Extrema values of consonant cluster accuracy with member accuracy in children's speech

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Abstract: The accuracy of consonant clusters and their members in child speech are usually evaluated separately in practice. The purpose of the present study is to investigate and decipher their relationship: first, to obtain extrema values of cluster accuracy with member accuracy, in general, and then to employ impaired child speech data to investigate the correlation between cluster and member accuracy. For clusters comprising two consonants, cluster accuracy is considered in terms of the number of accurately produced members: two accurate members (PCLC), no accurate member (PCL0), or one accurate member (PCL1) which can be deduced from PCLC and PCL0. The minima of PCLC and PCL0 are derived as ramp functions of member accuracy (PCC). 50% PCC is the start of PCLC progression with diminishing PCL0 and the vortex of an inverted V-shaped for the maximum PCL1 along PCC. The data employed comprise 26 speech samples from 12 children before and after speech therapy, providing accuracy values spanning the spectrum from 0 to 100%. For word-initial clusters, it is found that cumulative PCLC and PCL0 are strongly correlated with their minimum path along PCC and, by default, with their maximum PCL1 path. For word-final clusters, the correlation was not found to be as strong, indicating that they are acquired earlier. Conclusively, the results suggest that cluster and member accuracy can be predicted from each other and that a PCC of 50% sparks the production of accurate clusters whose progression is near its minimum path along PCC.

Keywords: consonant clusters, cluster accuracy, consonant accuracy, child speech

1 Introduction

There are twenty-five word-initial and twenty-five word-final consonant clusters in the English language [1]. Consonant clusters are a major source of errors in typical child speech during phonological development as well as in impaired child speech. Although there is evidence that some clusters are produced accurately as early as 2 years of age for English [2] or even earlier for German and Spanish [3], it is not until between ages 4 and 6 years that consonant clusters are typically acquired by monolingual ([4] for Spanish; [5] for Hebrew; [6] for French; [7] for English) or bilingual children ([8] for Greek-English; [9] for isiXhosa-English; [10] for Haitian Creole-English). It is estimated, however, that 5% of six-year olds are diagnosed with a speech sound disorder (SSD) [11] which delays the

acquisition of consonant clusters.

The acquisition of consonant clusters in children with SSDs has been studied by [12], [13], [14] and [15], among others. As first reported in [16] and discussed in [17], there are four main stages in the development of two-member consonant clusters: reduction, vowel epenthesis, two-member production with one member or both members substituted, and complete acquisition. Substitution patterns are generally similar between typically and atypically developing children [12], while sonority-governed reductions may differ between typically and atypically developing children [14], [18], [19], [20] and articles therein.

Common measures for the quantitative evaluation of consonant clusters in picture-elicited speech or in running speech are the percentage of consonants correct (PCC) [21, 22] and the percentage of clusters correct [23, 24]. The percentage of consonants correct measures the accuracy of cluster members while the percentage of clusters correct (PCLC) measures the accuracy of whole clusters, that is, both cluster members being accurate. More recently, in [25], the measure for cluster proximity (MCP) was proposed as a means of quantitatively differentiating different stages in the development of two-member consonant clusters. In this measure, besides accurately produced cluster members, inaccurately produced consonants as well as vowel-epenthetic and two-member productions are also credited with different weights. In [26, 27] a strong correlation between MCP and PCLC for word-initial and word-final clusters was found and in [28, 29] a strong correlation between MCP and PCC for word-initial and word-final clusters was also found.

The purpose of the present study is to decipher the relationship between the two commonly applied measures in practice nowadays, cluster accuracy and member accuracy, in impaired child speech. That is, to investigate how cluster accuracy progresses with progression of member accuracy. Cluster accuracy will be examined in terms of whole cluster accuracy (PCLC) as well as accuracy of clusters with only one accurate member (PCL1) and accuracy of clusters with no accurate members (PCL0). Looking into this, it will be first examined whether any of these accuracies are by definition related and, if so, what is the exact mathematical relationship between them, so that one can directly be calculated from the other one. As a second step, upper and lower limiting values for these three cluster accuracies will be obtained for given PCC values of member accuracy. These will be universal bounds for any cluster productions observed in practice in normal or impaired speech. Then, 26 speech samples before and after therapy from 12 children diagnosed with SSDs will be employed in order to investigate the correlation between the three aforementioned cluster accuracies and member accuracy as measured by PCC. If this correlation is strong and statistically significant, cluster accuracy can be predicted from member accuracy and vice versa. Particular attention will be paid to the progression paths of these

accuracies in order to find out whether there is a specific PCC value that sparks progress in the production of accurate clusters. The analysis will be carried out both for word-initial and word-final two-member consonant clusters.

2   Cluster accuracy and member accuracy identities

In terms of accuracy, productions of two-member consonant clusters will be classified in three groups: two accurate members (whole cluster accurate), one accurate member, no accurate member. It is noted that the second group includes reduced clusters with one accurate member, clusters with an epenthetic vowel between the two members of which at least one is accurate, and two-member clusters with one of them being accurate. The third group includes all the productions that are excluded from the first two groups, comprising complete omissions as well. Then, it follows that the sum of the productions in the three groups is equal to the targeted (intended) clusters. Defining accuracy as the proportion of productions to targeted clusters, results in the following identity:

$$PCLC + PCL1 + PCL0 = 1 \qquad (1)$$

where PCLC is the proportion of clusters in the first group, PCL1 is the proportion of clusters in the second group, and PCL0 is the proportion of clusters in the third group. It is clear that the three cluster accuracies are not all independent. If two of the three cluster accuracies are given, the third one can be determined from identity (1).

