$.

Results of Spearman's rho rank correlations between contrast categories and closed-set speech intelligibility scores revealed a significant correlation only for the Voice category, $r = -0.78$, $p < 0.001$; the remaining categories were not significantly correlated with intelligibility (Figure 2).

3.3 | Phonetic Profiles: Individual Contrasts

A visual depiction of error rates for individual phonetic contrasts is presented in Figure 3, and averaged proportions are listed in Table 3. Individual contrasts were analyzed in terms of the highest proportion of errors and the correlations of these errors with closed-set intelligibility scores. The five contrasts with the highest error proportions included: (1) Voicing: Coda; (2) Manner: Fricative-Affricate; (3) Place: Fricative; (4) Place: Nasal; and (5) Manner: /ʁ/-/l/. However, only the contrast of Voicing: Coda, $r = -0.78$, $p < 0.001$, was significantly correlated with closed-set speech intelligibility. The option of "Other" was chosen with a relatively low frequency across speakers and listeners, at an average proportion of 0.03 (SD: 0.03). This option was chosen at least once by most listeners, but to varying degrees, as related primarily to the speaker's production accuracy.

4 | Discussion

The main objective of the current study was to determine the feasibility of a preliminary phonetic-contrast intelligibility assessment for Hebrew speakers with developmental motor speech disorders in detailing phonetic error profiles. Primary findings are listed as follows: Closed-set intelligibility scores were slightly higher than open-set scores. Certain contrast categories (e.g., Voicing and Place), were differentiated from the others, with higher error rates, although only errors within the Voicing category correlated with Closed-set speech intelligibility scores. Individual contrasts with the highest error proportions included: (1) Voicing: Coda; (2) Manner: Fricative-Affricate; (3) Place: Fricative; (4) Place: Nasal; and (5) Manner: /ʁ/-/l/, of which the Voicing: Coda contrast correlated with closed-set intelligibility scores.

TABLE 3 | Means and standard deviations (SD) of category and individual contrast error proportions.

Phonetic Contrast	Error Proportion (Mean, SD)	
Category: Vowels	0.01	(0.01)
Vowel: Front—Back	0.00	(0.02)
Vowel: Open—Close	0.01	(0.02)
Category: Voicing	0.09	(0.08)
Voicing: Onset	0.04	(0.04)
Voicing: Coda	0.18	(0.15)
Category: Place	0.05	(0.04)
Place: Plosive	0.05	(0.07)
Place: Fricative	0.07	(0.08)
Place: Nasal	0.06	(0.09)
Category: Manner	0.03	(0.04)
Manner: Plosive—Fricative	0.01	(0.02)
Manner: Plosive—Affricate	0.01	(0.03)
Manner: Plosive—Nasal	0.00	(0.00)
Manner: /ʁ/—/l/	0.05	(0.06)
Manner: Fricative—Affricate	0.09	(0.14)
Category: Syllable	0.01	(0.03)
Syllable: Onset—Null	0.01	(0.02)
Syllable: Coda—Null	0.01	(0.07)
Syllable: Omission	0.04	(0.03)
Other	0.04	(0.03)

