A Comparative Study of Phoneme- and Word-Based Learning of English Words Presented to the Skin

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Abstract. Past research has demonstrated that speech communication on the skin is entirely achievable. However, there is still no definitive conclusion on the best training method that minimizes the time it takes for users to reach a prescribed performance level with a speech communication device. The present study reports the design and testing of two learning approaches with a system that translates English phonemes to haptic stimulation patterns (haptic symbols). With the phoneme-based learning approach, users learned the haptic symbols associated with the phonemes before attempting to acquire words made up of the phonemes. With the word-based approach, users learned words on day one. Two experiments were conducted with the two learning approaches, each employing twelve participants who spent 100 minutes each learning 100 English words made up of 39 phonemes. Results in terms of the total number of words learned show that performance levels vary greatly among the individuals tested (with the best learners in both methods achieving word-recognition scores >90%-correct on a 100-word vocabulary), both approaches are feasible for successful acquisition of word through the skin, and the phoneme-based approach provides a more consistent path for learning across users in a shorter period of time.

Keywords: haptic speech communication, language acquisition, phoneme-based learning, word-based learning, haptic symbols for phonemes.

1 Introduction

The sense of touch offers rich information about the world around us and past research has demonstrated that it is possible to communicate speech through touch. For example, the Tadoma method, where the listener places the hand on the speaker's face to feel the articulatory processes and associate the sensations with speech production [1], provides an existence proof that speech communication through the skin alone is entirely achievable [2]. Compared with this natural method, several man-made systems have been developed to display spectral properties of speech on the skin by relying on the principle of frequency-to-place transformation to convey speech information, or by extracting speech features before encoding on the skin (e.g., see reviews [3-8]).

In the current study, a phonemic-based approach to tactual speech communication was selected for several reasons. Because the phoneme is a basic unit of speech, it is more efficient to encode speech with phonemes than alphabets [9] in terms of the number of units needed per speech sound. In addition, once the phoneme set has been established, it can be used to encode any possible word or message in the language, as opposed to the use of tactile metaphors or semantics [Brunet articles] which must be developed to suit particular situations. Although other approaches to encoding tactile signals are also worthy of consideration (e.g., those based on tactile implementation of sign languages or other types of linguistic features), there is evidence to suggest that the information transfer rates that can be achieved with phonemic codes are at least as good as those of other coding methods[10]. Our initial findings demonstrate that, with sufficient exposure to the tactual display, users are capable of identifying phonemes at a high level of recognition rate [11, 12]. The next goal of our research plan is the exploration of effective approaches to training for minimizing the time required for users to reach a prescribed level of performance.

Previous studies have explored the role of training in the use of haptic devices. For example, a study concerned with the acquisition of Braille by sighted learners has demonstrated that a corresponding visual display was beneficial for the acquisition of haptic Braille [13]. This result suggests the use of a visual display in the current study, corresponding to the activation of vibrators on the tactual display. In addition, the efficacy of correct-answer feedback for perceptual learning tasks is well-established [14], indicating that correct-answer feedback should be employed in the learning procedure. With the phonemic-based tactual display designed for conveying English words, we consider two training approaches to training: phoneme-based and word-based [15]. The phoneme-based approach, which operates on a "bottom-up" theory of learning, concentrates on maximizing the individual's ability to discriminate between and identify the individual sound patterns of speech [15]. The word-based approach is based on a "top-down" theory of learning. It bypasses the training of basic phoneme patterns and starts with words directly [15]. Previous studies of speech training have employed single or combined approaches [16-18]; however, these studies have not led to definitive conclusions for choosing one approach over another.

The present study compares phoneme-based and word-based training approaches for learning 100 English words. To the extent possible, we have kept the learning environment and time similar for both approaches in order to examine outcomes under comparable conditions. In the remainder of this paper, we present the general methods, followed by two experiments with each of the two learning approaches, and compare their results. We conclude the paper with a discussion that includes a comparison of word-learning performance through our phonemic-based haptic display with that obtained in other recent studies of haptic displays for speech communication.