The purpose of the present study is to relate cluster accuracy to member accuracy which is expressed as the proportion of accurately produced consonants to consonants included in the targeted clusters. In other words, to relate PCLC, PCL1, and PCL0 to PCC. This is derived by noting that accurately produced consonants are the sum of consonants in accurately produced clusters (first group) and of consonants in clusters produced with one accurate member (second group). Dividing this by the number of consonants in the targeted clusters and noting that they are twice as many as the targeted clusters, one obtains

$$PCC = PCLC + \tfrac{1}{2}\,PCL1 \qquad (2a)$$

This identity relates member accuracy to cluster accuracy. Alternatively, PCC can be related to PCLC and PCL0 by incorporating identity (2a) into identity (1), resulting in

$$PCC = (1 + PCLC - PCL0)/2 \qquad (2b)$$

From this, it is concluded that when PCC=50%, PCLC=PCL0, that is, the number of accurately produced clusters is equal to the number of clusters produced with on accurate member. Furthermore, when PCC=75%, which is a criterion for consonant acquisition, PCLC=50%+PCL0, resulting in a minimum PCLC of 50%. When PCC=90%, the criterion for complete acquisition of consonants, PCLC=80%+PCl0, resulting in a minimum PCLC of 80%. The extrema of PCLC,

PCL0 and PCL1 for the whole spectrum of PCC values will be obtained in the following section.

3   Limits of cluster accuracy on member accuracy

It will be interesting to determine the limiting values (extrema) of PCLC, PCL1 and PCL0 for given PCC values between 0 and 1, for any speech sample in any language. This way, results obtained from specific speech samples can be put into perspective, as it will be done for the data employed in the present study.

In obtaining the limiting values for cluster accuracy, it is necessary to note that the PCC value of ½ (50% percentage correct) is *critical* insofar as cluster accuracy is concerned. This is because when the number of accurately produced consonants is smaller than or equal to the number of targeted clusters or, equivalently, when PCC $\leq$ ½, the minimum number of accurate clusters is zero. For example, let's say that 4 two-member clusters are targeted and the number of accurately produced consonants is 4 (PCC=1/2). Then, the minimum number of accurate clusters is zero as all 4 clusters can be produced with one accurate member. However, when PCC>1/2, there must be at least one accurate cluster produced to account for all the accurately produced consonants, and (PCL0)min=0. The two cases are treated separately as follows:

a) PCC $\leq$ 50%: Since (PCLC)min=0, identities (2a, b) yield respectively (PCL1)max=2PCC and (PCL0)min=1-2PCC.

b) PCC $\geq$ 50%: Since (PCL0)min=0, identities (2b) yields (PCLC)min=2PCC-1 and then identity (2a) yields (PCL1)max=2(1-PCC).

In either case, (PCLC)max=PCC, and identities (2a, b) yield respectively (PCL1)min=0 and (PCL0)max=1-PCC. In summary, (PCLC)min and (PCL0)min are ramp functions (piecewise linear) of increasing PCC, with the 50% PCC being the start and the end of the ramp, respectively. In contrast, (PCL1)min is zero for all values of PCC. (PCLC)max and (PCL0)max are linear increasing and decreasing functions of PCC respectively, while (PCL1)max is an inverted V (quasilinear) function of PCC, with the vortex at 50% PCC.

It is remarked that the above extrema values of cluster accuracy hold true when the number of accurately produced consonants is even. When this number is odd, while (PCLC)min remains the same, (PCLC)max becomes PCC-1/2n with n being the number of targeted clusters. This results in (PCL1)min=1/n and (PCL0)max=1-PCC-1/2n. The difference between these extrema values and the corresponding ones for an even number of accurately produced consonants is small (<10%) since the number of targeted clusters for computations is usually large (>10).

The derived extrema values of cluster accuracy with member accuracy will be depicted graphically, together with actual accuracy values obtained from data of impaired child speech, in the figures that will be presented hereon (Figures 1-6).

4   Word-initial clusters in impaired child speech

The data employed in the present study are comprised of 26 speech samples before and after therapy from 12 children diagnosed with SSDs. The 12 children with SSDs and the ages at which the speech samples were elicited are: Alan (5;11, 7;5), Barry (8;9, 8;10), Bobby (3;6, 4;5, 4;11), Danny (5;6, 6;5, 6;11), Jerry (5;7, 6;3), and Tim (5;0, 6;1) [30]; Annie (3;1, 4;4), Brad (4;11, 5;7), and Kirk (14;0, 14;3) [31]; male1 (3;1, 3;3) and male2 (4;1, 4;4) [32]; and male3 [33]. The first age in parenthesis denotes age before therapy while the following age(s) in parenthesis denote(s) age(s) after therapy. The speech samples of these children were elicited using the Hodson Assessment of Phonological Patterns (HAPP) [34] except for male3 whose speech was elicited using the Edinburgh Articulation Test (EAT) [35].

