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CASE STUDY

Development and evaluation of a dual-output vocal cord vibration switch for persons with multiple disabilities

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Abstract

Purpose. A novel dual-output vocal cord vibration switch is described and evaluated for two individuals with severe motor disabilities and complex communication needs. An evaluative case series was performed to compare the new device to its previously proposed single-output counterpart in terms of accuracy, speed and user fatigue.

Method. In an ABAB design, participants were followed for up to 16 days as they performed several image matching tasks. Custom-written software recorded the average time taken to match each item, as well as the total number of selection errors. Participants reported their fatigue levels using a modified five-point Borg scale.

Results. For one participant, the dual-output version significantly decreased task completion time and selection error ($p > 0.05$, Kolmogorov-Smirnov test), thus improving her communication ability. For the second participant, no significant differences were observed between the single- and dual-output systems. Fatigue associated with illness and self-reported stress with school exams were identified as limiting factors.

Conclusions. The dual-output vocal cord vibration switch provides a promising new alternative for individuals with severe and multiple disabilities who are able to hum or produce vocalizations. Both participants expressed desire to continue using the device for educational and entertainment purposes.

Keywords: *voice switch, augmentative and alternative communication (AAC), vocal cord vibration, dual-output access switch, complex communication needs*

Introduction

Daily interaction (e.g. expression of needs/desires and exchange of information/knowledge) and participation (e.g. development of social relationships) are usually achieved through verbal communication [1]. However, in 2006, Statistics Canada reported speech disabilities to be prevalent among individuals with a disability under the age of 15 years (44.8%), in particular, in individuals with severe and multiple disabilities [2]. As a consequence, augmentative and alternative communication (AAC) strategies and tools have been developed to help supplement or replace natural communication methods for these individuals.

Access tools, such as mechanical switches, have been commonly used to access computers and other communication devices, thus enabling individuals to interact with their surrounding environment, participate in social activities and develop complex linguistic skills [3]. For individuals with multiple and severe motor disabilities, however, access to communication devices via mechanical switches is extremely difficult, if not impossible. To overcome this barrier, camera or microphone-based micro-switch solutions have been proposed [4–8]. The performance of camera-based solutions, however, can be severely compromised due to poor lighting conditions or to spastic movements. Microphone-based solutions, in turn, are extremely sensitive to environment and user-generated noise (e.g. coughs) [9].

In order to overcome the aforementioned limitations of voice-activated switches, a vocal cord vibration switch, nicknamed 'the Hummer', was recently developed [8]. The device non-invasively

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measures vocal cord vibrations as the user vocalizes. Intended vocalizations (e.g. 'ah' or hums) generate periodic vocal cord vibrations, whereas unintended sounds (e.g. coughs or swallows) cause aperiodic vibrations. By monitoring specific vocal fold vibration patterns, the single-output device was shown to be more reliable than conventional sound-based systems [8,9] and to be the preferred mode of access for four children with severe motor disabilities [10].

Single-output devices can be used in conjunction with single-switch automatic row-column scanning software programs such as WiViK© or Clicker©. Automatic row-column scanning, however, limits communication speed as several undesired items need to be scanned before the desired item is reached [11]. If a two-output AAC device is used or two reliable access sites are available (e.g. button press and vocalization), two-switch directed scanning can be used to improve communication time and reduce errors [12]. In this article, we describe a modified two-output Hummer and evaluate its viability with two youth with severe and multiple disabilities. Two outputs were realized by discriminating between short- and long-duration intended vocalizations.