2 General Methods Common to Both Experiments

2.1 Learning Materials

One-hundred common English words were selected for the present study (see **Table 1**; the 8 groups are explained later in Sec. **Error! Reference source not found.**). They consisted of 50 CV (consonant-vowel) or VC words and 50 CVC or VCV words. The 100 words were transcribed into the 39 English phonemes [19]. **Table 2** shows the 24 consonants and 15 vowels making up the phonemes and example words containing the corresponding phonemes. It follows that the phoneme transcription for “ace” would be “AY” and “S,” etc. Each phoneme was mapped to a haptic symbol, as described in Sec. 2.2 below.

Table 1. The one hundred English words used in the present study

Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8
ace	key	ray	low	chow	jay	gay	all
aid	my	she	oath	cow	joy	go	fee
day	sigh	shy	row	how	knee	guy	off
may	they	shoe	show	vow	no	tie	on
me	way	us	so	wow	now	toe	ought
moo	why	come	the	cheese	pay	too	you
sue	woo	rock	though	choose	join	toy	fought
doom	dime	rum	base	hatch	keep	azure	pawn
dude	make	shave	dome	him	noise	book	ring
moose	seek	shock	like	loud	pen	gun	thing
same	side	vase	thumb	mad	them	put	young
seam	wake	wash	will	maze	then	shirt	your
seed	weed		wish			should	

Table 2. The thirty-nine English phonemes used in the present study

symbol	example word	symbol	example word	symbol	example word	symbol	example word
EE	meet	UU	hood	K	key	ZH	azure
AY	mate	UH	hut	P	pay	CH	chew
OO	mood	OE	boat	T	tea	J	jeep
I	might	OY	boy	B	bee	H	he
AE	mat	OW	pouch	G	guy	R	ray
AH	father	D	do	F	fee	L	lie
AW	bought	M	me	SH	she	Y	you
EH	met	S	see	TH	think	N	new
ER	bird	W	we	V	voice	NG	sing
IH	bid	DH	the	Z	zoo		

2.2 Haptic Symbols for Phonemes and Words

The experimental apparatus consisted of a 4-by-6 tactor array worn on the non-dominant forearm. The 24 tactors form four rows in the longitudinal direction (elbow to wrist) and six columns (rings) in the transversal direction (around the forearm). As shown in **Fig. 1**, two rows (i and ii) reside on the dorsal side of the forearm and the other two (iii and iv) on the volar side. A wide-bandwidth tactor (Tectonic Elements, Model TEAX13C02-8/RH, Part #297-214, sourced from Parts Express International, Inc.) was used as the actuator. A MOTU 24Ao audio device (MOTU, Cambridge, MA, USA) was used for delivering 24 channels of audio waveforms to the 24 tactors through custom-built stereo audio amplifiers. A Matlab program running on a desktop computer generated the multi-channel waveforms and ran the learning experiments. With this setup, the tactors can be driven independently with programmable waveforms.

Haptic symbols for phonemes consisted of vibrotactile patterns using one or more of the 4-by-6 tactors. The mapping of the phonemes to haptic symbols incorporated the articulatory features of the sounds, balanced by the need to maintain the distinctiveness of the 39 haptic symbols. The stimulus properties included *amplitude* (in dB sensation level, or dB above individually-measured detection thresholds), *frequency* (single or multiple sinusoidal components), *waveform* (sinusoids with or without modulation), *duration*, *location*, *numerosity* (single tactor activation or multiple tactors turned on simultaneously or sequentially), and *movement* (smooth apparent motion or discrete saltatory motion varying in direction, spatial extent, and/or trajectory). Examples of the use of articulatory features to construct the phonemes include the use of location on the array to map place of articulation (e.g., front sounds are presented near the wrist and back sounds near the elbow) and the use of unmodulated versus modulated waveforms to distinguish voiceless and voiced cognate pairs. Signal duration was also used as a cue, e.g., as in distinguishing brief plosive bursts from longer fricative noises. The individual haptic symbols ranged in duration from 100 to 480 ms. Details of the phoneme mapping strategies and the resultant haptic symbols can be found in [11].

To display a word, the haptic symbols corresponding to the phonemes making up the word were delivered in sequence, with a 300-ms gap inserted between phonemes. For the words used in the present study, the word duration varied from roughly 1 to 2s.