The children's speech was elicited from pictures shown to them. The words with word-initial two-member clusters that were associated with the pictures in the HAPP test are: *black, crayons, flower, glasses, glove, green, music box, plane, quarter, ice cubes, Santa Claus, school, screwdriver, slide, smoke, snake, spoon, star, sweater, three, toothbrush, truck*. These result in the elicitation of the following 21 word-initial two-member clusters: *sp, st, sk, sm, sn, fl, sl, θr, sw, pl, bl, kl, gl, br, tr, dr, kr, gr, kj, kw, mj*. In the EAT test administered to male3, clusters *pr* and *fr* were elicited instead of *kj* and *mj*, with the rest of the elicited clusters being the same as in the HAPP test. The cluster productions for each child are presented in Tables 1-3.

Table 1. Word-initial cluster productions for five children, Alan, Annie, Barry, Bobby, Brad, before and after therapy.

#CC	Alan		Annie		Barry		Bobby			Brad	
	5;11	7;5	3;1	4;4	8;9	8;10	3;6	4;5	4;11	4;11	5;7
sp	p	sp	b	sp	f	sp	∅	sp	sp	p	sp
st	t	st	d	st	tʃ	st	∅	t	st	t	st
sk	w	sk	g	sk	k	k	∅	ks	sk	s	sk
sm	m	sm	g	sm	m	sm	∅	sm	sm	m	sm
sn	n	sn	g	sn	tʃ	ᵗsn	∅	sn	sn	n	sn
fl	b	f	l	fl	f	f	w	f	fl	∅	f
sl	pw	sw	l	sl	ʃ	sl	∅	sl	sl	∅	sl
θr	t	tw	d	θw	θw	θw	∅	fw	θw	∅	θw
sw	pew	sw	b	sw	ʃ	s	∅	ʃw	sw	sw	sw
pl	pw	p	b	pl	p	p	∅	pw	pl	p	pl
bl	b	bl	g	bl	bl	bl	∅	bl	bl	b	bl
kl	t	k	g	kl	k	k	w	k	kl	∅	k

gl	d	gl / gw	g	gl	gw	gw / gl	w / ∅	gel	gl	∅	gəl
br	b	bw	b	bw	b	b	∅	b	bw	bw	bw
tr	t	tr	g	tr	tw	tw	∅	tw	tw	tr	kw
dr	d	d	d	dw	d	d	w	dw	dw	dw	gw
kr	∅	kw	g	kw	kw	kr	∅	kw	kw	kw	kr
gr	∅	gw	g	gw	gw	gw	∅	gw	gw	gw	gw
kj	tj	k	g	kj	k	k	w	kj	kj	∅	kj
kw	tɔ	kw	g	kw	k	k	∅	kw	kw	∅	kw
mj	m	m	m	mj	m	m	∅	m	mj	m	mj

Table 2. Word-initial cluster productions for four children, Danny, Jerry, Kirk, Tim, before and after therapy.

#CC	Danny			Jerry		Kirk		Tim	
	5;6	6;5	6;11	5;7	6;3	14;0	14;3	5;0	6;1
sp	p	sp	sp	p	sp	p	sp	b	sp
st	t	st	st	t	st	t	st	∅	sʔ
sk	ʔ	sk	sk	t	sk	k	sk	d	d
sm	m	sm	sm	m	sm	m	sm	m	sm
sn	n	sn	sn	n	sn	n	sn	n	sn
fl	s	fl	fl	s	fl	fw	fl	∅	fl
sl	h	sl	sl	d	sl	l	sl	∅	sl
θr	s	fr	fr	t	fw	f	f	∅	tr
sw	h	sw	sw	w	sw	w	sw	∅	fw
pl	h	pl	pl	d	pw	pl	pl	ʔ	pw
bl	b	bl	bl	d	bl	bl	bl	b	bw
kl	k	kl	kl	t	kw	kl	kl	ʔ	kl
gl	k	kl	gl	d	gl	gl	gl	d	gl
br	b	br	br	b	bw	bl	bl	b	br
tr	k	tr	tr	s	ʃr	t	tr	∅	tr
dr	k	gr	gr	d	dr	d	dw	d	d
kr	k	kr	kr	t	kr	kw	kl	∅	kr
gr	k	kr	gr	d	gr	gl	gl	d	gr
kj	kj	kl	kj	t	kj	kl	kl	∅	kj
kw	k	k	k	t	kw	kl	kl	∅	kw
mj	mj	m	mj	mj	mj	m	m	m	mj

Table 3. Word-initial cluster productions for three children, male1, male2, male3, before and after therapy.

#CC	male1		male2		male3	
	3;0	3;3	4;1	4;4	5;0	5;4
sp	p	p	p	sp	p	p
st	t	t	t	st	t	t
sk	p	t	k	k	k	k
sm	f	b	w	sm	m	m

sn	t	t	n	sn	n	n
fl	Ø	d	f	w	tl, l	fl
sl	Ø	d	w	w	kl	kl
fr	n/a	n/a	n/a	n/a	p, k	f
θr	Ø	p	tr	w	n/a	n/a
sw	t	t	w	w	k	kw
pl	d	p	p	p	pl, kl	pl
bl	f	b	b	b	dl	bl
kl	k	Ø	k	k	k	kl
gl	d	d	g	g	gl	gl
pr	n/a	n/a	n/a	n/a	pw, f	pw
br	t	b	b	b	b	bw
tr	t	t	k	k	t, k	tr twt
dr	n	d	r	d	d, g	dr
kr	t	t	k	k	k	kw
gr	d	d	g	g	g	gw
kj	b	t	k	k	n/a	n/a
kw	d	d	k	k	t	kw
mj	m	b	mj	m	n/a	n/a

For each child, the proportion of clusters correct (PCLC) and the proportion of consonants correct (PCC) is computed cumulatively for all clusters. Then, PCL0 is computed from equation 2b as PCL0=1+PCLC-2PCC, and PCL1 is computed from equation 1 as PCL1=1-PCLC-PCL0. The results are shown in Table 4 collectively for all the children considered.

