Haptic Communication of Language

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(Tutorial paper)

***Abstract*—In this review, the development of communication systems and devices that convey language tactually is examined, first from an historical perspective focusing on the communities who use the tactile modality to substitute for impairments in vision and/or hearing. Then, the more recent developments in wearable tactile communication systems for conveying text and speech to those without sensory impairments are reviewed. The performance of tactile display technology developed for these user communities is discussed in the context of the proficiency achieved by skilled users of natural methods of tactile communication. In tracing the history of tactile devices used to convey language, it is evident that technological advances in other domains, such as screen readers and speech synthesizers for the visually impaired and cochlear implants for those with hearing loss, have had a profound impact on the requirements for effective tactile language systems. For some communities, such as the Deafblind, it is essential that the tactile communication platform is bi-directional so that the user can both send and receive language. Devices developed to address such needs have yet to achieve commercial success. Recent research on wearable tactile displays has highlighted the importance of extensive training for learning and retaining languages presented tactually.**

***Index Terms*—Braille, information transmisson, phonemes, speech, tactile, tadoma, text.**

I. Introduction

THIS review focuses on how the sense of touch has been used to communicate language first from an historical perspective, and then focusing on more recent research on wearable tactile displays developed to communicate text and speech. A broad spectrum of systems and devices has been developed for this purpose, ranging from natural methods of communication such as tactile sign language, to devices like refreshable braille displays that present letters to the fingertips of users. Since many of these systems involve the hand as the site of interaction, tactile displays fabricated for language communication are often designed from the perspective of using the motor and sensory capabilities of the hand. A recent review [1] of tactile devices developed for displaying language focused only on systems that did not involve the hands (hands-free), and so did not examine the full spectrum of tactile language communication systems, particularly those involved in expressing language. In this review we consider both natural methods of language communication involving the sense of touch and tactile devices that present language on the skin. The evolution and performance of tactile display technology is discussed in the context of the proficiency achieved by skilled users of natural methods of tactile communication. Sign languages that are interpreted visually, are not included in the review.

In examining the various systems and devices that have been developed to communicate language tactually, it became clear that the different communities of users provided a framework for organizing this review. Four clear categories of users emerged that can be distinguished on the basis of the aspects of language that are presented tactually. These groups and associated language systems are depicted in Table I. First, there are the communication systems and devices used to present text on the skin with the goal of enabling people who are visually impaired to read. The second category relates to representing characteristics of speech with the objective of assisting people with hearing impairments to understand spoken language. The third group encompasses the systems and devices that have been developed to enable those who are both deaf and blind to understand speech. Finally, there is the more recent work that has focused on using the skin as a medium of language communication for individuals who have intact hearing and sight. In this application the objective of the tactile device is to offload the overworked visual and auditory systems using a neglected sensory channel. When examining how language is represented tactually in each of these areas, a distinction is made between phonology (the system of sounds of a language) and orthography (the spelling system of a language).

II. Historical Overview of Tactile Language Communication

A. *Systems for the Visually Impaired*

Some of the earliest tactile systems for language communication were developed for the visually impaired and involved presenting letters on the skin. In the seventeenth century the Italian Jesuit scholar Francesco Lana de Terzi proposed a system of letters represented by dashes on the skin that would enable the

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TABLE I
TACTILE LANGUAGE COMMUNICATION SYSTEMS AND DEVICES DEVELOPED FOR DIFFERENT COMMUNITIES OF USERS

Visually Impaired/Blind	Hearing Impaired/Deaf	Deafblind	Intact vision and hearing
Text	Text - Speech - Signing	Text - Speech - Signing	Text - Speech
Braille alphabet Moon alphabet	Fingerspelling Tactile speech aids Sign Language	Lorm alphabet Tactile fingerspelling Finger braille Tadoma Tactile sign language	Letters Tactons Phonemes
Communication Devices (representative)			
Braille Refreshable braille Optacon Visotactor Optohapt Vibraille	Tactaid 1, 2, 7 Queen's Vocoder Tacticon 1600 Tickle Talker Portapitch	Lorm glove dbGlove UbiBraille Hapticomm	Vibratese Tactile Glove TAPS MISSIVE WhatsHap

Blind to read. Although he did not pursue the use of this system in educating the Blind, his contribution lies in recognizing that an alphabet for the Blind does not have to replicate the physical form the sighted use. A century later in 1785 Valentine Haüy founded the first school for the Blind in Paris where he adapted the reading system of sighted people by printing the Roman alphabet in relief form for the Blind. It was this school that Louis Braille attended at the age of ten in 1819 where he was taught raised-letter reading. A different form of tactile writing had been developed around this time by a French Army captain, Charles Barbier, whose goal was to create a communication system that could be used by soldiers to read battle commands silently and in the absence of light. It was known as night writing and was based on a 12-dot (6×2) matrix [2]. Louis Braille recognized the two limitations of Barbier's alphabet: first, that the 12-dot matrix was too large in that it required moving a fingertip across each pattern to decode it, and second, that each pattern should represent a letter rather than a sound (phoneme). These limitations were overcome in the tactile alphabet that bears his name in which individual letters are represented by the pattern of raised dots in a 3×2 braille cell. A further important contribution of Louis Braille was adapting a slate writing device that Barbier had devised so that the Blind could write as well as read [3].

The six-dot braille cell can produce 64 unique patterns including a blank cell which enables punctuation, common letter combinations and whole words to be represented in addition to the basic alphabet for many languages. From its inception, braille has been able to convey mathematical notation in addition to musical scores. Interestingly, the physical structure of each braille cell used at present with an inter-dot distance of 2.28 mm and a dot height that varies from 0.38 mm to 0.51 mm, depending on the printing materials, is very close to that originally proposed by Louis Braille. These values have been shown to be optimal in terms of reading speed and accuracy. When printed, braille is a static display that is read by moving the fingers across the line of text from left to right.

Although braille has been the most extensively used tactile alphabet, other alphabets have been proposed over the years to provide the visually impaired with access to text. One such system was developed by William Moon in the 1840 s in which letters of the Latin alphabet were represented by raised shapes, many of which bore some similarity to the written form of the letters being depicted [4]. One feature of reading the Moon alphabet that differentiated it from braille was the change in the direction of the text on alternate lines so that the finger scanned from left to right and then right to left on each successive line. While not achieving the pervasive use of braille, the Moon system has survived, particularly in the U.K.. It is considered easier to learn than braille and has primarily been used by people who have lost their vision later in life.

Beginning in the 1950 s, a number of direct translation reading aids were developed for the visually impaired in which an optical character recognition device, such as a camera or a probe, was moved across text and the image of letters was then converted into a two-dimensional tactile pattern typically displayed on the fingers [5]. One early device was the Optacon (OPtical to TActile CONverter) developed by Bliss in the 1960 s that converted printed letters into a spatially distributed vibrotactile pattern on the fingertip using a 24 by 6 pin array [6]. A small hand-held camera was used to scan the text with one hand and an image roughly the size of the print letter was felt moving across the tactile display under the fingertip on the other hand. Reading rates with the Optacon were much slower than those achieved with braille, with 85% of 100 blind users in one study reporting that they could read at rates between 30 and 60 words per minute after a year or two of experience [7]. Two highly proficient users were able to achieve reading rates of 70–100 words per minute. At the time of its development, the Optacon was one of the first devices that provided visually impaired people with immediate access to text and graphics [8].

A device related to the Optacon was the Visotactor that imaged a narrow slit in the text using eight photocells that were mapped onto an array of eight stimulators, two per fingertip vibrating at 150 Hz. In this device, the stimulators were built into the optical probe and reading rates in the order of 30 words/minute were reported [9]. The Kinotact was based on a mapping system similar to the Visotactor with a 10-by-10 array of photocells that was used in conjunction with a 10-by-10 array of vibrators mounted on the back of a chair to display block letters. When the light to a specific photocell was switched off the corresponding vibrator would be activated. The focus of research on the Kinotact was the spatial-temporal mapping of visual images to vibration patterns, rather than letter recognition rates [10]. A different approach was adopted by Geldard in the development of the Optohapt which used nine spatially dispersed locations across the body to present vibrotactile signals that were mapped to the output of a photoelectric device encoding text [11]. For this device it was determined that a presentation rate of 70 characters per minute was appropriate for users to discern the tactile signals.

The Optacon was the only one of the tactile reading aids described above that achieved widespread use. Over 15,000 Optacon devices were sold between 1970 and 1990, but by the mid-1990 s such aids were replaced by page scanners with optical character recognition which were less expensive and easier for people with visual impairments to learn to use [12]. These in turn have been replaced by speech synthesizers and screen reader technologies such as Job Access with Speech (JAWS) and Non-visual Desktop Access (NVDA), among others.

B. Systems for the Deaf and Deafblind

The introduction of natural methods of tactual communication can be traced to educators of deafblind children in the mid-to-latter part of the 19th century. Emerging from within the deafblind community, these methods do not involve the use of any artifical device. Instead the hands of the deafblind receiver are used for direct tactual sensing of either the speech or manual signals produced by a sender. The tactual reception of speech was introduced in Norway in the 1890 s by a teacher named Hofgaard in the education of a deafblind student. Hofgaard taught his student, Petra Heiberg, to both understand and produce speech by placing her hand on his face while he was speaking. In this method, which was later referred to as Tadoma (based on the combination of the first names of two American students, Tad Chapman and Oma Simpson), one or both hands of the receiver are placed on the face of a talker such that the thumb rests lightly over the lips and the fingers fan out over the cheek and neck. The tactual cues that can be felt through this system include up-down movements of the lips and jaw, vibration on the face and neck, and airflow at the lips. These cues have been shown to be sufficient for learning both to receive and produce speech (see [13], [14], [15], [16]). This method enjoyed popular use in schools for the Deafblind throughout the United States in the period between 1920 and 1960 [17].The use of Tadoma as the sole method of instruction has declined since then (primarily due to changes in the etiology of deafblindness and associated impairments in children), but it continues to be used as a supplement to other methods in institutions across the United States [18].