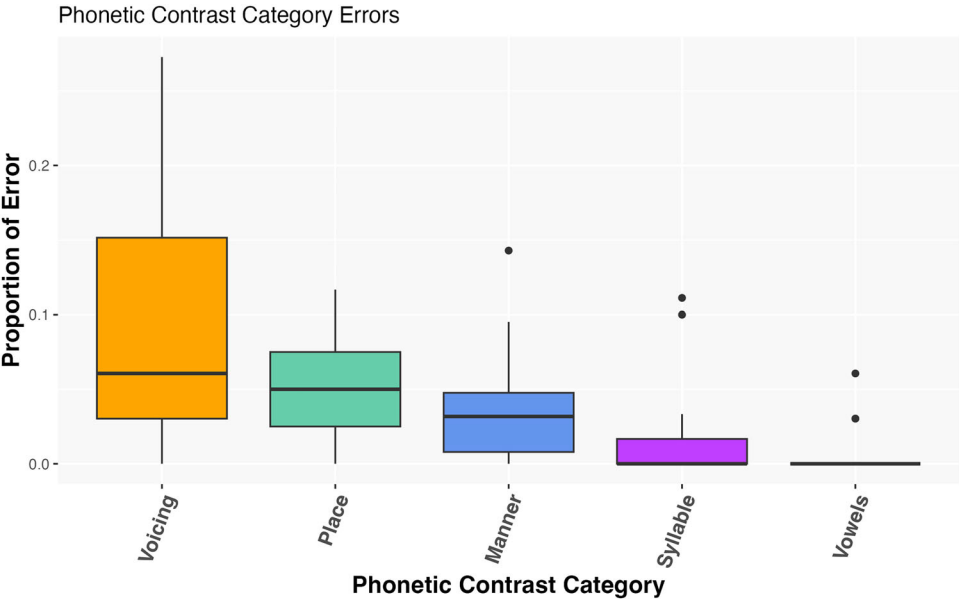


FIGURE 1 | Results of error proportions of phonetic contrast categories.

TABLE 4 | Summary of the linear mixed effects model, to determine potential differences between contrast categories within the speaker group.

	Estimate	Std. Error	df	t value*	
(Intercept)	0.03	0.01	102.28	3.69	***
Category: Place	0.02	0.01	88.00	1.48	
Category: Syllable	−0.02	0.01	88.00	−1.59	
Category: Voice	0.06	0.01	88.00	4.49	***
Category: Vowels	−0.03	0.01	88.00	−2.38	*

Note: *Significance is listed as follows: * = $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