The participants sat comfortably in front of a computer monitor and wore noise-reduction earphones (see **Fig. 2**). The non-dominant forearm was placed on the table with the volar side facing down. The elbow-to-wrist direction was adjusted to be roughly parallel to the torso. To ensure that the haptic symbols were presented at 30 dB sensation level (SL) for all participants, a two-step calibration procedure was carried out for each participant prior to the experiments. First, detection thresholds at 60 and 300 Hz were estimated with one tactor (the "reference tactor") using a one-up two-down adaptive procedure [20]. Second, the intensities of all 24 tactors were adjusted to match that of the reference tactor using the method of adjustment [20].

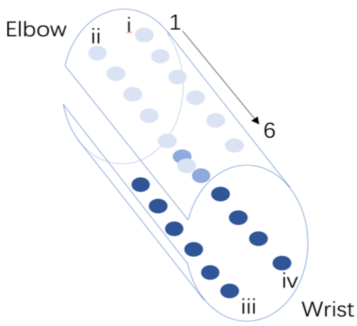

Fig. 1. Illustrations of tactor layout

Fig. 2. Experimental setup

2.3 Learning with Time Constraints

Our earlier study showed evidence of memory consolidation [21] meaning that learning took place even when the participants weren't being trained or tested [12] . This motivated us to design a 10-day curriculum where learning time was capped at 10 minutes per day, for a total of 100 minutes, for either phoneme- or word-based learning. In order to assess learning progress, a phoneme or word identification test without feedback was conducted after the 10-min learning period on some days. The test typically took less than 10 minutes and did not count towards learning time since no correct-answer feedback was provided. The combined experiment time, excluding the pre-experiment calibration time, reached 80 hours (12 participants × 2 learning approaches × 10 days × 1/3 hour per day).

3 Experiment I: Phoneme-Based Learning

3.1 Methods

A total of 12 participants (P01-P12; 6 females; age range 18-26 years old, 21.9 ± 1.7 years old) took part in the phoneme-based learning experiment. All were right handed with no known sensory or motor impairments. Six of the participants are native English speakers. The other 6 participants speak English fluently and their first languages include Bulgarian, Chinese and Korean. Most of the participants received early childhood music training including piano, violin, guitar, flute, and cello.

The 10-day curriculum for phoneme-based learning was as follows:

- Day 1: 6 Cs (consonants) – P T K B D G
- Day 2: 12 Cs – Day 1 + F V TH DH S Z
- Day 3: 18 Cs – Day 2 + SH ZH CH J H W
- Day 4: all 24 Cs – Day 3 + M N NG R L Y
- Day 5: 8 Vs (vowels) – EE IH AH OO UU AE AW ER
- Day 6: 15 Vs – Day 5 + AY I OW OE OY UH EH
- Day 7: all 39 phonemes (> 90% correct required before learning words)
- Day 8: 50 VC/CV words if > 90% correct achieved with 39 phonemes
- Day 9-10: all 100 words, after 1 day with 50 VC/CV words

With the phoneme-based learning approach, the participants learned the haptic symbols associated with the 39 phonemes before learning the 100 words presented as sequences of phonemes. As shown above, the 24 consonants were divided evenly into 4 groups and learned during Days 1 to 4. The 15 vowels were divided into two groups and learned during Days 5 and 6. On Day 7, all 39 phonemes were available for learning and each participant had to achieve at least 90% correct on a phoneme identification test before proceeding to learning words. Therefore, all 12 participants had the same learning tasks from Day 1 to 7. The 100 words were divided into two groups: the first 50 words contained only CV/VC words and the rest included CVC/VCV words. After reaching the 90% criterion for phoneme learning, each participant learned the 50 CV/VC words for one day, and then all 100 words afterwards until 10 days were reached. It follows that the participants proceeded at different paces from Day 8 to 10.

During Days 1 to 7, the 10-min learning time per day included two activities: free play and practice test. During free play (see **Fig. 3**), the participant could either "Play" a phoneme selected from the left panel or "Show" its visual representation in the right panel. During the practice test, the participant would feel a haptic symbol and then respond by selecting a phoneme button on the computer screen. A trial-by-trial correct-answer feedback was provided. The participants were encouraged to spend time with both activities during the 10-min learning period, and could decide how much time to spend on each task. After the 10 minutes were up, each participant completed a closed-set phoneme identification test without any feedback.