Another early approach to the education of deafblind persons involves the tactual reception of the manual alphabet, which was originally developed for the education of sighted deaf persons. The use of this method was reported for the education of a deafblind student named Laura Bridgman by Dr. Samuel Howe at the Perkins School for the Blind in Watertown, MA (USA) in the mid-1800 s. Most famously, this method was used by Anne Sullivan (herself a graduate of the Perkins School) in the education of Helen Keller beginning in the late 1800s [16], [19].

The first systematic studies of artificial devices for transmitting speech information through the tactile sense were conducted by R. H. Gault and colleagues during the 1920 s and 1930s [20], [21], [22]. Their earliest approach involved the application of the raw acoustic speech signal directly to the skin by speaking into a hollow tube, and was later followed by the use of amplified speech which was presented through a hand-held earphone driver. The most advanced tactile device developed and tested by these early investigators involved filtering the speech signal into five frequency bands each of whose outputs was presented to one of five earphone drivers held in the fingers. This device was used for training and testing deaf persons on the reception of speech through the tactile aid alone and in combination with lipreading. The device was limited by the inability of the skin to perceive much of the information in the high-frequency bands due to the rapid increase in tactile thresholds above 500 Hz [23].

A solution to this problem was achieved in work conducted by Wiener et al. (1949–1951) [24] in the development of FELIX, which applied vocoding technology to the development of a tactile speech communication device. As in Gault [22], Wiener's device also employed filtering of the acoustic speech signal into five spectral regions; however, rather than applying the raw output to a transducer a signal transformation was employed to accommodate the perceptual characteristics of the tactile sense. This transformation first involved detection of the envelope of the acoustic signal within each frequency band, and then using this envelope to modulate the amplitude of a 300-Hz tone at each of five locations (the fingertips of one hand). This modification allowed for detection of the tactile signal within each of the five spectral bands. Although limited evaluations were conducted with the FELIX device, its use of a vocoder approach has formed the basis for the design of many tactile speech-communication devices over the ensuing years.

C. Tactile Communication Capacity of Those With Intact Vision and Hearing

In the 1950 s, there was interest in exploring the communication capabilities of skin and the sense of touch which was perceived as an intermediary sense in terms of its spatial and temporal processing capacity. That is, touch is not as efficient as the ear in temporal discrimination but is superior to the

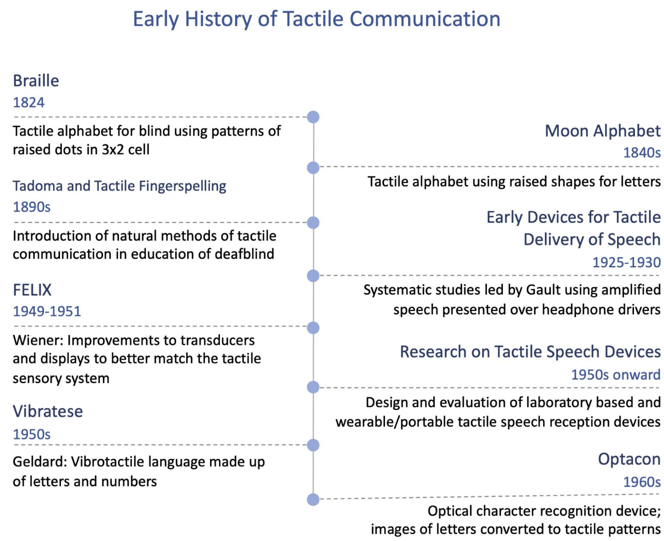

Fig. 1. Timeline of major historical developments.

eye in this respect, and shares with the eye a capacity (more limited) for spatial discrimination which is better than that of the ear [25], [26]. A tactile language called "Vibratese" was developed to explore the possibilities of communication via the skin [27]. It consisted of 45 basic letters and numbers each of which was mapped onto a unique vibrotactile pattern that varied with respect to intensity (three levels), duration (three magnitudes), and location on the chest (five). Vibratese was initially tested on three individuals who were able to learn the language in only 12 hours with one individual reaching a plateau at a receiving rate of 38 words per minute [27]. However, as groundbreaking as Vibratese was, this communication method was considered arduous to learn and it was not until the advent of small, lightweight and inexpensive actuators that could be wirelessly controlled that we see an explosion of interest in tactile communication systems for those with intact hearing and vision (see Section IV). A timeline of the major developments described in this historical overview is provided in Fig. 1.

III. Haptic Language Systems

A. Structure of Language

Tactile communication has been explored for spoken and written forms of language, with the ultimate goal of conveying messages constructed with the grammatical, semantic, syntactic, and prosodic rules used to create the sentences of a particular language. In many of the tactile devices described here, the fundamental units of phonemes for speech and alphabetic characters for text are used to create messages following the grammatical rules of the language. The suprasegmental aspects of speech (including pitch and stress) may or may not be conveyed, depending on the particular type of device. For the purposes of this paper, a brief summary is provided below of the properties of the basic units of speech (phonemes) and of text (alphabetic characters).

1) Speech: Speech is produced by specialized movements of the human vocal system [28], [29], consisting of a passageway starting at the lungs and progressing upwards through the trachea, larynx, pharynx, nose, and mouth. Exhaled air passing through the lungs provides the source of energy for speech production, and vibration of the vocal cords produces an audible buzz that is modified by the acoustic properties of the vocal tract. Different speech sounds are created by various movements of the vocal-tract articulators including the tongue and lips. These articulatory properties correspond to the phonemes of a given language, defined as those sounds that are perceptually distinct to speakers of that language. A complete description of the sounds across all the spoken languages of the world is contained in the International Phonetic Alphabetic [30] where each distinct sound is associated with a unique symbol.

TABLE II
Phonemic and Orthographic Features of Languages Associated With Tactile Inputs

Basic Elements of Language Mapped onto Tactile Signals	
Phonemes	f ō n ē m
Alphabetic characters	a b ö ä
Groups of letters	
Shortform words	and for with
Contractions	ing st dis ed
Words	send mail come
Groups of words	
Tactons	Turn to the right Important message Meeting in 5 minutes

All languages have an inventory of sounds, which nearly always includes vowels and consonants. Vowels are produced with a relatively open configuration of the vocal tract accompanied by vocal-cord vibration (or voicing) and are distinguished from each other through different positioning of the tongue and lips. In terms of their acoustic properties, vowels are characterized by resonant frequencies in the vocal tract that are described with reference to the frequency, bandwidth, and amplitude of the formants (i.e., resonant frequencies of the vocal tract) present in the spectrum. Consonants, which may be voiced or unvoiced, are formed by constrictions or the release of complete blockages at various places in the vocal tract, with noise arising from the resulting turbulent air flow. In addition to the feature of voicing, consonants are distinguished by different manners and places of articulation. Acoustic descriptions of consonants include spectrotemporal properties such as the spectral shape and duration of turbulent noise bursts, the frequency and duration of formant transitions between consonants and vowels, the presence of low-frequency energy associated with nasality, and voice onset time (the duration between the release of a noise burst and the onset of laryngeal vibration). Different languages are distinguished by the particular vowels and consonants that are used to create perceptual distinctions in the formation of words, and in tone languages different pitches and pitch patterns can be applied to words to create different meanings.

2) Text: Orthography is defined as the representation of the sounds of a language by written or printed symbols (see Table II).

Alphabets have evolved for this purpose, some of which are more consistent than others in relating alphabetic characters to the phonemes of the language [31]. The orthography of some languages, referred to as shallow, is closely tied to the phonemic system with a nearly one-to-one correspondence between a phoneme and a written character (e.g., Spanish and Finnish). Other languages have a deep orthography, in which there is a more complex relationship between written characters and phonemes (e.g., English and Hebrew). In English, for example, the Latin alphabet has only 26 letters for representing the 44 phonemes, and there are many irregularities in the spelling of English words. In writing systems based on alphabetic characters, a grapheme is defined as a written symbol that is used to express a given phoneme, and can consist of one or more letters. In some written languages there is a close (but not one-to-one) correspondence between phonemes and graphemes, while in other languages a given phoneme can be represented by multiple graphemes. For example, in English the phoneme /k/ is represented in the spelling of different words as k, c, ck, ch, qu. The 44 phonemes of English are represented by an estimated 284 graphemes in the spelling of English words [32].

B. Braille

A braille code is available for over 120 languages, enabling the visually impaired to read and write. A skilled reader of braille generally uses the index finger on each hand to move across lines of text at a relatively fast and constant speed, while maintaining a low contact force to facilitate detecting the raised dot patterns. Most braille readers prefer to use two hands rather than one, and bimanual reading is faster than unimanual reading, in part because it enables faster transitions between lines of text [33], [34]. One finger can be used for reading the textural information and the other finger can process more spatial information such as inter-letter or inter-word spaces and ensure type alignment. Some braille readers use the left hand to read the first half of the line and then the right hand reads the remainder of the line while the left hand moves back to locate the beginning of the subsequent line. Proficient readers can read braille at around two words per second which is about one half to one quarter the rate typically achieved for visual reading of English text (five words per second) [35]. At this reading rate, a single index finger scans 100-300 separate braille cells in 60 seconds. Scanning speed, that is the speed of intra-cell scanning, does not change substantially as a function of reading proficiency and so probably represents a basic parameter of the braille reading process, similar to saccades in the visual system [36].

In English, the braille code has two main levels of complexity, the first of which allocates 26 of the 63 available dot patterns to letters of the alphabet and other patterns represent punctuation marks. The remaining dot patterns are not assigned any meaning. In Grade II braille, these remaining dot patterns are used to represent groups of letters that occur with high frequency in English (e.g. ing, st), called contractions, and abbreviations of words, called short-form words (see Table II). The reading rates reported for highly proficient braille readers are from this Grade II category in which it is not only single letters that are being encoded in each cell. Although the mean or median reading rate of proficient braille readers is reported to be around 90 words per minute (wpm), braille reading rates as fast as 200-300 wpm have been reported [37].