Several remarks are made based on these results: i) half of the PCLC and PCL0 are minimum and, thus PCL1 is maximum, for the corresponding PCC. These extrema for PCLC, PCL0, and PCL1 are shown in bold in Table 4. As a reminder to the reader, the minimum PCLC is zero for $0 \leq PCC \leq 50\%$ and the minimum PCL0 is zero for $50\% < PCC \leq 100\%$. It is also seen that the remaining 13 PCLC and PCL0 are less than 10% off their minimum zero values for the corresponding PCC, except for the 50% PCC. This is a singular case in the sense that the equal PCLC and PCL0, shown in bold and italics in Table 4, are 19%, deviating the largest from their minimum zero value, and ii) there are two pairs of test results, each with equal PCC (shown in bold and italics in Table 4), whose corresponding PCL1 deviate by about 10%, owing it to the addition of 5% deviation in each of PCLC and PCL0 in accordance with Equation 1. Based on these observations, it is expected that the PCLC and PCL0 values shown in Table 4 will be strongly correlated to their corresponding minimum values along PCC and, therefore, to PCC as well, since their minimum values are perfectly correlated to PCC, as they are piecewise linear functions of PCC. Furthermore, it is expected that the PCL1 values shown in Table 4 will be strongly correlated to their maximum values along PCC and, therefore, to PCC as well, since its maximum values are perfectly correlated to PCC, as they are piecewise linear functions of PCC.

Table 4. Mean word-initial cluster (PCLC, PCL0, PCL1) and member (PCC) accuracy for 26 child speech samples before and after therapy.

child & age	PCLC	PCL0	PCL1	PCC
Alan 5;11	**0%**	**42.9%**	**57.1%**	28.6%
Alan 7;5	45.5%	4.5%	50%	70.5%
Annie 3;1	**0%**	**66.7%**	**33.3%**	16.7%
Annie 4;4	**76.2%**	**0%**	**23.8%**	88.1%
Barry 8;9	4.8%	23.8%	71.4%	40.5%
Barry 8;10	**31.8%**	**0%**	**68.2%**	65.9%
Bobby 3;6	**0%**	**100%**	**0%**	0%
Bobby 4;5	33.3%	9.5%	57.2%	61.9%
Bobby 4;11	**71.4%**	**0%**	**28.6%**	**85.7%**
Brad 4;11	9.5%	33.3%	57.2%	38.1%
Brad 5;7	61.9%	9.5%	28.6%	76.2%
Danny 5;6	9.5%	47.6%	42.9%	31%
Danny 6;5	**66.7%**	**0%**	**33.3%**	83.4%
Danny 6;11	**85.7%**	**0%**	**14.3%**	92.9%
Jerry 5;7	4.8%	61.9%	33.3%	21.5%
Jerry 6;3	76.2%	4.8%	19%	*85.7%*
Kirk 14;0	19%	4.8%	76.2%	57.1%
Kirk 14;3	**61.9%**	**0%**	**38.1%**	*81%*
Tim 5;0	**0%**	**71.4%**	**28.6%**	14.3%
Tim 6;1	66.7%	4.8%	28.5%	*81%*
male1 3;1	**0%**	**76.2%**	**23.8%**	11.9%
male1 3;3	**0%**	**66.7%**	**33.3%**	16.7%
male2 4;1	4.8%	14.3%	80.9%	45.3%
male2 4;4	*19%*	*19%*	62%	50%
male3 5;0	8.3%	25%	66.7%	41.7%
male3 5;4	**38.1%**	**0%**	**61.9%**	69.1%

NB. In bold: extrema of PCLC, PCL0, PCL1 with PCC; in bold and italics: i) equal PCLC and PCL0 at 50% PCC, and ii) equal PCC with different PCLC, PCL0, PCL1.

The cumulative PCLC and their corresponding PCC values of Table 4 are depicted graphically in Figure 1 in a (PCC-PCLC) plane. The (PCC, PCLC) pairs are shown in dots, while the minimum and maximum PCLC values along PCC are shown in dashed lines. For PCC less than 50%, PCLC is smaller than 10%, with the minimum at zero. PCLC progression starts at 50% PCC, with the PCLC values lying on or near the minimum PCLC path. In fact, the correlation between actual and minimum PCLC values for PCC larger than 50% is strong and statistically significant as indicated by a Pearson coefficient equal to 0.984, a p value equal to 1.14E-09, and a standard error equal to 4.8%. Given the perfect correlation between the minimum PCLC and PCC, it is concluded that the correlation between PCLC and PCC is also strong and statistically significant.
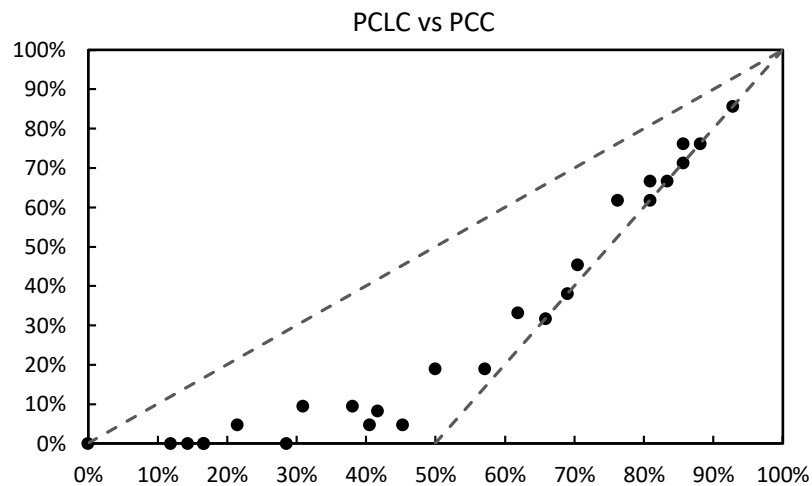
Figure 1. The (PCC, PCLC) pairs for 26 samples of impaired speech with 21 word-initial clusters each, are shown in dots; the limiting PCLC values are shown in dashed lines.