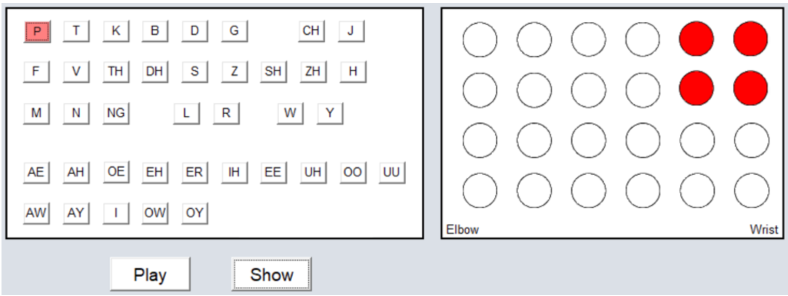

Fig. 3. User interface for phoneme free play. The phoneme highlighted in the left panel shows the phoneme being learned ("P"). The 4 red circles in the right panel represent the 4 activated tactors on the dorsal side and near the wrist of the forearm.

From Day 8, the participants who had successfully passed the 90%-correct phoneme identification criterion spent their 10-min learning time on free play and practice test, this time with words instead of phonemes. The user interface for word free play was similar to that shown in **Fig. 3** except that the phonemes in the left panel were replaced by words. Again, the participant completed a word identification test without any feedback after the 10-min learning period was over.

3.2 Results

The results of phoneme-based learning are summarized in terms of the time taken to reach performance criteria and the performance levels reached. Figure 4 shows the individual progress of the twelve participants in the order of their performance levels. For example, the best learners P06 and P08 reached 90% correct phoneme identification on Day 7, 90% correct word recognition with 50 words on Day 8, and learned the 100 words on Day 9 and Day 10. The percent-correct scores on the right of individual progress bars show that these two participants achieved 95% correct word recognition with the 100 English words used in the present study. The next group of six participants (P02, P03, P04, P09, P11 and P12) passed phoneme identification on Day 8, learned 50 words on Day 9, and tried all 100 words on Day 10. Their word recognition rate with 100 words ranged from 50% to 90% correct. The next two participants (P01 and P05) took longer to reach the phoneme identification criterion on Day 9, and tried 50 words on Day 10. The last two participants (P07 and P10) learned the 39 phonemes by Day

10 but never progressed to words. For the top eight participants who progressed to 100 words, their word recognition accuracy on Day 10 was 80.0%±5.9% correct.

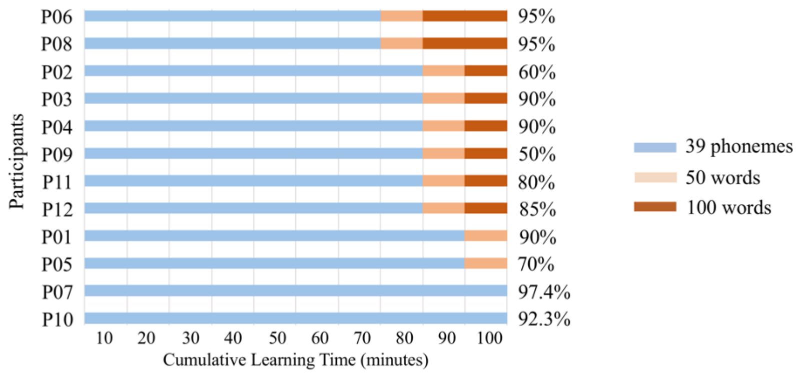

Fig. 4. Individual progress of participants P01 to P12 over the 10-day learning period with the phoneme-based approach. Shown on the right are their final performance levels on Day 10.

A more detailed look at the percent-correct scores per learning day is shown in **Fig. 5**. Since all 12 participants performed the same phoneme learning tasks during Day 1 to 7, their individual percent-correct phoneme identification scores for each 10-min learning period can be compared directly (left panel of **Fig. 5**). Also shown as the solid line is the daily average which remained above 80% correct. The right panel shows the word recognition performance levels for the 10 and 8 participants who learned 50 and 100 words, respectively. The average word recognition scores were 79.5% and 80.6% correct for 50 and 100 words, respectively.