Over the past 20 years, the enhanced availability of electronic formats for printed materials has enabled the visually impaired to access a vast spectrum of reading material that was previously unavailable. For most blind computer users, speech is the preferred mode for interacting with this material since compared to braille it is relatively inexpensive and does not require specialized hardware to access [38].

Refreshable electronic braille displays that render braille characters dynamically enable visually impaired individuals to read text on any computer or mobile device. In these displays movable pins generate a single line of braille text with between 40 and 80 characters from a screen being displayed, depending on the particular electronic braille model [39]. One factor limiting their more widespread use is the high cost of refreshable braille displays, which in part reflects the actuation requirements, namely a compact form factor and high refresh rate. Actuator technologies other than the piezoelectric bimorphs typically used in displays at present are being explored for use in refreshable displays; these include electromagnetic motors, electro-active polymers, electro-rheological fluids, shape memory alloys and thermo-pneumatic actuators [40]. To date, none of these technologies has garnered widespread support due to issues associated with, among other things, power consumption, operating voltages, cooling requirements and manufacturing costs.

C. Methods Used by the Deafblind

Natural methods of tactual communication not involving the use of an artificial device have emerged out of necessity within the deafblind community. These include the Tadoma method of speechreading, the tactile reception of sign language, and the tactile reception of fingerspelling. These methods are based on direct application to the skin of methods of communication originally intended for the auditory or visual modality.

1) Tadoma: In the Tadoma method of speechreading, the deafblind person gains access to spoken speech by placing one or both hands on the face and neck of the speaker. Mechanical actions that occur during speech production, such as lip and jaw movements, airflow at the lips, and laryngeal vibration, are monitored through the tactile sense and used to understand speech. Although the use of Tadoma is in decline, this method is important to the field of tactile speech communication in its demonstration of the capacity of the tactile sense for communication, and in particular for the understanding of speech which requires no special training on the part of the speaker. The speech-reception abilities of experienced adult users of the Tadoma method have been documented through laboratory studies with various types of speech materials. These results are summarized here using data from in-depth study of three highly experienced Tadoma users [41], [42]. Identification of monosyllabic words from an unrestricted vocabulary was roughly 40% correct. This score was higher than predicted based on performance at the phonemic level. Identification of 24 initial consonants (C) in C-/a/ context and of 16 medial vowels (V) in /h/-V-/d/ context was roughly 60% correct. The reception of key words in conversational sentences, in turn, was higher than expected from the word scores: sentence scores were roughly 85% correct for a speaking rate of 2.5 syllables/sec (half that of the normal speakiing rate). These results strongly suggest that knowledge of the semantic and syntactic properties of English contributed to the Tadoma users' ability to understand connected speech [43].

2) Tactile Sign Language: A tactile communication method used by individuals who are both deaf and blind is the haptic reception of sign language. This method is generally employed by deaf people who acquired sign language before becoming blind [44]. The deafblind individual perceives the signs produced by the signing hand(s) by placing a hand or hands over the signer's hand(s) and follows the motion of the signing hand(s) using tactile and proproprioceptive cues. There are regional variations in the reception of tactile sign languages which may be one-handed (e.g., in the United States, Sweden and France) or two-handed (e.g., Norway and Australia), depending on a number of factors including the language itself and the community that uses it [45]. Typical communication rates achieved with haptic reception of American Sign Language (ASL) or Pidgin Sign English (PSE) are lower than those with visual reception of signs, 1.5 signs/second as compared to 2.5 signs/second, and errors are more common with tactual reception [46], [47]. In a group of ten deafblind participants, Fischer et al. [47] reported that for the tactual reception of conversational sentences using ASL or PSE, scores for key signs ranged from 73% to 96% correct as compared to an average of 90% correct for visual reception of ASL. Nonetheless, this haptic method of communication is effective in deafblind individuals who are skilled in its use, and the levels of accuracy achieved make it an acceptable means of communication. The laboratory study reported here was concerned with the reception of key signs in sentences; however, the practical use of tactile sign language involves numerous additional non-linguistic aspects to enhance aspects of the two-way communication between the sender and receiver. Recently, there has been a movement within the deafblind community in the United States to create a new form of tactile communication, known as "Protactile" which modifies and diverges from tactile ASL including the use of "backchanneling" to convey signals associated with active listening, such as head nodding and brief verbal expressions of agreement or disagreement, to the deafblind receiver through tactile cues [48], [49]. For similar reasons, a method known as Social-Haptic Communication has been introduced in northern Europe to share information about the environment and orientation in space with a deafblind person [50].

3) Tactile Fingerspelling: Fingerspelling consists of a letter-by-letter representation of the words that would occur when speaking. The letters of AOHMA (the American One-Handed Manual Alphabet) are characterized by different handshapes and configurations that are typically received through the visual modality (see Fig. 2). In the United States the most commonly used manual alphabet is AOHMA. Although the AOHMA is used primarily to complement ASL, it has also been employed

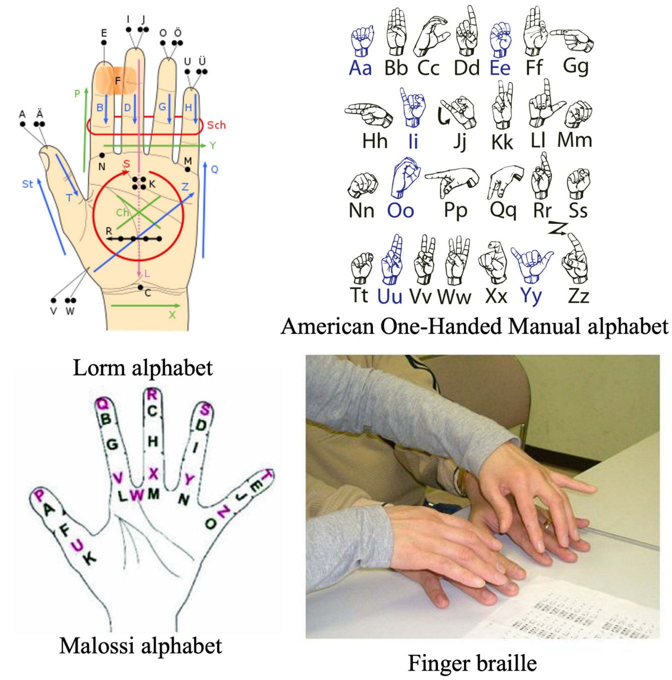

Fig. 2. Upper left: German Lorm alphabet: letters are encoded using gestures traced across the skin and contact with specific locations. Upper right: American One-handed Manual Alphabet. Lower left: Malossi alphabet in which letters are indicated by either pressing (black letters) or pinching (purple letters) specific locations on the hand [52]. Lower right: Finger braille in which the six dots of a braille cell are mapped onto six discrete locations on the fingers. Reprinted from [53] with permission of the IEEE.

as a primary means of communication for deaf persons (as in the Rochester Method). The tactile reception of fingerspelling is most commonly used by persons with onset of deafblindness in adulthood, after the acquisition of speech and language through the auditory modality or through oral education for deaf persons. In the tactile reception of fingerspelling, the deafblind receiver places a hand in contact with the hand of the sender to feel the various shapes and configurations of the hand in producing the letters of AOHMA. Studies conducted with experienced deafblind users of tactile fingerspelling indicate a high level of accuracy for the reception of key words in conversational sentences [51]. For conversational sentences produced at rates of two to six letters/sec (the maximum rate that could be achieved by the tester), scores ranged from 85-100% across deafblind participants. This performance was similar to that obtained for sighted deaf receivers of fingerspelling. The communication rates achieved with tactile fingerspelling, however, are somewhat lower than those obtained with either Tadoma or the tactual reception of sign language. Estimates of effective communication rates in bits/sec across these three systems of tactual communication [35] indicate that tactile reception of fingerspelling (7 bits/sec) is roughly twice as slow as either Tadoma or tactual reception of ASL (both with rates of approximately 12 bits/sec).

4) Other Tactile Alphabets: Braille represents one type of tactile alphabet in which letters are defined in terms of the raised dots in a braille cell. A number of other tactile alphabets have been developed over the years which in their simplest form rely on hand-to-hand communication between a speaker and listener. Typically the letters are presented on the receiver's palm and fingers by the speaker (see Fig. 2). Such alphabets have been used by people who are deafblind and, as with all languages, various tactile languages have evolved in different countries. The Lorm alphabet which is used in Austria, Germany and Poland was developed in the late nineteenth century by the Austrian writer Heinrich Landesmann who wrote under the pseudonym Hieronymus Lorm [54]. This was a precursor to the Malossi alphabet developed in Italy [52] and the deafblind manual alphabet used in the U.K. [55]. As can be seen in Fig. 2, these alphabets can be distinguished in terms of how the speaker's and listener's hands interact and the manner in which the fingers and palm of the hand are touched. The Lorm alphabet encodes letters using both gestures in which lines and shapes are traced on the skin and contact with specific locations on the hand. All letters in the Malossi alphabet are represented at specific locations on the digits and palm. In addition, when making contact with the receiver's hand at each location the speaker either presses or pinches the skin surface to further aid character identification [56].

Other tactile languages used by the Deafblind include finger braille that maps the six dots of a standard braille cell onto six discrete locations, three on each hand. Finger braille is a communication system widely used in the Japanese deafblind community and is universal in the sense that braille is the underlying alphabet. The Japanese braille code system consists of 46 characters including both kana characters and special codes [57]. Braille characters are written directly by the speaker on the index, middle and ring fingers of each hand of the listener, as if the fingers were a braille keyboard (see Fig. 2). The speaker may be adjacent to the listener or face them directly [53].