Materials and methods

Participant descriptions

Two youth consented to participate in this study, which was approved by the hospital research ethics board. The first participant, Dorothy (pseudonym), is a 15-year-old female diagnosed with spastic quadriplegic cerebral palsy. She has severe hypertonia in her limbs and spastic head movements. Dorothy spent most of her time in a wheelchair and was dependent on others for mobility and activities of daily living. Cognitively, Dorothy demonstrated the ability to learn and understand instructions. At the time of this study, she was undergoing reading assessment, but was known to be reading at the primary level. Although Dorothy's main mode of communication was verbal speech, dysarthria limits her to single words and occasionally short phrases (i.e. 'how are you'). She did not have access to a computer at school, but was looking for a suitable access solution to play video games, send emails and access the internet. Dorothy was previously prescribed various switches, including sip-and-puff and button-style mechanical switches. These devices, however, were not viable due to her numerous spastic head movements and unreliable limb movements secondary to severe hypertonia. The Hummer showed great promise as it did not require mounting, was less effortful to use and functioned regardless of her head and limb movements.

The second participant, John (pseudonym), is a 20-year-old male with a history of severe hypotonia possibly related to a prenatal encephalopathy. He spends the majority of his time in a wheelchair, has minimal motor abilities, and is dependent on others for mobility and activities of daily living. John has also been diagnosed with mitochondrial myopathy which causes irreversible muscle deterioration. As a result, premature fatigue is an added physical limitation that greatly affects his alertness. Cognitively, John is considered to be functioning at an age-appropriate level. He is able to understand everyday conversation and to readily learn new instructions. John has a long history of experience with assistive devices and microswitches, namely, blink, chin, eyebrow, proximity, sip-and-puff, tongue, mechanical squeeze, and respiratory band switches. Notwithstanding, all proved to be either unreliable or overly fatiguing. Since John is able to vocalize and to produce a few intelligible words (e.g. 'thank you') when his fatigue level is low (i.e. early in the morning), he has been using the single-output Hummer for 1 year [9]. While proficient with the Hummer, he finds the single-output exceptionally limiting and is interested in finding a more efficient alternative for computer access.

Technology development

The modified device consists of a software upgrade and minor hardware changes to the existing single-output Hummer solution described elsewhere [8]. Figure 1a depicts a diagram of the updated dual-output device. The sensor, containing a dual-axis accelerometer, is held in place on the neck in the proximity of the vocal cords with a neckband made of a mixture of 86% nylon and 14% lycra. The elasticity and moisture-wicking properties make this material suitable for prolonged usage. The axes of acceleration are aligned to the anterior–posterior and superior–inferior anatomical axes. The sensor is connected to a microcontroller box wherein input vocal cord vibration signals are monitored and analyzed in order to detect short- or long-duration intended sounds (i.e. voiced sounds or hums). To account for individual differences in vocal fold function and vocalization abilities, adjustable sensitivity and timing dials are implemented in the final hardware solution. The latter allows the caregiver to adjust the threshold between short- and long-duration vocalizations while the former sets the level of compensation for less periodic vibrations (i.e. breathy speech) as the user fatigues.

In addition to the sensitivity and timing dials, the switch box includes three indicator lights (one red and two green). A blinking red light indicates that the system is in pause mode, whereby vocalizations do not produce switch activations. The pause mode is useful for individuals who intend to converse with their communications partners while donning the neckband; the mode is activated via an external toggle switch. The two green lights indicate that vocalizations were detected. As illustrated in Figure 1b, the middle green light blinks upon the detection of a long vocalization, whereas the bottom green light blinks upon the detection of a short vocalization. The microcontroller can be programmed to output any combination of pre-specified keystrokes or a mouse click upon detection of short- or long-duration vocalizations. In addition, short vocalizations can be used to produce a conventional switch output once a switch cable is connected. For the purpose of this study, the microcontroller was programmed to output an F12 keystroke for long-duration vocalizations and an F11 keystroke for short-duration vocalizations. This choice of keystrokes mimics the inputs needed to operate the commercial virtual keyboard WiViK®, commonly used by John and currently being taught to Dorothy. Finally, the microcontroller has been set up to be powered by either a USB connection or by two AA batteries, thus making it portable.