The cumulative PCL0 and their corresponding PCC values of Table 4 are depicted graphically in Figure 2 in a (PCC-PCL0) plane. The (PCC, PCL0) pairs are shown in dots, while the minimum and maximum PCL0 values along PCC are shown in dashed lines. For PCC larger than 50%, PCL0 is smaller than 10%, with the minimum at zero. For PCC smaller than 50%, PCL0 values are on or near the linearly decreasing minimum. The correlation between actual and minimum PCL0 values for PCC smaller than 50% is strong and statistically significant evidenced by a Pearson coefficient equal to 0.993, a p value equal to 1.47E-10, and a standard error equal to 3.3%. Since the minimum PCL0 is perfectly correlated with PCC, it is concluded that the correlation between the actual PCL0 values and their corresponding PCC values is also strong and statistically
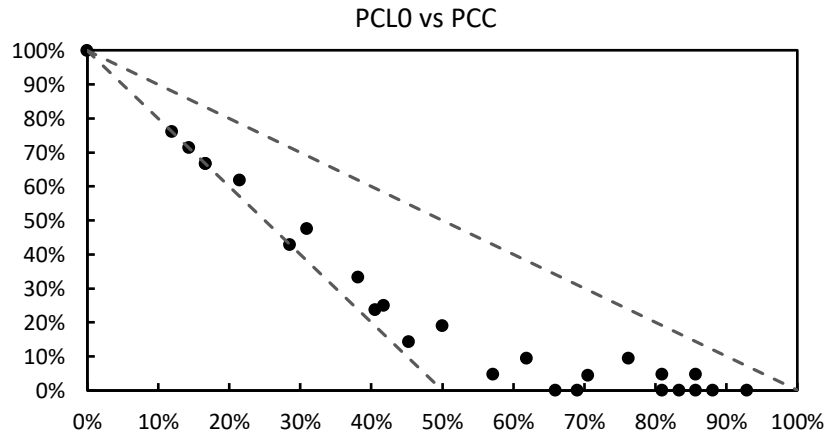
significant.

Figure 2. The (PCC, PCL0) pairs for 26 samples of impaired speech with 21 word-initial clusters each, are shown in dots; the limiting PCL0 values are shown in dashed lines.

The cumulative PCL1 and their corresponding PCC values of Table 4 are depicted graphically in Figure 3 in a (PCC-PCL1) plane. The (PCC, PCL1) pairs are shown in dots, while the maximum PCL1 values along PCC are shown in dashed lines. It is observed that PCL1 is on or near the maximum PCL1 for all PCC. This may be deduced from equation 1, since PCL0 and PCLC are on or near their minimum values for all PCC. It is also observed that the maximum PCL1 is linearly increasing for PCC less than 50% and is linearly decreasing for PCC greater than 50%, forming an inverted V-shape development with PCC. This may be deduced from equation 1, since the minimum PCL0 is linearly decreasing for PCC less than 50% and the minimum PCLC is linearly increasing for PCC greater than 50%. It is found that the correlation between the actual PCL1 and the minimum PCL1 is strong and statistically significant in each of the two PCC regimes: PCC less than 50% and PCC greater than 50%. For PCC less than 50%, the Pearson coefficient is equal to 0.967, the p value is equal to 2.63E-07, and the standard error is equal to 7.5%. For PCC greater than 50%, the Pearson coefficient is equal to 0.918, the p value is equal to 9.99E-06, and the standard error is equal to 8.3%.
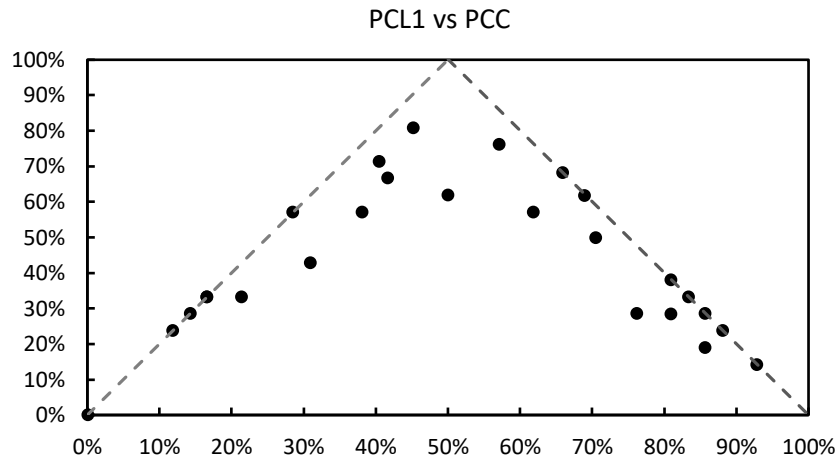
Figure 3. The (PCC, PCL1) pairs for 26 samples of impaired speech with 21 word-initial clusters each, are shown in dots; the maximum PCL1 values are shown in dashed lines.