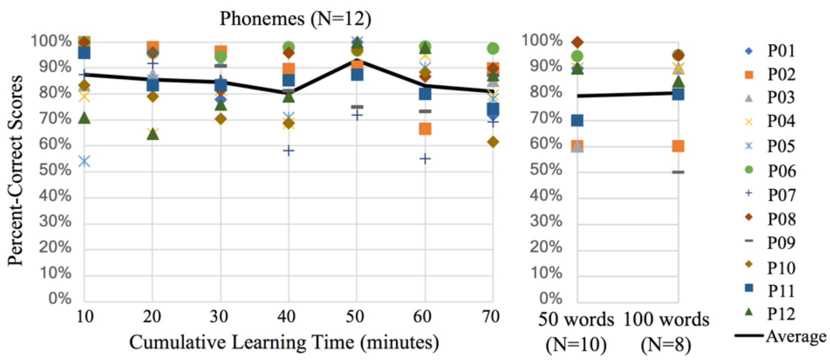

Fig. 5. Individual phoneme identification scores on Days 1 to 7 (left panel) and word recognition scores for some of the participants (right panel).

The results obtained with the phoneme-based learning approach demonstrate that all the participants were able to learn the haptic symbols associated with the 39 English phonemes with a > 92% accuracy within 100 minutes. Individual learning outcomes vary, and half of the twelve participants were able to learn the 100 English words with a > 80% correct score by the end of the 100-min learning period.

4 Experiment II: Word-Based Learning

4.1 Methods

Twelve new participants (P13-P24; 6 females; age range 19-39 years old, 25.0 ± 5.7 years old) took part in the word-based learning experiment. They were similar to P01-P12 in terms of handedness, language background and early childhood musical training.

With the word-based learning approach, all participants started with the learning of words on Day 1. To gradually increase the difficulty levels, the 100 words were divided into 8 groups with increasing number of phonemes contained in each group (see the grouping in **Table 1**). For example, the 13 words in Group 1 were made up of 6 phonemes: D, M, S, AY, EE and OO. Each successive group contained 12 to 13 additional words with 4 to 5 additional phonemes, as shown below.

- Group 1: 13 words (6 phonemes)
- Group 2: Group 1 + 13 words = 26 words (10 phonemes)
- Group 3: Group 2 + 12 words = 38 words (15 phonemes)
- Group 4: Group 3 + 13 words = 51 words (20 phonemes)
- Group 5: Group 4 + 12 words = 63 words (25 phonemes)
- Group 6: Group 5 + 12 words = 75 words (30 phonemes)
- Group 7: Group 6 + 13 words = 88 words (35 phonemes)
- Group 8: Group 7 + 12 words = 100 words (39 phonemes)

The participants split each 10-min learning period between free play and practice test with the word group for the day. Afterwards, a word identification test was conducted without any feedback. The word test was conducted with a closed set of words shown on the computer screen and the participant responded by typing the word that was just felt on the forearm. A performance level of 80% correct had to be reached before a participant could move onto the next word group. This criterion was based on the average performance level of the 8 participants in Exp. I who reached all 100 words by Day 10. The process continued until 10 learning days were completed. If a participant reached Group 8 before Day 10, then s/he continued with Group 8 until Day 10.

4.2 Results

Figure 6 shows the individual progress of participants P13-P24 over the 10 learning days. The cross "×" marks the day that the participant reached the 80% correct performance criterion and was qualified to move to the next word group. Of the twelve participants, 2 participants (P17 and P13) were able to reach the 80% correct word recognition rate with Group 8 (all 100 words), 5 participants (P19, P22, P18, P15, and P14) with Group 5 (63 words), 4 participants (P20, P23, P16, P21) with Group 4 (51 words), and 1 participant (P24) with Group 3 (38 words). It thus appears that there is a large gap in performance between the top 2 participants and the other 10 participants. On average, it took 21.5 minutes to learn and pass each group for the 12 participants.