Experimental setup

A picture matching game was developed in Visual Basics for the purpose of this study; Figures 2a,b depict screenshots of the program developed for usage with single- and dual-output Hummer versions, respectively. The task involved matching a string of 4–7 images randomly chosen from 4 categories of 12 images; the images to be matched appear on the top of the screen (see Figure 2). Images belonging to a specific category, namely, animals, numbers, words and symbols, appear in a separate 'keyboard' and users cycle between image category keyboards (or grids) by either using a long hum (with dual-output Hummer) or by selecting the 'change keyboard' virtual button (single-output) on the software's graphical user interface. With the former, items are selected using a short-duration hum/vocalization. The current image to be matched is highlighted with a box. Once the first image in the target string has been matched, the next target image is highlighted, and so on, until all target images have been matched by a keyboard selection.

The study followed an ABAB design with 'A' representing baseline and 'B' denoting the intervention [13]. The difference in the two phases was the

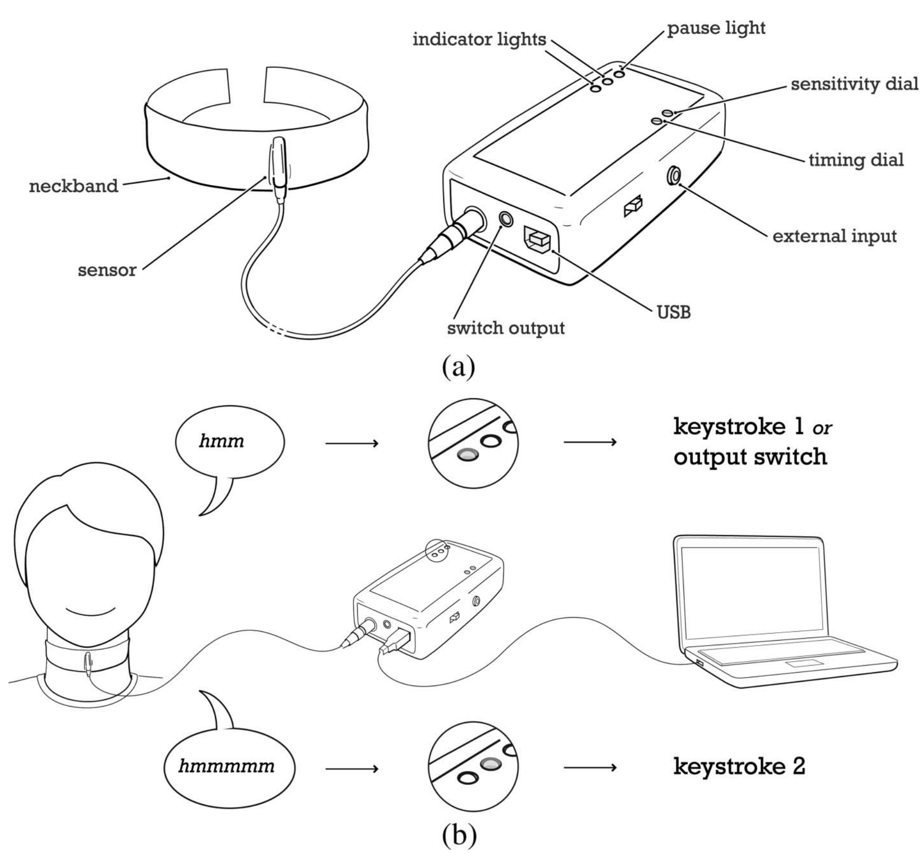

Figure 1. Dual-output throat vibration (a) diagram and (b) its usage with two-switch scanning software.