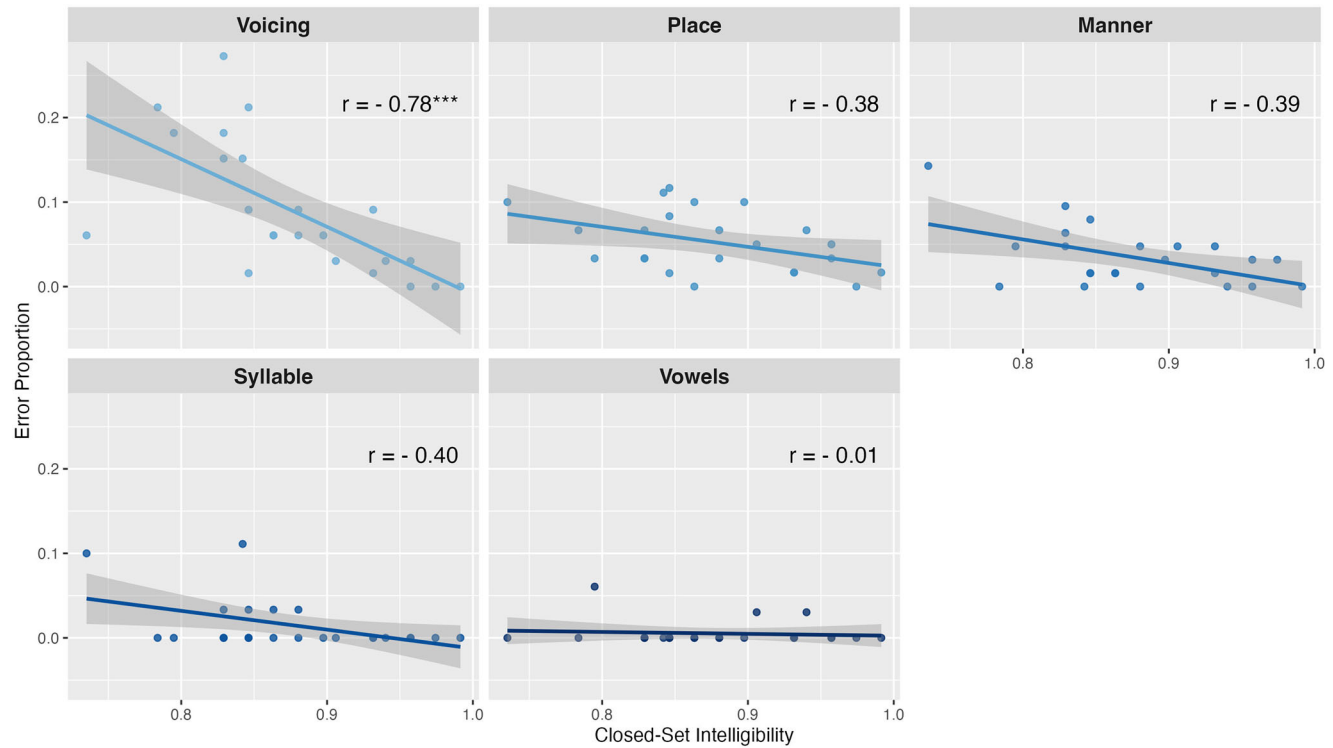


FIGURE 2 | Spearman rho rank correlations of contrast category (Voicing, Place, Manner, Voicing, Syllable, Vowels) with closed-set intelligibility scores.

4.1 | Contribution of Closed-Set Intelligibility Assessment in Hebrew

The advantage of a closed-set intelligibility assessment can be attributed to the careful selection of target contrasts that may affect speech intelligibility in the population of interest (Kent et al. 1989). Such assessments are available in English (Hodge and Gotzke 2014; Kent et al. 1989), but are limited, if at all available, in languages other than English. The current study contributes to this gap by offering preliminary evidence for the clinical utility of a Hebrew-language closed-set intelligibility tool for individuals with developmental motor speech disorders. The phonetic profiles obtained for the speakers with DS speaker in the current study, as well as the relatively small proportion of “Other” responses (e.g., listener-generated alternatives outside the provided options) in the current findings, support the validity of the selected contrasts and the

feasibility of this preliminary tool for assessing speech intelligibility among Hebrew speakers with motor speech disorders.

A comparison of the current results with previous findings from articulation testing among Hebrew speakers with DS further illustrates the unique contribution of a closed-set assessment. Articulatory profiles of speakers with DS (Carl and Icht 2025) indicate that the affricate /tʃ/ was the most frequently misarticulated consonant across word positions. However, in the current data, while certain manner contrasts of affricates were among those produced with the highest error proportions, they were not significantly correlated with overall closed-set speech intelligibility scores. In contrast, speakers demonstrated high proportions of voicing-contrast errors, of which voicing errors in coda position correlated with closed-set speech intelligibility scores.