The type of tactile communication system used by deafblind individuals often depends on the relative degree of hearing and vision loss and the time of occurrence of the loss. Some people who are deaf and later become blind may be skilled in sign language, whereas people who are blind and later become deaf may be proficient in reading braille [45]. All of the above tactile languages require that both the speaker and listener are trained in the language of communication. Since only a small percentage of people with intact hearing and vision have such a skill set, the simplest way for them to communicate with deafblind people who are familiar with the alphabet is to trace out block letters on the palm of the listener's hand. This system has been referred to as Spartan and is the slowest of all tactile communication systems [58].

D. Tactile and Kinesthetic Morse Code Reception

Tactile Morse code has been explored as an avenue of communication for those with visual and/or auditory impairments, although most of the research conducted to date has involved individuals with normal vision and hearing (e.g., [59], [60], [61], [62]). In the typical implementation of tactile Morse code, the duration of a dot (one unit) is around 100 ms and a dash is 300 ms (three units) which means that a typical five-letter word such as "touch" takes over 3 seconds to present. For auditory Morse code, the duration of dots and dashes is proportional rather than fixed, with the code being transmitted at the highest rate a receiver can decode.

A number of variables have been studied in experiments on tactile Morse code, including determining the optimal training strategy [62], examining whether the location on the body where the vibration motors are mounted affects learning [61], [63] and evaluating how prior experience with auditory Morse code impacts the acquisition of tactile Morse code [60], [63]. In most of these experiments the time spent training participants to identify letters has been short, typically less than 45 minutes, and usually only a subset of letters in the alphabet has been learned and tested (e.g. 12–15 characters). With these limitations in mind, it has been shown that participants can learn such a limited set of characters and then identify words created using these letters, but their ability to do so decreases rapidly as a function of word length. For example, Plaisier et al. [62] reported that 75% of words with two characters were identified correctly after 30 minutes of training but that when the word length increased to four characters performance was now around 8% correct. The difficulty with word reception is not unique to the tactile modality. Research on auditory Morse code reception has shown that it can take three to four months of training before a person develops the ability to receive multiple letters as a "chunk," that is, a word [64].

When different sites on the body have been compared, the ability to identify tactile Morse code has been found to be superior on the hand as compared to the wrist and the abdomen, and signals presented on the wrist are easier to identify than those on the abdomen [63]. These findings are consistent with the tactile sensitivity of the locations being tested. It is also possible to vary the locations at which dots and dashes are presented, for example by placing one vibrating motor on the left arm and the other on the right. Under these conditions, the ability to identify letters is considerably better than when a single motor is used at one location [61]. In one study with two participants who were Morse code operators electrocutaneous stimulation was used to deliver tactile Morse code [59]. Following limited practice with the tactile stimulus, one participant was able to receive ten five-character groups of code per minute with an accuracy of 96%.

Tan et al. [60] used the full set of 26 letters in training their participants with Morse code reception using motional (up-down finger movements with $\approx$ 10 mm displacement) and vibrotactile stimuli, and compared the performance to that with auditory stimuli. The participants included two experienced ham radio operators and two people who had no prior experience with Morse code. Although all participants learned to receive single letters and 3-letter random sequences with comparable learning time and performance levels, the experienced participants outperformed the inexperienced participants at recognition of common words that contained at least seven letters per word. The experienced participants went on to perform sentence reception whereas the two inexperienced participants were unable to perform the task after 75 hours of training. It was clear that prior experience with auditory Morse code facilitated the learning of tactile and kinesthetic

Morse code when the task became more complex (i.e., long words and sentences). The equivalent reception rates (product of percent-correct scores and stimulus presentation rate) were nearly twice as high for auditory presentation as for vibrotactile stimulation, which in turn was about 1.3 times that for motional stimulation. The rates varied from $\approx$10 wpm (inexperienced participants with motional and vibrotactile Morse code) to $\approx$40 wpm (experienced participants with auditory Morse code). The corresponding information transfer rates were estimated to be roughly 1.3 to 5.4 bits/sec (see note 6 in [60] for explanation of conversion).

IV. Tactile Devices for Encoding Language

Over the past 20 years there has been an explosion of interest in developing wearable systems that incorporate some form of tactile communication be it an alert or more detailed notification. Much of this was been made possible by advances in actuator, battery, and microprocessor technology, as well as in wireless communication systems. These developments have enabled the fabrication of wearable tactile displays that can be used to assist in navigation, monitor health/wellness/exercise or directly communicate language. For the latter application, tactile devices have been designed for use by those with sensory impairments as well as those with who are unimpaired, with the objective of enhancing the communication options available to the user, as detailed in the following sections.

The performance of the various tactile devices that have been designed and built to encode speech or text has often been evaluated with reference to the system that has been traditionally used by the relevant community. For example, the reading rates associated with refreshable braille displays are compared to those achieved by proficient braille readers [40], and the performance of hand-based tactile displays for encoding letters is compared to that achieved using fingerspelling [65]. However, for many of the devices described in this section there is not a “gold standard” that can be used to assess performance and so comparisons between them are usually based on the proficiency with which users can learn to recognize or identify linguistic elements (e.g. individual letters or short words) after a period of training. As detailed below, there is substantial variability across devices in terms of the average duration of individual phonemes or letters (70–1500 ms), the period of training (5-170 hr) and the size of the vocabulary tested after training (20–250 words), which makes direct comparisons difficult. As this field matures it will be essential to develop a set of benchmarks that enable the performance of different tactile devices to be meaningfully compared.

A. Letter-Based Encoding

There has been recent work focused on developing hand-based tactile displays for encoding letters of the English alphabet. Luzhnica et al. [65] reported on the development and evaluation of a six-channel tactile glove with vibrotactile actuators that stimulated the dorsal surface of each digit and the base of the hand near the wrist. Letters were coded using one, two, or three vibrators; tactile codes with multiple vibrators employed overlapping spatio-temporal stimulation, with an average letter duration of 75 ms. Following five hours of training, participants were able to recognize the encoded letters in isolation with an accuracy of 92% correct and to identify the letters in words (ranging in length from 2 to 5 letters) with greater than 90% accuracy. In a later study, Luzhnica and Veas [66] modified their earlier display to include seven channels (with an extra motor added to the back of the hand). In this modification, the number of vibrators used to encode a letter was limited to either one or two, and letters were coded based on the statistical properties of written English, such that frequently occurring sequential pairs of letters were less likely to share a vibrator in their tactile codes. With this new version of the wearable display, letter recognition improved to 98% correct and word-recognition accuracy (using a Levenshtein distance measure) was 0.97. The transmission times included letter codes with durations as short as 70 ms and an inter-letter duration of 100 ms, with an average word length of 3.5 letters. These conditions yielded transmission rates of roughly 7 letters/sec, comparing favorably with the maximum rate of 6 letters/sec achieved with tactile fingerspelling (see Section III.C.3). Letter recognition remained high in tests conducted 10 days after the initial training, and also remained high in the presence of a competing primary task in the visual modality [67]. Different approaches to training were then examined by Luzhnica and Veas [68], who reported better performance and subjective reports of reduced workload when feedback included a visual display of the motors on the hand as compared to only a visual display of the corresponding orthographic character.

An alphabetic tactile code, called vibraille, was also developed by Liu and Dohler [69] who conceived of it as a replacement for braille in the reception of short messages. This system uses vibrotactile stimulation delivered by a voice-coil actuator held between the thumb and index finger of one hand. Two coding systems were implemented on the basis of a set of vibratory elements that were combined to encode the 26 letters of the alphabet. One system employed a set of six vibratory elements formed from a combination of three frequencies (50, 100, and 400 Hz) with two durations (75 and 300 ms), while the other employed a set of four vibratory elements using two frequencies (50 and 300 Hz) with the same two durations. In the six-element set, letters were formed by a sequence of two elements separated by 75 ms. The four-element set required a sequence of three elements to code letters, again with 75 ms between elements. Participants were first trained on the identification of individual letters and three-letter sequences and were then tested on their ability to identify a set of 90 words ranging in length from two to five letters. The interval between letters in a word was set for individual participants and averaged 422 ms. At the end of the training, both single letters and words were identified with an accuracy of greater than 90% correct for both systems, although average training times were shorter for the four-element coding system (roughly 6 hours) compared to the 6-element system (roughly 7.5 hours). The authors estimated the rate of transmission at 2.1 characters/sec for the 6-element system and 1.4 characters/sec for the 4-element system, which is roughly 2.5 to 4 times slower than for braille.

In contrast to the two previous systems that used vibration to encode letters of the alphabet, Gaffary et al. [70] developed a one-channel tactile device that stimulated the fingertip using skin stretch. Three different tactile alphabets were evaluated. First, an alphabet based on Morse Code was implemented using different durations of skin stretch for the short (300 ms) and long (900 ms) elements of the letter patterns with an inter-element interval of 300 ms. The second alphabet used skin stretch to create different patterns of movement between two locations on the motor. The starting and ending points of the patterns were at the four corners of the motor, with vertical, horizontal, or diagnonal displacements. The rate of the diagonal movements (6 mm/s) was half as slow as that of the non-diagonal movements (3 mm/s). The third alphabet was based on Unistrokes [71] in which skin stretch was used to draw spatial representations of the letters on the fingertip. The patterns were created by a series of inflection points with breaks between points, using a motor speed of 5 mm/s and break durations of 400 ms. Across the three alphabets the mean transmission rates in letters/min were 24.3 for Morse Code, 27.9 for the two-dashes method, and 20.9 for Unistroke. In five 30-min sessions, participants were asked to identify randomly presented letters for each alphabet with the aid of visual codes corresponding to each letter. Averaged over the final four sessions, the letters were identified with an accuracy of 97% for the Morse Code alphabet, 80% for the two-dashes method, and 73% correct for Unistrokes. Response times were significantly slower for the two-dashes method compared to the other two alphabets. The results indicate that with skin-stretch feedback, the temporal cues provided by the Morse Code alphabet were more easily learned than the movement cues of the other two alphabets.