5   Word-final clusters in impaired child speech

The word-final clusters to be examined are taken from the same children's speech samples that the word-initial clusters were taken from, as described above. The elicited words were: *boats, crayons, fork, horse, ice cubes, jump rope, mask, music box*, thus, providing for study the word-final clusters: *bz, ts, ks, sk, mp, nz, rk, rs*. However, because male3 was not tested for word-final clusters, a total of 24 speech samples are considered that contain these 8 word-final clusters. The children's cluster productions are listed in Tables 5-7.

Table 5. Word-final cluster productions for five children, Alan, Annie, Barry, Bobby, Brad, before and after therapy.

CC#	Alan		Annie		Barry		Bobby			Brad	
	5;11	7;5	3;1	4;4	8;9	8;10	3;6	4;5	4;11	4;11	5;7
bz	∅	bz	∅	bz	bts	bz	∅	bz	bz	b	bz
ts	n/a	n/a	∅	ts	n/a	n/a	n/a	n/a	n/a	t	ts
ks	∅	ks	∅	ks	t	ks	∅	ts	ks	s	ks
sk	∅	sk	∅	sk	ts	ks	∅	sk	sk	s	sk
mp	∅	mp	m	mp	mp	mp	∅	mp	mp	mp	mp
nz	n	nts	∅	nz	nts	nz	∅	nz	nz	n	nz
rk	∅	ʊk	ʊ	ʊk	k	k	∅	ʊk	ʊk	əʔ	ʊk
rs	∅	rs	∅	ʊs	ts	ts	∅	ʊs	ʊs	ʊs	ʊs

Table 6. Word-final cluster productions for four children, Danny, Jerry, Kirk, Tim, before and after therapy.

CC#	Danny			Jerry		Kirk		Tim	
	5;6	6;5	6;11	5;7	6;3	14;0	14;3	5;0	6;1
bz	b	bz	bz	bz	bz	b	bz	d	bd
ts	n/a	n/a	n/a	n/a	n/a	∅	ts	n/a	n/a
ks	k	ks	ks	ks	ks	s	ks	t	t
sk	t	ks	sk	ks	sk	s	ks	t	t
mp	m	mp	mp	mp	mp	ʔ	mp	mʔ	mp
nz	m	nz	nz	n	nz	m	nz	nʔ	nz
rk	∅	k	rk	ʊk	ʊk	ʊk	ʊk	ʔ	rk
rs	∅	s	rs	ʊs	ʊs	ʊs	ʊs	t	rs

Table 7. Word-final cluster productions for two children, male1, male2, before and after therapy.

CC#	male1		male2	
	3;0	3;3	4;1	4;4
bz	ps	b	bz	bz
ts	∅	t	ts	ts
ks	cs	t	ks	ks
sk	t	t	ks	k
mp	mp	mp	∅	mp
nz	∅	∅	nz	nz
rk	t	t	rk	k
rs	t	t	s	t

Based on the productions in Tables 5-7, the cumulative PCLC and PCC as well as PCL0 and PCL1 from Equations (1, 2b) are computed for each child. The results are shown collectively for all the children in Table 8. It is observed that: i) there is a 50% PCC for which PCLC=PCL0 shown in bold and italics, ii) there are 13 performances for which PCC correspond to minimum PCLC and PCL0 and, thus, maximum PCL1 shown in bold. However, the remaining PCLC and PCL0 are not as near their minimum paths as they were for word-initial clusters, indicating that word-final clusters are acquired earlier. The largest deviation from the minimum paths is 24.9% for PCL0 when PCC is 68.8%, and iii) there is a PCC of 64.3% for two children (Jerry 5;7 and Tim 6;1) with corresponding PCLC and PCL0 differing by about 14%, and PCL1 by 28%. The difference in PCL1 is twice as large as the difference in PCLC or PCL0 in accordance with equation 1.

Table 8. Mean word-final cluster (PClC, PCl0, PCl1) and member (PCC)accuracy for 24 child speech samples before and after therapy.

child & age	PClC	PCl0	PCl1	PCC
Alan 5;11	**0%**	**85.8%**	**14.2**	7.1%
Alan 7;5	**71.4%**	**0%**	**28.6%**	85.7%
Annie 3;1	**0%**	**87.4%**	**12.6%**	6.3%
Annie 4;4	**75%**	**0%**	**25%**	87.5%
Barry 8;9	14.3%	28.5%	57.2%	42.9%
Barry 8;10	57.1%	14.3%	28.6%	71.4%
Bobby 3;6	**0%**	**100%**	**0%**	0%
Bobby 4;5	**57.1%**	**0%**	**42.9%**	78.6%
Bobby 4;11	**71.4%**	**0%**	**28.6%**	85.7%
Brad 4;11	*12.5%*	*12.5%*	75%	50%
Brad 5;7	**75%**	**0%**	**25%**	87.5%
Danny 5;6	**0%**	**57.2%**	**42.8%**	21.4%
Danny 6;5	57.1%	14.3%	28.6%	71.4%
Danny 6;11	**100%**	**0%**	**0%**	100%
Jerry 5;7	42.9%	14.3%	42.8%	*64.3%*
Jerry 6;3	**71.4%**	**0%**	**28.6%**	85.7%
Kirk 14;0	**0%**	**37.4%**	**62.6%**	31.3%
Kirk 14;3	62.5%	12.5%	25%	75%
Tim 5;0	**0%**	**71.4%**	**28.6%**	14.3%
Tim 6;1	57.1%	28.5%	14.4%	*64.3%*
male1 3;1	12.5%	74.9%	12.6%	18.8%
male1 3;3	12.5%	62.5%	25%	25%
male2 4;1	62.5%	24.9%	12.6%	68.8%
male2 4;4	62.5%	24.9%	12.6%	68.8%