Figure 7 compares the 12 participants' performance with the word-based learning approach. Since the participants could be learning a different number of words on any learning day, we derived a new performance metric called the "equivalent number of words correctly identified" by multiplying each percent-correct score with the number of words in the word list that was used in the word recognition test. This metric

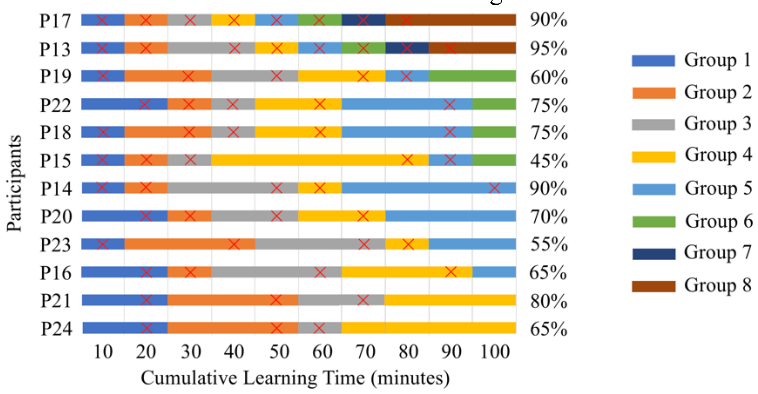

Fig. 6. Individual progress of P13 to P24 over the 10-day period with the word-based approach. Shown on the right are the percent-correct scores for the respective word lists on Day 10.

provided a common basis against which the participants' performance could be compared. It can be seen that the top two participants (P13 and P17) learned English words at a rate of roughly 1 word per minute until they reached 95 and 90 words, respectively. The remaining ten participants started to lag behind the two top performers after about 30 minutes of learning and their performance plateaued at 57 or fewer words (about half the number of words learned by P13 and P17) at the end of 100 minutes.

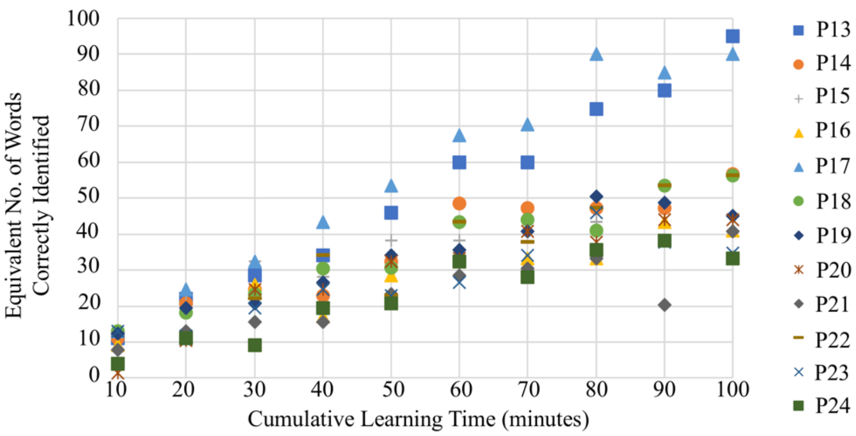

Fig. 7. Performance with word-based learning approach. See text for details.

5 Discussion

Both experiments demonstrated that participants were able to distinguish vibrotactile patterns and learn English phonemes or words presented to the skin. It is difficult to compare the two approaches during the initial stages of learning because one group learned phonemes first and the other learned words. Thus, our comparisons focus on word learning using the derived measure of "equivalent number of words correctly identified" (**Fig. 8**). Recall that the participants in the phoneme-based learning experiment did not reach word learning until at least Day 8 of the 10-day learning period. Therefore, the data from the two experiments are plotted for the last 30 minutes only for each learner. For the learners trained with the phoneme-based approach (left panel of **Fig. 8**), the equivalent number of words correctly identified was calculated for the 10 participants who were tested with 50 CV/VC words and the 8 participants who were tested with all 100 words (see **Fig. 4**). It can be seen in the left panel of **Fig. 8** that two participants (P06, P08) learned 47.5 and 50 words on Day 8, respectively, jumped to 80 and 95 words on Day 9, respectively, and both ended at 95 words by Day 10. Six participants joined on Day 9 and two more on Day 10. The dashed lines demonstrate a clear upward trend for each participant, especially the four participants in the middle (P03, P04, P11 and P12) whose performance jumped from about 39 words on Day 9 to about 86 words on Day 10. Although to a lesser extent, the two remaining participants (P02 and P09) clearly improved from Day 9 to 10. It is therefore conceivable that given more learning time, the participants in the phoneme-based learning experiment would continue to improve and eventually learn the 100 English words. Data for the learners trained with the word-based approach (right panel of **Fig. 8**) show a different pattern. There are clearly two groups of learners, with the 2 participants P13 and P17 significantly outperforming the remaining 10 participants. More critically, all participants appear to be reaching plateaus from Day 8 to Day 10, leaving it unclear whether the 10 participants in the lower group would ever reach 100 words.