B. Tactile Codes for the Display of Speech

The goal of these devices is to encode the acoustic speech signal through tactile displays which can serve as a substitute for hearing in the reception of speech for persons with severe to profound hearing loss. In one major category of devices (spectral-based displays), the acoustic speech signal is processed for conveying information to the skin. One common approach uses a vocoder-based frequency-to-place transformation that mimics cochlear processing. The acoustic speech signal has also been processed to extract various types of speech features for presentation to the skin. Much of the older research and development of tactile speech displays has grown out of this type of spectral-based approach (see Section IV.B.1). A second category of devices (phoneme-based displays, see Section IV.B.2) has emerged primarily in more recent research, in which automatic speech recognition (ASR) is assumed to be used for front-end extraction of phonemes in the acoustic speech signal which are then encoded by a tactile device. Although both categories of devices ultimately present information about the acoustic speech signal, the two approaches have different consequences for the issue of variability in the speech spectrum across different productions of the same sound. For spectral-based displays, the inherent variability in speech tokens within and across talkers is passed on to the tactile domain and ultimately to the user. For phoneme-based displays, on the other hand, the burden associated with this variability is placed on the ASR system in its phoneme identification task. A set of fixed tactile signals is then associated with each phoneme, thus simplifying the task of phoneme recognition through the tactile display.

1) Spectral-Based Displays: Spectral-based displays of speech for communication through the tactile sense include vocoder-based and feature-based displays. This area of research has a long history, and bibliographies and reviews of the literature have appeared periodically over the past half century (e.g., [1], [72], [73], [74], [75], [76], [77], [78], [79], [80]). Rather than attempting to provide a comprehensive review of this literature, we will cite specific studies to provide examples of the types of parameters that have been explored in this work and the results of evaluations of the reception of speech through tactile aids.

(a) Vocoder-based displays: Various multi-channel vocoders have been evaluated in studies concerned with the acquisition of tactile single-word vocabularies in children and adults, including those with both normal hearing and hearing loss. These devices vary with respect to a number of properties including the number of channels (in the range of 16 to 32), the geometry of the display (linear or planar), body site (fingers, hand, abdomen, forearm, neck), and the type of transducer (vibrotactile or electrotactile). Signal processing is similar across these devices. The acoustic speech signal is bandpass filtered into some number of channels, and the outputs of the bands are used to control the intensity of a signal delivered to mechanical or electrotactile transducers.

Examples of vocoders with mechanical stimulation include the tactual vocoder developed by Engelmann and Rosov [81] at the University of Oregon and the Queen's University Tactile Vocoder [82], [83] [84]. The Engelmann and Rosov [81] vocoder consisted of a 23-channel linear array of 60-Hz solenoid vibrators which could be applied to the forearm, thigh, or fingers. Normal-hearing adult participants were able to identify words from a 60-item vocabulary with an accuracy of 90% correct after 70 hours of training. Of four deaf children, only one made substantial progress with the device, acquiring a vocabulary of 165 words (at a proficiency of 80% correct) following 170 hours of training. The Queen's University Tactile Vocoder consisted of a 16-channel array of solenoids driven by 100-Hz square waves and attached to the ventral surface of the forearm. Evaluations with two normal-hearing participants indicated performance of 80% correct identification of words from a 70-word vocabulary following 40 hours of training for one participant and from a 150-word vocabulary following 55 hours of training for the other participant [82]. This latter participant advanced to the acquisition of a 250-word vocabulary with 80% correct accuracy after 80 hours of training [83]. Two adolescents with prelingual deafness achieved criterion performance of 80% correct on a 50-word tactile vocabulary following roughly 25 hours of training [84].

Examples of vocoders employing electrotactile stimulation include the MESA [85] and the Tacticon 1600 [86]. The MESA consisted of a 36 $\times$ 8 array of electrodes, worn as a belt, in which the 36 rows were used to code frequency and the 8 columns to code amplitude (only one of which was activated at a time). Through the MESA alone, normal-hearing participants had scores of 95% correct on the identification of 8 vowels spoken by one talker after roughly 50 hours of training, with effective transfer to a new talker (76% correct). For consonants, identification reached 50% correct for a set of 8 plosive and nasal stimuli following roughly 30 hours of training and 70% correct for a set of 9 fricatives following roughly 12 hours of training. Saunders et al. [86] conducted testing with a 20-channel electrotactile vocoder (the Tacticon) that consisted of a set of 20 biphasic, constant-current electrodes arranged linearly in a belt worn around the abdomen. Testing included pairwise discrimination of consonants (72% correct) and vowels (80% correct) by eight participants and acquisition of a 33-word vocabulary by one participant with performance of roughly 80% correct following 3 hours of training. A 16-channel version of this electrotactile device (the Tacticon 1600) was subsequently used in laboratory evaluations with two profoundly deaf adults who achieved word identification scores of 41.6% correct after roughly 43 hours of training on a 50-word vocabulary [87]. The Tacticon 1600 was also used in training and testing of word acquisition in young children with profound deafness [88]. Post-training tests conducted with a seven-alternative forced choice procedure indicated a mean word-identification score of 42% correct following roughly 5 hours training. In addition, electrotacile aids with variations on the Tacticon (e.g., in terms of number of channels) have been included in speech and language training programs for children with profound deafness [89].

(b) Feature-based displays: A variety of tactile displays have been developed specifically as aids to lipreading for persons who are deaf and use lipreading as a primary channel for the reception of speech. Only partial cues about the speech signal are available through lipreading, and so tactile aids have been designed to provide supplemental cues. Information that is not well-conveyed through lipreading include prosodic cues such as stress and intonation, as well as cues at the phonemic level including consonantal voicing and manner of articulation [90], [91].

The most basic type of tactile aids to lipreading involve one channel for signal processing and display to the skin (see [77], [79] [92] for reviews). These devices generally convey gross temporal and spectral properties of the speech signal. While different approaches to signal processing (see [93]) and type of transducer have been employed, the information conveyed by such devices is often related to properties of the amplitude envelope of the acoustic speech signal. Several different single-channel tactile aids have been available over the years as wearable devices (see [94]), including the Tactaid 1 (Audiological Engineering Corporation, Somerville, MA), Minifonator (Seimens Hearing Instruments), TAM (Summit, Birmingham, U.K.), and MiniVib3 (AB Special Instrument). In the Minivib3, for example, the amplitude envelope of the broadband speech signal is extracted and used to modulate the amplitude of a 250-Hz vibrator attached to the wrist. Although this type of processing leads to reductions in the rapidly fluctuating energy of speech, it nonetheless preserves information about the gross time-intensity contour of the original speech signal.

Evaluations of the performance of single-channel aids have compared aided to unaided lipreading for various types of speech-reception tasks. Modest benefits to lipreading have been reported for consonant identification on the order of 5 to 10 percentage points [91], [94] [95], sentence reception on the order of 5 to 10 percentage points [91], [94] [96]; and connected-discourse tracking on the order of 5 to 40 words/min [94], [95].

Other feature-based tactile aids to lipreading have been designed to provide specific information which is not well-conveyed through lipreading. One such feature is consonantal voicing which carries a high information load in speech. Tactile displays of fundamental frequency (F0) have been developed to convey voicing information which is highly related to the presence or absence of vocal-fold vibration provided by F0.

Signal processing is used to estimate F0 as a function of time, which is then encoded and displayed to the tactile sense in various ways across studies. As an example, the frequency of F0 was encoded by location of stimulation in a multi-channel array known as the Portapitch ([97] [98]). A long-term study of the Portapitch conducted on three participants with severe-to-profound hearing impairment demonstrated that the reception of key words in conversational sentences was improved by 11 to 20 percentage points over lipreading alone.

In a wearable device referred to as the Tactaid 7 (Audiological Engineering Corporation), the frequency and amplitude of the first two formants of speech were estimated using a zero-crossing analysis and displayed on a seven-channel linear array of vibrators worn on the forearm, neck, abdomen, or sternum. Several studies have examined the benefits to lipreading for hearing-impaired users of the Tactaid 7 [99], [100]. In the field study conducted by Reed and Delhorne [99], aided improvements to lipreading of sentences ranged from none to 23 percentage points across eight deaf participants. Weisenberger and Percy [101] trained and tested noise-masked normal-hearing participants on the discrimination and identification of phonemes using the Tactaid 7. Consonant identification was improved by 6 percentage points over lipreading alone with no benefit observed for vowels.

Another feature-based display that has been studied extensively is the wearable electro-tactile device (the "Tickle Talker") developed at the University of Melbourne [102]. The Tickle Talker consists of an eight-channel array of electrodes worn on four fingers of the hand which are used to encode information about F0, F2, and speech amplitude through the electrical parameters of pulse rate, electrode position, and charge per pulse, respectively. The Tickle Talker has been evaluated in children and adults as a supplement to lipreading. Following periods of training with the device, substantial benefits with have been shown for the reception of speech features, words, and sentences by adults with normal hearing and profound hearing impairment [103]. Benefits to lipreading of sentences averaged 14 percentage points for the normal-hearing group and 21 percentage points for the hearing-impaired group. In testing with 14 children with profound deafness, Cowan et al. [104] demonstrated an improvement of 21 percentage points for aided lipreading of closed set sentences over lipreading alone.

The benefits described above for tactile aids have been overshadowed in the last 30 years, however, by the success that has been achieved with cochlear implants. While both tactile aids and cochlear implants can serve as supplements to lipreading for understanding speech, a significant fraction of implanted adults are able to achieve high levels of speech reception through the implant alone, and some children implanted at a very young age may develop speech and language at levels comparable to their normal-hearing peers [105], [106]. To date, the number of persons with cochlear implants far outnumbers those using tactile aids. However, not every person with profound hearing loss is a candidate for or desires cochlear implantation, and some implantees receive little or no benefit from their implants [105], [107]. Thus, a need still exists for tactile aids as an option for communication of speech among persons with severe-to-profound hearing loss.