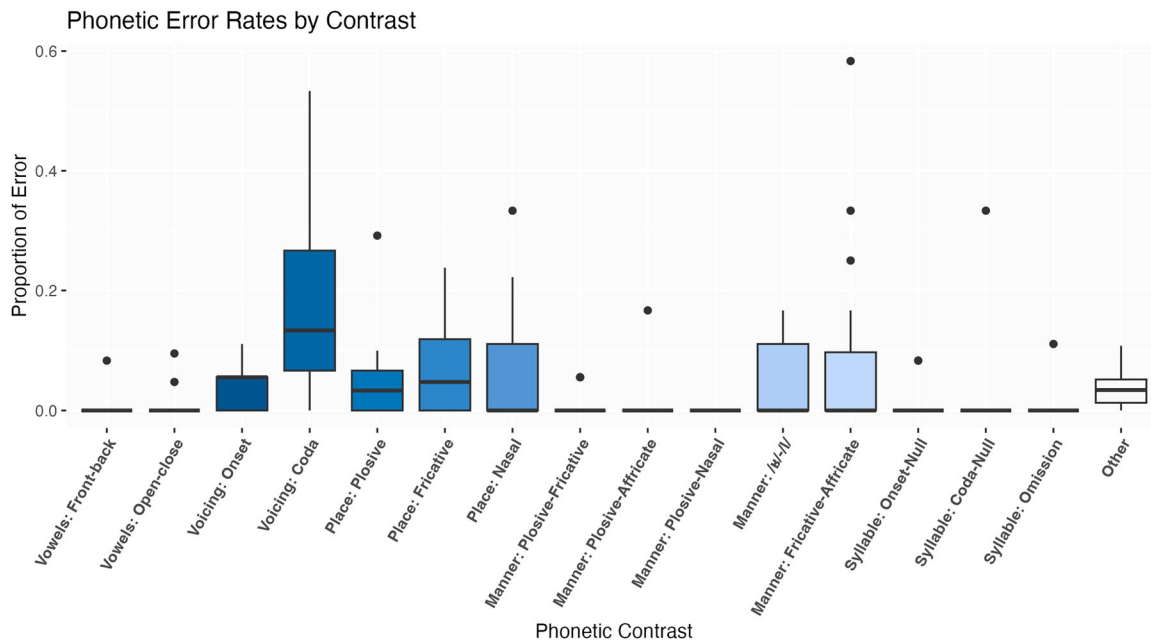


FIGURE 3 | Error proportions of individual phonetic contrasts.

This discrepancy can perhaps be attributed to the fact that articulation assessment is conducted with knowledge of the target word and typically by an experienced judge (Shriberg et al. 1997). However, phonetic intelligibility assessments allow the identification of contrasts that impact upon speech intelligibility as perceived by naïve listeners (Allison et al. 2025), thus capturing the listener's real-world experience of understanding speech without contextual scaffolding. This distinction is a critical one for intelligibility assessment of speakers with motor speech disorders, as it highlights the fact that not all articulatory errors negatively impact speech intelligibility, as perceived by the listener (Hustad et al. 2012). It also reinforces the need for tools that reflect not just articulatory accuracy, but also those that can measure functional communication outcomes associated with speech disorders (Borrie et al. 2022).

4.2 | Comparative Analysis of Contrast Categories

Analysis of the phonetic profile for the current speaker group, as demonstrated by the comparison of overall contrast categories (vowels, place, manner, voicing, syllable), revealed a phonetic profile that is generally consistent with previously recorded findings in this population. For example, the contrast category with the highest error proportion was the Voicing category, and specifically voicing errors in Coda position. This finding supports recent outcomes of correlations between overall voice quality during word production and speech intelligibility scores among young adults with DS (Carl and Icht 2025), suggesting a difficulty of coordination between speech subsystems. Furthermore, voicing errors in final word positions could be related not only to difficulty at the level of vocal fold functioning, but also to production of the immediately preceding vowel, for which its length is noted to be a strong acoustic cue of voicing in final position (Raphael 1972). While vowels, on the whole, were not impaired in terms of their perceptual between-vowel contrasts, precision of rate and timing are noted areas of difficulty

in speakers with DS (Auzou et al. 2000). It should be noted that the phonetic profile in the current speaker group may also reflect phonological and/or phoneme representation level difficulties (Diez-Itza et al. 2021). Speakers with DS demonstrate phonological processes both within childhood (Barnes et al. 2009; Stephanie 2024) and adolescence (Wong et al. 2015), which may impact upon speech intelligibility.

In addition to voicing contrast errors, speakers with DS demonstrated both Place (Fricative, Nasal) and Manner (Fricative-Affricate, /ʁ/-/l/) contrast errors. These findings may reflect underlying neuromotor underpinnings and are supported by the existing literature: Bunton et al. (2009) reported both place and manner errors among adult speakers with DS, attributing these errors to difficulty with lingual control and posture. This latter finding may be associated with the reported characteristics of childhood apraxia of speech, often reported among individuals with DS (Wilson et al. 2019). However, further information regarding speakers' dysarthria and/or CAS diagnosis must be available in order to fully substantiate this point.