NB. In bold: extrema of PClC, PCl0, PCl1 with PCC; in bold and italics:
i) equal PClC and PCl0 at 50% PCC, and ii) equal PCC with different
PClC, PCl0, PCl1.

The cluster accuracy values (PCLC, PCL0, PCL1) of Table 8 are plotted against
PCC in Figures 4-6. In Figure 4, PCLC is plotted against PCC. The (PCC, PCLC)
pairs are shown in dots, while the extrema PCLC are shown in dashed lines. It is

observed that for PCC less than 50%, PCLC is less than 15%, near its minimum path of zero. However, for PCC greater than 50%, PCLC is scattered further away from its minimum path than it was scattered for word-initial clusters shown above in Figure 1. This indicates that for a given PCC, word final clusters are produced overall more accurately than word-initial clusters. Thus, the correlation between PCLC and the minimum PCLC will not be as strong for word-final clusters either. In fact, the Pearson coefficient is calculated now as 0.926, p is 7.32E-07, and the standard error is 9.9%, compared to the word-initial respective values of 0.984, 1.14E-09, and 4.8%.
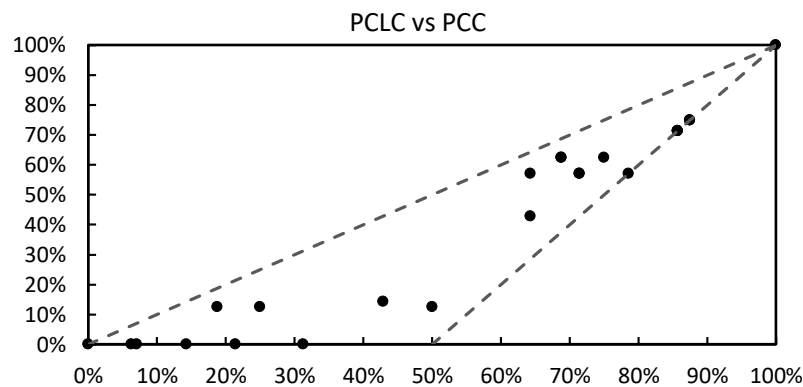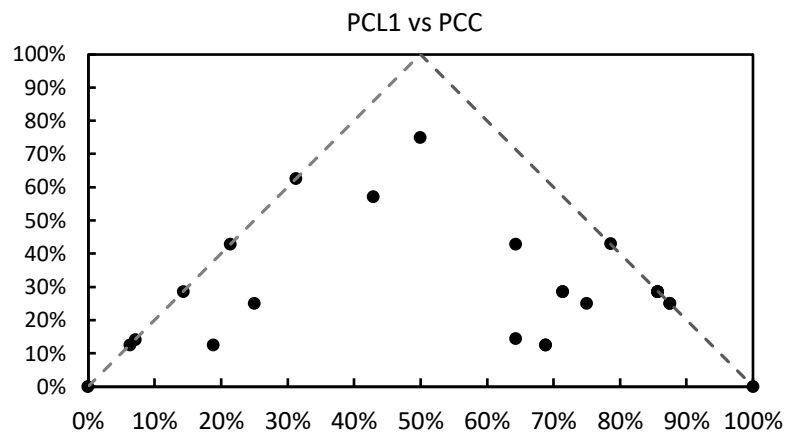

Figure 4. The (PCC, PCLC) pairs for 26 samples of impaired speech with 8 word-final clusters each, are shown in dots; the limiting PCLC values are shown in dashed lines.
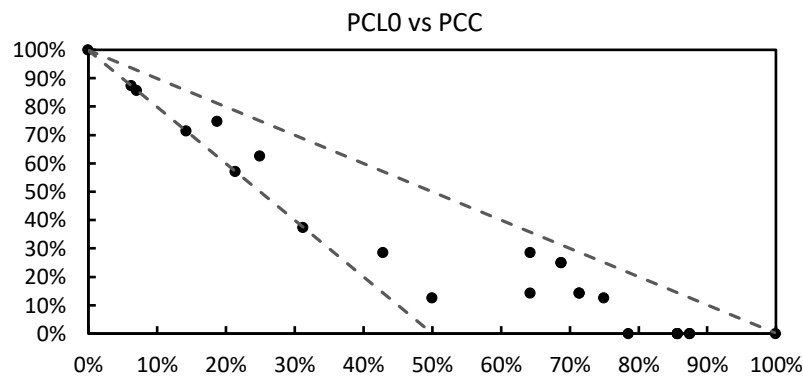
Figure 5. The (PCC, PCL0) pairs for 26 samples of impaired speech with 8 word-final clusters each, are shown in dots; the limiting PCL0 values are shown in dashed lines.