2) Phonemic-Based Displays: There has been recent research concerned with the development of laboratory systems focused on a phoneme-based approach to encoding speech for display to the tactile sense. Within the deaf and deafblind communities, such aids have potential use for persons who are adventitiously deaf or who have acquired speech in an oral educational setting. Among the general population, such devices can be used in situations where the auditory and visual sensory systems are overloaded or compromised. Wearable versions of these systems are dependent on the use of signal processing at the front end for extraction of phonemes. With advances in the performance of automatic speech recognition (ASR) algorithms, such devices may become a reality in the near future. In the meantime, assuming the possibility of near instantaneous phoneme recognition, research has been conducted to develop and evaluate sets of tactile codes corresponding to sets of English phonemes. The characteristics of phonemic-based tactile displays differ across the various laboratories that have undertaken these studies, and include variations in factors such as the number of phonemes under consideration, the type of tactile stimulation and cues that are used to encode the phonemes, and the communication rates that can be achieved with these signals. All of these tactile systems are hands-free and mounted on the arm. Studies will be grouped and summarized below according to the different research groups in which the work was performed, including studies at Facebook [108], [109] [110], Rice University [111], [112] [113], McGill University [114], [115], [116] and a collaboration between Purdue University and MIT [117], [118], [119], [120], [121], [122].

In the initial work conducted at Facebook, a 2×3 array of voice-coil actuators, called tactors, was mounted on the dorsal surface of the forearm and used to present tactile codes for nine English phonemes (five consonants and four vowels) [108]. Consonants were coded by a 250-Hz vibration presented at one of the six tactors and vowels by sequential activation of two tactors. After receiving training on the recognition of individual phonemes (whose mean duration was 280 ms), observers were trained and tested on the identification of a set of 20 words, where performance averaged 83% correct. In subsequent work [109], a larger array with 16 tactors was applied to the dorsal and ventral surfaces of the forearm, and used for presentation of tactile codes for 10 phonemes (5 consonants and 5 vowels). Consonants were coded as static patterns with a duration of 120 ms and vowels as dynamic patterns with a duration of 220 ms. After roughly one hour of training, closed-set identification of a set of 10 words composed of these phonemes (with a 200 ms inter-phoneme interval) was 76.3% corrrect. Finally, this 16-channel array was expanded by 8 additional tactors applied to the dorsal upper arm, and used to encode 13 phonemes (7 consonants and 6 vowels) [110]. Identification of a set of 100 words composed from these phonemes was reported for participants under two types of training: a fixed-schedule regimen versus a self-guided approach. Following 65 minutes of training over three days, mean scores for the fixed-schedule group (86%) exceeded those of the self-guided group (72%), with more learners in the former group achieving scores in excess of 90%.

In the research at Rice University, Dunkelberger et al. [111], [112] developed a device, referred to as MISSIVE, that consisted of four tactors for vibratory stimulation in addition to a radial squeeze band and a lateral skin stretch rocker mounted on the forearm. The device was used to encode 23 English phonemes. Following 100 minutes of training on the identification of isolated phonemes and words from a 150-word vocabulary, participants were tested with a closed subset of 50 words. Using a self-paced rate of phoneme presentation for the word identification test (resulting in an average phoneme presentation rate of 3.5 sec/phoneme), performance averaged 87% correct. Dunkelberger et al. [113] extended the testing with this device to a larger group of 18 participants, again with 100 minutes of training on phoneme identification and identification of words with a self-paced delivery of individual phonemes. Phoneme identification scores averaged 61.4% and words from a 50-word set were identified at a rate of 89.9% correct in a 12-alternative forced-choice procedure. A subset of 5 participants continued with an additional 60 minutes of training on phoneme identification and identification of 50 words using a free form response. The performance of these participants improved by 10 percentage points on the phoneme identification task, with a mean word identification score of 67% correct (compared to 94% correct in the forced-choice procedure).

Two tactors worn on the forearm, one near the wrist and the other near the elbow, were used in the work on phoneme-based displays conducted at McGill University. In this research, de Vargas et al. [114] developed tactile codes for 16 consonants (based on salient features derived from the acoustic waveforms associated with each consonant) and 9 vowels and diphthongs (generated using speech synthesis). The cues were adapted for presentation through the tactile sense, including use of lowpass filtering at 700 Hz. The duration of the cues was 750 ms for vowels, 1500 ms for diphthongs, and ranged from 20 to 550 ms across the 15 consonants. Differences in intensity between the two vibrators were used to manipulate the perception of spatial locations along the forearm. After 100 minutes of training on the identification of phonemes and words, participants were tested on their ability to identify words constructed with an inter-phoneme interval of 1 sec (yielding an average duration of 3.1 sec/phoneme). Performance was 94% correct using a 12-interval forced-choice paradigm for identifying words from the 150-word training set, but fell to 51% correct for open-set identification of these words and again to 39% correct for novel words.

In further work with this system, de Vargas et al. [115] tested a new group of 14 participants on the identification of phonemes, words, and phrases. Following 100 minutes of training, scores averaged 74.7% correct for phoneme identification. Open set recognition of words using a 1-s inter-phoneme interval was similar to that reported by de Vargas et al. [114]: 68% correct for words from a training set of 150 words to which the participants had been previously exposed and 45% correct for novel words. Half of the participants received an additional 100 minutes of training directed toward identification of phrases constructed from a mixture of words from the training set and novel words. On a phrase identification test using self-paced presentation of words, the entire phrase was identified with an accuracy of 42%, while 65% of the words were correctly identified. Finally, a study of two-way communication was conducted in which five users of the tactile system received messages from a partner for problem-solving tasks [115] [116]. The partner's spoken messages were delivered through a messaging app and were subsequently translated into phonemes. The problem-solving tasks were nearly always completed successfully (87.5% of the time), although this required multiple presentations and incomplete phonemic accuracy.

In the collaboration between Purdue University and MIT, the tactile system (referred to as TAPS) consists of a 4-by-6 array of tactors worn on the forearm, with four rows in the longitudinal direction (elbow to wrist) and six columns in the transversal direction (around the forearm). Two rows reside on the dorsal surface and two on the volar surface of the forearm, respectively. The tactors are wide-bandwidth audio speakers each of which is activated independently. The properties of the tactile signals used to encode each of the 39 phonemes of English (24 consonants and 15 vowels) are described in [119]. The dimensions used to create these haptic codes include: frequency (60 and 300 Hz), duration (100 ms for short-duration and 400 ms for long-duration consonants; 240 ms for short-duration and 480 ms for long-duration vowels), place of stimulation (wrist, mid-forearm, and elbow; dorsal and volar), waveform (e.g., modulated or unmodulated), and the use of different types of movement patterns for vowels (e.g., saltatory versus smooth apparent motion). Articulatory properties of speech sounds (such as voicing, manner, and place of articulation) were also used to guide the mapping of phonemes to tactile codes (e.g., modulated versus unmodulated sinusoidal waveforms were used to code voiced versus unvoiced phonemes, and sounds made at the front or back of the mouth were coded at the wrist or elbow, respectively).

Using a set of 10 consonants and vowels presented through the TAPS system, Jung et al. [117] trained participants on the identification of individual phonemes and a set of 51 words composed from these phonemes with 300 msec between phonemes. Within 60 minutes of training spread out over 10 days, participants were able to achieve near perfect identification of both phonemes and words. Additionally, one participant was trained in the identification of the full set of 39 phonemic codes introduced daily in small groups of 4-6 phonemes, achieving 95% correct recognition. Further results on the identification of the 39 phonemic codes presented through TAPS indicated average performance of 85% correct across 10 participants following 1.5 to 4 hours of training [119]. Two different approaches to training were studied for the acquisition of a 100-word vocabulary through TAPS [118], [120], one in which participants were trained on phonemes prior to words (bottom-up approach), and the other in which words were learned without the introduction of isolated phonemes (top-down approach). With a total of 100 min of training spread out over 10 days, the best learners in both methods achieved scores in excess of 90% correct. However, the phoneme-based approach provided a more consistent path for learning across users in a shorter period of time. In further studies using an inter-phoneme interval of 150 ms, participants progressed to learning the 39 phonemes and a 500-word vocabulary with performance in the range of 50–85% correct after total training times of 4.5 to 8.0 hours [120]. The identification of two-word phrases by trained users of TAPS averaged roughly 75% correct with an inter-phoneme interval of 150 ms and an inter-word interval of 1000 ms [122], resulting in an effective transmission rate of 30-35 words/min. To increase transmission rates, Martinez et al. [121] introduced modifications to the tactile phoneme codes taking into account the statistics of spoken English as well as introducing new codes as contractions for the 10 most frequent pairs of phonemes. Although these 49 tactile codes were identified with a high degree of accuracy (>80% correct), they also led to an increase in response time compared to the original 39 codes.

Research is ongoing in the area of phoneme-based tactile devices with a focus on developing wearable, real-time devices that allow two-way communication between users. The major problems that remain to be addressed are sufficient accuracy and time delay of phoneme recognition by ASR, presentation at rates that are at least as fast as those realized through the Tadoma method, and solution of a variety of technological issues associated with wearable devices including actuators that are small but with sufficient bandwidth, power, and battery life.

C. Tactons

The coding schemes discussed to date for representing language have all involved some system of mapping the individual letters, groups of letters or phonemes of a word onto a tactile cue. There has also been interest in creating more complex tactile signals that represent abstract concepts or structured messages, called tactons by analogy to icons in the visual modality [123], [124] [125]. In this tactile language system there is no attempt to map the phonetic or orthographic aspects of the concept onto a vibrotactile code, the focus is on how to create tactons that are easily identified. As they are conceptual, the association between the tactile signal and the concept that it represents must be learned. It appears that these arbitrary associations are readily acquired [126], [127], particularly when the tactons have intuitive meaning, for example by using stimulus intensity as a cue for the relative importance of an event or tempo to represent distance. Examples of different types of tactons are shown in Fig. 3.