4.3 | Cross-Linguistic Comparisons

When presented in a cross-linguistic context, the current findings highlight the need to consider language-specific factors in the assessment of speech intelligibility. The phonological structure of Hebrew may influence the intelligibility of particular contrasts differently than in English or other Indo-European languages. This may include, although is not limited to: the Hebrew phonemic inventory, phonotactic limitations (e.g., reduced use of consonant clusters), and morphophonemic alternations (e.g., phonemic changes within verb derivations, such as spirantisation and vowel changes; Asherov and Bat-El 2019; Asherov and Cohen 2019). While common errors across languages point to difficulties of lingual control, articulatory timing, and coordination, the relative contribution of individual contrasts differs in each

language. For example, Bunton et al. (2009) reported vowel contrasts as a primary contributor of reduced speech intelligibility for speakers with DS. In comparison, vowel contrasts in the current study were the least impaired and not correlated with intelligibility scores, despite previous reports of group differentiation for vowel space measures within this speaker group (Carl and Icht 2025). This may be attributed to increased perceptual identification accuracy of vowels within smaller vowel systems. Voicing contrasts, though, were of primary association with intelligibility scores in the current study, a finding which has little precedence in previous investigations. These comparisons indicate an influence of language characteristics on perceptual presentation of motor speech disorders (Kim and Choi 2017) and underscore the importance of developing language-specific tools for the assessment of intelligibility impairment in these populations.

4.4 | Clinical Implications

Beyond its research contribution, the closed-set phonetic intelligibility tool developed in this study holds practical clinical value. By providing a structured and efficient method for evaluating phonetic contrasts that impact intelligibility, it can support clinicians in identifying specific areas of difficulty that are most relevant to functional communication. Unlike traditional articulation tests, which may not reflect real-world intelligibility challenges, this tool offers a more ecologically valid assessment that aligns with how speech is perceived by unfamiliar listeners. As such, it may be particularly useful for goal setting, treatment prioritization, and monitoring progress in therapy for individuals with developmental motor speech disorders.

The design of the tool itself also presents several strengths. The selection of phonetic contrasts was grounded in both cross-linguistic research and phonological patterns relevant to Hebrew, ensuring clinical relevance while maximizing diagnostic sensitivity. The relatively low frequency of “Other” responses suggests that the stimuli were well targeted to common intelligibility-relevant contrasts, minimizing ambiguity for naïve listeners. Furthermore, the ability to quantify contrast-specific error patterns supports more fine-grained analysis of a speaker’s intelligibility profile than is typically available through open-set transcription tasks. Further studies may well benefit from an in-depth analysis of speakers’ error profiles, in order to document the potential heterogeneity, or lack thereof, in the speaker population.

4.5 | Limitations and Future Directions

The current study represents a preliminary step in the development of a novel tool for a Hebrew-language intelligibility assessment. However, certain limitations require further study as well as future changes, development, and implementation. The relatively small number of items within each phonetic contrast, as well as the small speaker sample size and limited speaker data, are limitations of the current preliminary version of the closed-set assessment tool; these limitations necessitate the expansion, development, and further application of the tool. Furthermore, due to the limited participant data in the current study, including

type of motor speech disorder (dysarthria, CAS) and severity, care must be taken in interpreting and generalizing the current results.

The inclusion of additional stimuli is recommended to provide sufficient items within each phonetic contrast, to control for word position, as well as to create alternating stimulus lists (as in Hodge and Gotzke 2014). A reconsideration of consonant clusters within the closed-set stimulus list is also recommended, or at least within a word list to be used within open-set intelligibility assessments. The external and construct validity (e.g., across different time points and in comparison to TD peers, respectively) of the tool should also be determined. Future investigations may also choose to include both the target word and the foils, in order to allow for analysis of acoustic correlates (as in Ansel and Kent 1992) and to determine the relationship between physiological correlates and perceptual judgments. Furthermore, it is necessary to apply this tool to varying speaker groups with motor speech disorders (e.g., speakers with cerebral palsy).