In Figure 5, PCL0 is plotted against PCC from their values given in Table 8. The (PCC, PCL0) pairs are shown in dots, while the extrema PCL0 are shown in dashed lines. It is observed that PCL0 is scattered further away from its minimum path than it was scattered for word-initial clusters shown above in Figure 2. Thus, the correlation between PCL0 and the minimum PCL0 will not be as strong for word-final clusters either. The Pearson coefficient is now 0.984, p is 2.44E-07, and the standard error is 6%, compared to the word-initial respective values of 0.993, 1.47E-09, and 3.3%.

Figure 6. The (PCC, PCL1) pairs for 26 samples of impaired speech with 8 word-final clusters each, are shown in dots; the limiting PCL1 values are shown in dashed lines.

In Figure 6, PCL1 is plotted against PCC form their values given in Table 8. The (PCC, PCL1) pairs are shown in dots, while the maximum PCl1 values along PCC are shown in dashed lines. It is observed that PCL1 is scattered further away from its maximum path than for word-initial clusters of Figure 3. This may be deduced from equation 1, since PCLC and PCL0 are further from their minimum paths than word-initial clusters. It is observed that the correlation between PCL1 and its minimum path seems stronger for PCC less than 50% than for PCC greater than 50%. In fact, for PCC less than 50%, the Pearson coefficient is 0.92, p is 1.62E-04, and the standard error is 10.4%, while for PCC greater than 50%, the Pearson coefficient is 0.561, p is 2.9E-02, and the standard error is 21.7%.

6   Discussion

The commonly used measure for cluster accuracy is the proportion of clusters correct (PCLC) while for consonant accuracy it is the proportion (percentage) of consonants correct (PCC). The two measures are usually applied separately when consonant clusters are evaluated in articulation/phonology tests administered to

children. The purpose of the present study was to investigate whether there is a relationship between the two measures and, if so, to decipher this relationship. It was derived that the minimum PCLC is a ramp function of PCC with the 50% PCC being the spark of increasing PCLC. It was also derived that the maximum PCLC is equal to PCC. These extrema values of PCLC along PCC can place into perspective any data obtained from any test or in any language in child speech. Furthermore, identities were derived between these two measures and cluster accuracy insofar as accuracy of one cluster member (PCL1) or no cluster member (PCL0) is concerned. These identities enabled determination of extrema values of PCL0 and PCL1 along PCC, again setting upper and lower bounds for universal data of productions of two-member clusters in any language.

The pertinent question concerning the universal bounds obtained for cluster accuracy (PCLC, PCL1, PCL0) along PCC is whether actual child speech data will follow any specific cluster-accuracy to member-accuracy path and, specifically, whether there is any correlation between cluster and member accuracy and, if so, how strong it is. Because, if there is such a correlation, then in evaluating in practice children's cluster performance, cluster accuracy and member accuracy ought not to be looked at separately since one measure can be predicted from the other measure.

Twenty-six child speech samples were employed from 12 children diagnosed with SSDs. These data provided 21 word-initial clusters and 8 word-final clusters for each of the children before and after therapy. It was found that PCLC and PCL0 values were on or near their minimum values along PCC, while PCL1 values were on or near their maximum values along PCC. This provides evidence for a strong correlation between cluster and member accuracy since the extremum cluster accuracy was derived to be linearly related to PCC. It should be pointed out, however, that the correlation between actual cluster accuracy and minimum cluster accuracy was stronger for word-initial than for word-final clusters, providing evidence that word-final clusters are produced more accurately than word-initial clusters for a given PCC. Perhaps, the fact that more word-initial than word-final clusters were used had something to do with the stronger correlation of the former's cluster accuracy with the minimum path along PCC. The use of such data from impaired child speech was not intentional but rather unavoidable because the articulation/phonology tests that are administered in practice elicit many more words with word-initial clusters than words with word-final clusters. Last, it is pointed out that the research topic undertaken here can and should be extended. Although strong correlation was found between cluster accuracy and its extremum path along PCC for data from impaired child speech, the finding should also be tested for the longitudinal development of normal child speech in English and for normal and impaired speech in other languages permitting two-member clusters. The author expects that the results of the present study will be consistent with such future findings. Extension to three or more member clusters

is also a prospective research activity, even though these consonant clusters are limited in numbers within a language as compared to the two-member clusters that were investigated in the present study.

7   Conclusions

The relationship between the accuracy of two-member clusters and their member accuracy was deciphered in the present study. Extrema values were derived between clusters with two (PCLC), one (PCL1), or zero (PCL0) accurate members and PCC yielding ramp functions for the minimum PCLC and PCL0 and linearly increasing and decreasing functions for their maxima respectively. The 50% PCC sparks linear progress in PCLC and denotes the beginning of diminishing PCL0. PCL1, which is deduced from PCLC and PCL0, has a zero minimum all along PCC and an inverted V-shaped maximum with its vortex at 50% PCC. Employment of sufficient data from impaired child speech in English showed that PCLC and PCL0 strongly correlate with their minimum values along PCC, while PCL1 strongly correlates by default with its maximum values along PCC. Word-initial clusters were found to have a stronger correlation than word-final clusters implying the latter's higher accuracy along PCC. The results also suggest that cluster and member accuracy can be predicted from each other. Extension of this research to incorporate longitudinal data of normal child speech as well as child speech in other languages will test the universality of these conclusions.

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