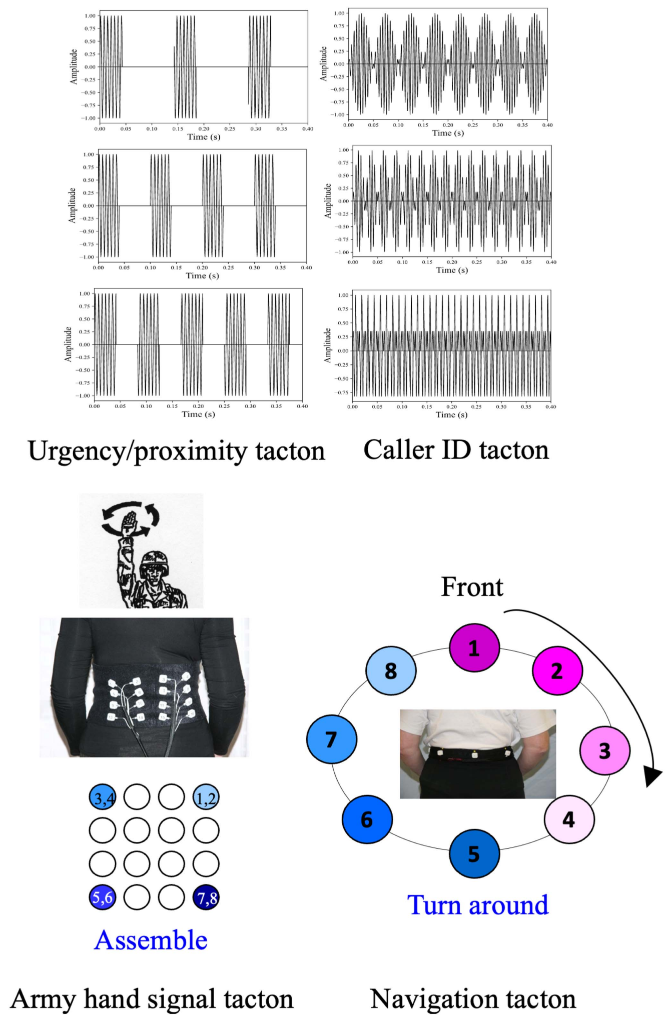

Fig. 3. Upper left: Tactons created by varying the inter-pulse interval to create a sense of urgency or proximity. Upper right: Frequency modulation of a base signal that creates tactons of varying perceived roughness that can be associated with a concept. Lower left: The visual Army hand signal indicating "assemble" is converted into a tactile signal presented on the back with the tactors in the four corners of the display being activated sequentially in an anti-clockwise direction. Lower right: The eight tactors in a waist mounted tactile display are sequentially activated to convey to the user that they should turn around. Redrawn and adapted from [127], [128].

Tactons have been studied in a variety of domains from providing navigation cues to assist people walking in unfamiliar environments to managing interruptions in complex event-driven domains (see Fig. 3). In the latter situation, properties of the interrupting task are encoded in a vibrotactile signal that assists a person in determining whether or not to re-orient their attention immediately or after some delay [129]. Tactons have also been implemented as alerts on mobile phones to communicate the type of notification (e.g. voice call, text message or multimedia message) and its priority [130]. Their use has been explored in the blind and deafblind communities with the objective of creating a more efficient method of communicating simple instructions as compared to letter-by-letter wording [131]. Non-verbal communication systems based on hand signals such as those used by the military, rock climbers and divers are another domain in which tactons have been developed as an alternative communication system [132]. In the latter applications, it is essential that the tactile display is non-intrusive and does not impede movements and so the displays have been mounted around the waist or on the back. In all of these areas, it has been demonstrated that simple concepts represented by brief tactile signals can be learned and responded to with a reasonable degree of accuracy.

The process of designing tactons has generally involved exploring which of the various parameters of vibrotactile stimuli, such as their frequency, amplitude, waveform and temporal profile, result in tactons that are easy to learn and discriminate [133]. The capacity to render these features is a function of the type of actuator used in the tactile display and as a consequence it has often been difficult to generalize from the results of different studies of tactons due to inherent variations in the performance of various types of actuator. For example, the frequency and amplitude of vibration cannot be independently controlled in inertial shakers such as eccentric rotating mass (ERM) motors and so changes in vibration frequency always result in concomitant changes in amplitude [134]. In addition, the slow rise time of these motors limits their capacity to produce dynamic tactile stimuli. A further consideration in comparing the results from experiments using different types of actuators is the mechanical coupling between the motor and the skin which can have a profound effect on the mechanical inputs delivered [133].

Despite the considerable number of experiments on tactons, there is not a cohesive framework to guide designers in selecting particular vibrotactile parameters for specific types of tactons. Early efforts focused on creating tactons by varying first-order dimensions such as frequency, amplitude, waveform and temporal profile, sometimes using a single actuator mounted on the skin [135] or held in the hand [126], other times using an array of actuators [136]. This research demonstrated that variations in the temporal profile of tactile signals by varying either the inter-pulse interval or pulse duration were a readily recognized feature of a tacton and intuitively interpreted as representing its cadence or rhythm [135], [137]. This can in turn be used to encode features such as an object's proximity, the urgency of an incoming message or an impending event. In contrast to the auditory system, variations in the waveform (e.g. sinusoid, square wave) of vibrotactile signals are not readily distinguished [138]. It has been found, however, that more complex waveforms such as those created by amplitude modulation of sinusoids results in a tactile input that is perceived to vary in roughness. This provides a dimension for creating tactons whose perceived roughness increases as the frequency of the modulated signal decreases [135], [139]. Variations in vibrotactile frequency and amplitude have been shown to be more difficult to identify particularly when stimulus amplitude is not initially set to create signals of equal perceived intensity.

The features of vibrotactile signals described above can be controlled in a single actuator, but if the tactile display comprises an array of actuators then it becomes possible to use spatial cues to represent information. By activating specific motors individually or sequentially, it is possible to direct the user's attention to a particular spatial location or convey a sense of movement that represents an intended direction of navigation. The latter is achieved by controlling the temporal sequence of motor activation. When mounted on the forearm or torso such displays have been shown to be very effective at conveying spatial information about the environment [136], [140] [141]. It appears to be quite intuitive to interpret an external direction emanating from a point of tactile stimulation on the body.

Most of the research on tacton identification has involved small sets of stimuli (6-15 tactons) that users become familiar with and then identify in context (e.g. using the cues accurately to navigate) or from a visual template of the signals that depicts the waveform of the tacton or its abstract meaning as shown in Fig. 3. In most of these studies the learning phase is typically brief, less than 30 minutes, and the level of performance achieved is measured in terms of percent correct scores and/or information transfer (IT) units (bits) [142]. Across studies these range from 70-95% correct or in IT terms 2-7.2 bits [143], [144]. There has been considerable variability across studies in the stimulus ranges used to create tactons, which in part reflects the issues related to the variability in performance of different types of actuator highlighted above. Even more systematic approaches to designing tactons such as the use of multi-dimensional scaling techniques (MDS) suffer from the same limitations, namely the results are highly dependent on the stimulus sets studied and actuators on which they were implemented [145].

D. Devices for the Deafblind

There have been many attempts to develop assistive technology for the deafblind community due to the complex communication challenges they encounter and the requirement of physical proximity for two-way communication. The objective of these technologies is to enhance the opportunities available for interaction and enable the Deafblind to access information. Although a number of devices have been developed over the years to facilitate communication, most remain at the prototype or research stage and have not been fully evaluated by the target population of users [146], [147]. For this community in particular, there is a compelling need for devices that enable bidirectional communication so that they can communicate with family members, caregivers and the general public, the vast majority of whom are not skilled in using tactile methods of communication.

Early systems were often based on the American deafblind manual alphabet and were designed to facilitate communication with a deafblind person. Text entered on a keyboard was translated into letters that were displayed sequentially on a mechanical hand that was manually explored by the deafblind individual. In one such system a pneumatically actuated mechanical hand with five movable digits was used to display ASCII characters that could be interpreted by deafblind individuals [148]. This finger-spelling hand underwent a number of design iterations over the years which included improving the mechanical system used to actuate the fingers, thereby reducing the volume of the hand and enhancing the speed with which it could present letters [149].

More recent devices have typically been in the form of smart gloves due to the essential role of the hand in natural communication systems. These can be gesture-based or touch-based systems or a combination of the two depending on the particular communication method being simulated [147]. In contrast to the early systems which generally supported communication in one direction only (i.e., receiving or sending), most recent devices have been designed as both input and output systems so that communication with the Deafblind is bidirectional.

The mobile Lorm glove is an example of a communication device developed for the Deafblind which was designed to function both as a communication and translation device [54]. The glove displays the Lorm alphabet (see Fig. 2) which encodes letters using gestures traced across the skin in addition to contact with specific locations on the hand (see Section III.C.4). It comprises an array of 35 pressure sensors on the palmar surface of the glove which is the input unit and a matrix of 32 vibrating motors on the dorsal surface of the glove which is the output unit. The particular locations of the sensors and motors define the characters of the Lorm alphabet being transmitted. The control unit is mounted on the forearm. The concept for this device is that the deafblind user would wear the glove on the left hand and compose messages by making contact with the appropriate locations for letters on the palmar surface using the fingers on the right hand. The text generated would be transmitted to a mobile device. Incoming messages would be rendered on the dorsal surface of the glove after processing. Although the mobile Lorm glove was developed in collaboration with deafblind partners it appears to have remained a prototype and did not undergo any formal evaluation [54].