Finally, given the considerable advancement of artificial intelligence and its growing clinical applications (e.g., Carl et al. 2024), it is recommended to determine the feasibility of an automated closed-set intelligibility assessment, which can potentially provide a prompt judgment of target phonetic contrasts and a phonetic profile for the purpose of assessment and intervention.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The datasets generated and/or analyzed during the current study are not publicly available due to ethical and legal restrictions but are available from the corresponding author upon reasonable request.

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Appendix A: Wordlist and contrasting foils presented to listeners in the closed-set intelligibility assessment.

Target Word	Contrast 1	Contrast 2
/matana/ (gift)	/matala/ (task)	/mana/ (dose)
/naʔal/ (shoe)	/naʔa/ (moving)	/naʔaʁ/ (boy)
/dag/ (fish)	/gag/ (roof)	/tag/ (label)
/dag/ (fish)	/dak/ (thin)	/daʁ/ (live in)
/tof/ (drum)	/of/ (chicken)	/kof/ (monkey)
/tof/ (drum)	/toχ/ (within)	/tov/ (good)
/tik/ (bag)	/tit/ (clay)	/pik/ (peak)
/gezeʁ/ (carrot)	/gezel/ (robbery)	/geveʁ/ (man)
/gefem/ (rain)	/gefex/ (bridge)	/kesem/ (magic)
/kelev/ (dog)	/χelev/ (candle wax)	/kele/ (prison)
/kova/ (hat)	/tova/ (good)	/gova/ (height)
/lexem/ (bread)	/ʁexem/ (womb)	/loχem/ (fighter)
/limon/ (lemon)	/ʁimon/ (pomegranate)	/hamon/ (a lot)
/sakin/ (knife)	/sakit/ (bag)	/sakim/ (sacks)
/sefex/ (book)	/sefel/ (cup)	/tefex/ (stitch)
/ʃaʔon/ (clock)	/ʃaʔot/ (hours)	/ʃaʁon/ (name)
/χatul/ (cat)	/χitul/ (diaper)	/ʃatul/ (planted)
/χulʃa/ (shirt)	/χulda/ (rat)	/χulʃa/ (weakness)
/haʁ/ (mountain)	/al/ (on)	/aχ/ (brother)
/agas/ (pear)	/agav/ (by the way)	/gas/ (rude)
/eʃs/ (tree)	/ef/ (fire)	/et/ (pen)
/tuʃ/ (marker)	/duʃ/ (shower head)	/tus/ (fly)
/paχ/ (can)	/puχ/ (covers [duvet])	/kaχ/ (take)
/pil/ (elephant)	/bil/ (name)	/til/ (rocket)
/sus/ (horse)	/tus/ (fly)	/tut/ (strawberry)
/kof/ (monkey)	/tof/ (drum)	/χof/ (beach)
/kof/ (monkey)	/kaf/ (spoon)	/kef/ (fun)
/guʁ/ (puppy)	/gaʁ/ (live)	/giʁ/ (chalk)
/siv/ (pot)	/ʃiv/ (song)	/ʃiv/ (hinge)
/χof/ (beach)	/χov/ (debt)	/χaf/ (innocent)
/kis/ (pocket)	/gis/ (brother-in-law)	/kif/ (high five)
/kis/ (pocket)	/kos/ (glass)	/kif/ (quiche)
/χalon/ (window)	/χalom/ (dream)	/χolon/ (name of city)
/ʃamajim/ (sky)	/majim/ (water)	/ʃinajim/ (teeth)
/maχat/ (needle)	/maχak/ (eraser)	/naχat/ (relaxed)
/degel/ (flag)	/dekel/ (palm tree)	/egel/ (calf)
/kaf/ (spoon)	/af/ (nose)	/taf/ (children)
/kaf/ (spoon)	/kof/ (monkey)	/kav/ (line)
/ʃsipov/ (bird)	/sipov/ (story)	/ipov/ (makeup)