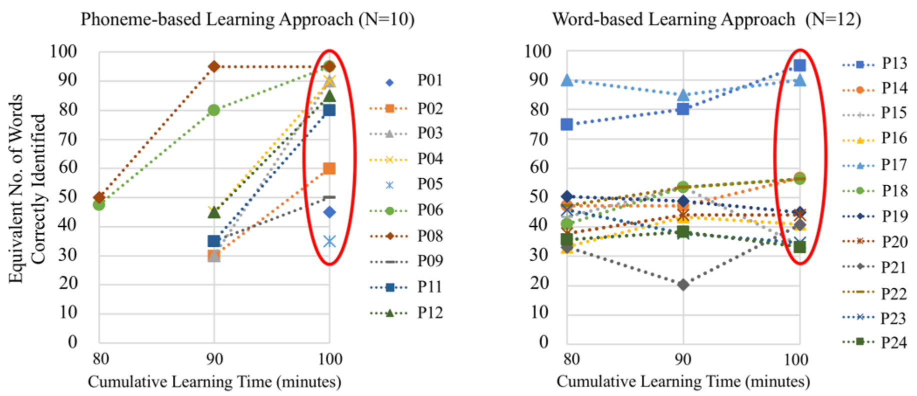

Fig. 8. Performance comparison of (left) phoneme-based and (right) word-based approaches.

Focusing on the last day of performance for both learning approaches (see encircled data points in **Fig. 8**), it is apparent that word acquisition levels at 100 minutes vary significantly among the participants in each group. On the one hand, both approaches are feasible in that there are examples of highly-performing participants with scores above 90% correct for 100 words in either approach. On the other hand, the distributions for the two approaches suggest that the phoneme-based approach would be a safer and more reliable choice. With the phoneme-based approach, half of the 12 participants learned 80 or more words in 100 minutes. In contrast, only 2 of the 12 participants with the word-based learning approach learned more than 80 words.[1] The comparatively poorer performance of the word-based learners may be considered in light of the phoneme-based approach taken in constructing the words, which may have introduced a bias in favor of the participants who were introduced to the phonemes.

The current study demonstrated that 10 of the 24 participants were able to achieve proficiency on a 100-word haptic vocabulary composed of 39 phonemes within 100 minutes of training. These results may be compared to other recent studies also concerned with the acquisition of words through haptic displays. Zhao et al. [22] mapped 9 phonemic symbols to 6 tactors on the arm and trained participants to recognize words composed of these symbols. After roughly 30 min of training, participants could recognize 20 words at an accuracy of around 83%. Turcott et al. [8] also included a phonemic approach to encode 10 symbols using 16 tactors on the arm. The participants achieved an accuracy of 76% correct on 20 words after 50 min of training. Novich developed and tested a spectral-based haptic vest containing 27 tactors to present 50 words in a 4-alternative forced-choice identification paradigm [7]. After 11 to 12 days of training with 300 trials per day, participants achieved scores of 35-65% correct (chance = 25%). Thus the results obtained in the present study in which 39 phonemes were used for word construction compare favorably to these other studies. For the phoneme-based learners in the present study, 10 of 12 were successful at identifying 50 words with an average score of 80% correct (chance = 2%) and 8 of 12 achieved an average score of 80% correct with 100 words (chance = 1%).

The results reported here provide insight for future work on improved training protocols that minimize the amount of time required to achieve criterion levels of performance on word recognition. Our ultimate goal is to develop a haptic speech communication system for people with all levels of sensory capabilities.

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[1] Debriefing with participants after the experiments revealed that even though 8 of the 12 participants with the word-based approach noticed on Day 1 the repeating haptic symbols associated with the phonemes making up the words, only 2 of them were able to "decode" the phonemes successfully. These two top performers then focused on the learning of new phonemes on subsequent learning days and contrasted them with the old phonemes learned on previous days. The other participants appeared to be less efficient at learning the haptic symbols for phonemes. As more phonemes and words were added to the task, learning became even more challenging since confusions with similar haptic symbols remained unresolved.

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