Other glove-type devices have been developed to convey the Malossi alphabet used by the Deafblind in Italy (see Fig. 2). It is a simpler alphabet to implement in a wearable device compared to the Lorm alphabet, as letters are indicated by either pressing or pinching specific locations on the fingers and palm. The devices developed to convey the Malossi alphabet such as the dbGLOVE have incorporated actuators that provide tactile inputs on the locations representing specific letters and the output from the glove is then displayed to the reader either visually on a screen or via auditory cues. The glove is worn on the left hand and the deafblind user can type messages on the palm as if they were using a keyboard. Incoming messages can be displayed tactually on the hand with vibration intensity and frequency being used to signify touch or pinch inputs [150]. It has been reported that in users with no previous training the speed and accuracy of letter recognition with the dbGLOVE is greater than that with braille [150] These gloves were initially developed more as a proof-of-concept than a functional prototype [52], [56]. More recently, however, the dbGLOVE has been redesigned and commercialized as a functional interface for the Blind and Deafblind (see Fig. 4) [151]

Interfaces have also been fabricated to replicate communication via finger-braille in which each of the six dots of a braille cell is assigned to one of three fingers (index, middle and ring) on the left and right hands, with the left hand receiving the code from the left column of the braille cell and the right hand from the right column of the cell. In these glove-type

Fig. 4. Upper left: HaptiComm: a 24-actuator array used for tactile finger spelling [152]. Reproduced with the permission of Springer Nature. Upper right: dbGLOVE designed to convey letters of the Malossi alphabet [151]. Reproduced with the permission of Springer Nature. Lower left: TAPS system, 4 by 6 array of tactors for displaying phonemes [119]. Lower right: BrailleSense 6, a refreshable braille display. The photograph of the BrailleSense 6 is reproduced with the permission of HIMS.

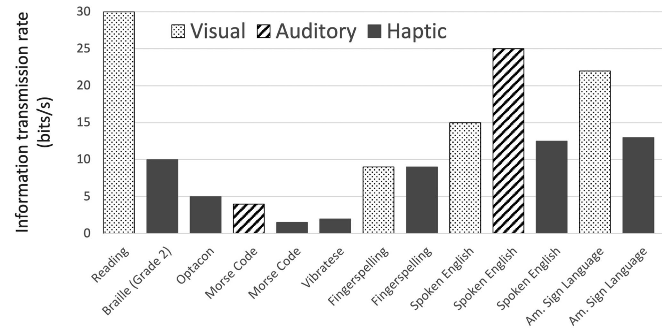

Fig. 5. Communication rates in bits/sec for different methods of language communication and different sensory modalities (from Table I of Reed and Durlach [35]).

devices a motor is attached to the dorsal surface of each of the six fingers. [153]. A braille character is rendered by simultaneously activating the motor or motors representing the relevant dot locations for the character. The design of these systems is therefore similar to a braille keyboard which consists of seven keys, six of which represent the dots of a braille cell with the seventh being a space key. User evaluation of one of these braille-reading devices, called UbiBraille revealed that the average overall accuracy in identifying letters was 82% and that word recognition accuracy was optimal when characters were presented for at least 2000 ms/character. In this study, it was found that visually impaired individuals who were more proficient in reading and writing braille were better at identifying braille characters presented on the UbiBraille [154]. Other finger-braille devices have co-located the actuating and sensing elements of the six element display so that users can both perceive the finger-braille characters from vibrotactile inputs delivered by the motors and output Braille characters that are detected using piezoresistive sensors and Bluetooth wireless communication [155]. Very limited user testing was undertaken with this device, although its functionality and wearability was evaluated by a group of 10 deafblind participants.

Tactile finger spelling is a letter-to-letter representation of words in which each letter is represented by a specific finger movement (tapping and swiping) on the hand. A device that has recently been developed to replicate this form of linguistic communication is the HaptiComm illustrated in Fig. 4. It is a hardware and software platform comprising an array of 24 actuators that is in contact with the volar surface of the user's hand. The device can tap specific loci on the hand and when the actuators vibrate sequentially at specific temporal intervals the sensation of sliding over the skin surface is elicited as occurs with tactile finger spelling [152], [156]. The system is designed to translate speech into tactile symbols that are interpreted by the user. Although this device is a working prototype, the design process has focused on creating an interface that is both robust and easy to replicate at low cost [152], [157].

In summary, a number of tactile displays have been developed for the Deafblind that have attempted to replicate the various forms of tactile communication used by this community. User surveys involving the Deafblind have indicated the importance of creating devices that are wearable, can support more than one input option (e.g., deafblind manual alphabet and braille) and can be used for both face-to-face and long-range communication, the latter via access to other devices [55]. Recently, there has been a significant amount of research on developing smart gloves and smart skin [147]), much of which has focused on sensor and actuator technology and performance in the context of soft robotic systems, rather than wearable devices for the Deafblind. It is clear, however, that these technologies hold considerable promise in creating more versatile and robust tactile displays for the Deafblind.

V. Learning and Retention

The performance of the various tactile communication systems described in this review can be compared in terms of words/second or information transfer (bits/second) [120], [142], [158]. The latter is defined as the increase in information that follows the transmission of a signal, which is simply a measure of how much more the receiving system knows about the state of the transmitting systems after a signal is received than before [159]. A comparison of the rates of communication and of information transfer for a number of different language communication methods in different sensory modalities is shown in Fig. 5, using estimates of rates in bits/sec reported in Table 1 of Reed and Durlach [35]. Communication rates were compared across different methods and modalities using the following steps. First, rates for each method/modality were converted into a normalized unit of transmission of words/sec, followed by conversion into IT rate in bits/s using Shannon's redundancy calculations [160]. As evident in the figure, the highest rates of information transfer (20–30 bits/sec) are achieved through reading by sight, listening to spoken English, and visual reception of sign language (ASL). For each of these three communication methods, information rates are roughly twice as slow through the haptic modality. For spoken English received visually through Cued Speech [161], the information transfer rate is slightly higher than for the haptic modality (Tadoma). If the methods of communication involve interpreting sequential presentation of letters, such as Vibratese, Morse code or finger spelling, the information transfer becomes much less efficient through any modality. Auditory reception of Morse code is only 4 bits/sec, dropping to 1.5 bits sec for haptic reception (similar to that for Vibratese), and information transfer through visual and haptic reception of fingerspelling occurs at a rate of 9 bits/sec, as compared to speech and sign language (22-25 bits/sec). In spite of this limitation, such communication options may be very accurate [35], [42].

An important issue related to learning tactile communication systems is understanding the factors that influence tactile language retention, such as the duration of learning and the effects of continued practice on retention. Braille is one of the few tactile languages that has undergone extensive study in terms of the amount of training required to become proficient and then maintain a high level of skill. In the context of understanding the training required for tactually communicated languages to be retained, it is important to note that proficient braille readers usually spend 5–10 hours daily reading braille [162]. Very few studies have examined the retention of tactile languages over long time intervals and many of the experiments described in this review have involved a brief training period followed by measuring acquisition. The metrics used to measure this have varied: recognition of the phoneme/letter/word, identification of the letter/word (free recall) or matching the tactile signal to an abstract cue, with the result that comparisons across studies must be made with caution. It is much easier to recognize the word or phrase in a prescribed set than to recall the word from memory with no cues available.

VI. Conclusion and Future Directions

In this review we have examined the development of communication systems that convey language tactually, first from an historical perspective and then with respect to the communities who use the tactile modality to substitute for impairments in vision and/or hearing. The more recent developments in wearable tactile communication systems for those without sensory impairments are also reviewed; these systems may come to provide a meaningful communication option for those with visual or auditory impairments.

In tracing the history of tactile communication systems, it is evident that technological advances in other domains have had a profound impact on the "requirements" for effective tactile language systems. For example, the advent of screen reader technologies and speech synthesizers provided access to text for many people with visual impairments but these devices are unable to convey the highly spatial or technical content that may accompany text [38]. Effective means of conveying such graphical content tactually is critical to improving accessibility for the visually impaired. Similarly, hearing-assistive devices such as hearing aids and cochlear implants have had a fundamental impact on those with hearing impairments, many of whom can now follow conversations in quiet environments [80]. However, significant limitations remain in locating and segregating sounds and so tactile aids that can assist in sound localization (i.e. spatial hearing) and improve speech-to-noise performance are a particular need for this community. A number of devices have been developed for the deafblind community over the past decade, most of which have remained at the prototype stage, but several of which hold promise as bi-directional language communication systems. Although none of these have reached the performance levels of natural methods of tactile language communication used by the Deafblind, such as Tadoma or tactile sign language, they do provide a much-needed mechanism for the Deafblind to communicate with people who are unfamiliar with tactile methods of communication. Finally, the successful implementation of the recent research on developing wearable tactile displays for communicating language [113], [119] will very much depend on the accuracy and latency of automatic speech recognition algorithms, since fast, accurate output will be crucial to user acceptance.

Most of the tactile language communication systems that have developed naturally have used the hands to "listen/read" and/or "speak," and so this has been the preferred site for devices designed to emulate these systems. Other locations on the body have been used for displays that do not require two-way communication (i.e. the user "listens or reads") such as spectral-based displays for speech communication that have been mounted on the abdomen, forearm or neck [163], [164] and phonemic-based displays worn on the arm [113], [122]. Much of the research on tactons has also used sites other than the hand for tactile communication, in order to free the hands to perform other tasks. These latter studies have demonstrated that tactile signals delivered to such locations can be processed with sufficient accuracy to enable effective communication and that the more extensive areas of skin available on sites such as the arm or torso enable spatial and illusory movement cues to be incorporated in coding language tactually [136], [165].

Tactile language communication systems are slow when compared to reading and speech, reflecting the more limited bandwidth of touch as compared to vision and audition, and inherent limitations in the speed with which hand movements can be executed and sustained [166]. Of all the tactile language systems that have been studied, the fastest rates of information transmission (defined in terms of bits/s or words/s) are achieved when communicating using Tadoma or the haptic reception of sign language (ASL), as illustrated in Fig. 5. In the recent research on wearable tactile communication systems for those with intact sensory function (see Section IVB.2) reception rates around 30-35 words/min (0.5 words/s) have been reported for two-word phrases [122]. Although the latter study did involve a prolonged period of training and evaluation, proficient users of Tadoma and the haptic reception of sign language have many years of experience in acquiring and maintaining their level of skill.

In conclusion, the requirements for effective language communication devices based on the sense of touch vary across the communities of use. As highlighted above, future development of these devices cannot occur in isolation from other technological improvements that provide enhanced access to language, be it text, speech or signs. The challenge is to identify how the sense of touch can complement these advances so as to augment language expression and comprehension.

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