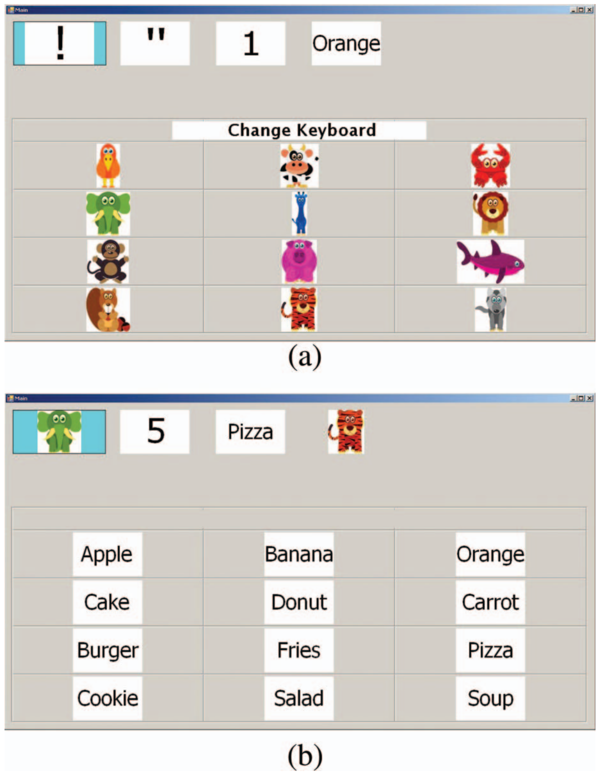

Figure 2. Screenshots of the software developed using Visual Basic for (a) single- and (b) dual-output switches.

method by which the participant cycled through the four different image category keyboards. For the baseline phase, the single-output Hummer, which participants were familiar with, was used to both select items on the screen as well as to cycle through the different keyboards via the 'change keyboard' button (see Figure 2a). The baseline phases consisted of two days with 8–10 sessions per day, depending on participant fatigue levels. The intervention phases invoked the dual-output Hummer, which the participants had never seen before. Short vocalizations activated the select item keystroke (F11) while long vocalizations activated the grid change keystroke (F12). Intervention phases consisted of 3–8 days with 6–10 sessions per day, depending on participant availability and fatigue.

To evaluate the accuracy and speed of communication, two measures are used, namely, the number of image matching errors per session and the average time per item (total task execution time divided by the number of images to be matched, which ranged from 4 to 7). Since the users were not given the option to undo an erroneous selection, the measures need to be jointly assessed, as a high number of errors can lead to very short task execution times. Additionally, a five-point Borg scale (1 = *not tired*; 2 = *a little tired*; 3 = *moderately tired*; 4 = *a lot tired* and 5 = *very tired*) was used to gauge participant fatigue levels. Participants were asked to rate their fatigue levels both before and after completing the image matching sessions. A relative tiredness measure was developed and given by:

$$\text{Relative Tiredness} = \frac{\text{final tiredness} - \text{intial tiredness}}{5 - \text{initial tiredness}} \tag{1}$$

The participants' responsiveness and body language were also noted throughout the sessions by the experienced therapists present in the sessions.

Results

The timing and error results per day (averaged over all sessions in 1 day) for baseline and intervention phases are depicted in Figures 3 and 4 for Dorothy and John, respectively. As can be seen from Figure 3, Dorothy's mean time during the first and second baseline phases was 33.8 s and 31.1 s per item, respectively. The mean time decreased to 24.2 s and 20.5 s in the first and second intervention phases, respectively. As mentioned previously, due to the nature of the task, both the timing and error measures need to be assessed jointly. As observed, the average percentage error during the first and second baseline phases were 11.25% and 6.25%, respectively. The errors decreased during the first and second intervention phases to 4.4% and 0.8%, respectively. A Kolmogorov–Smirnov test shows that these differences were significant ($p < 0.05$). Collectively, these results suggest that the decrease in timing was not related to erroneous item selection, but to Dorothy's improvement in communication skills, that is more reliable item selection with the dual-output access solution.

In terms of fatigue levels, Dorothy did not report any change in tiredness levels during any of the sessions. Since she constantly reported a fatigue level of 1 (not tired) both at the beginning and at the end of the sessions, the fatigue measure (Equation 1) could not be computed. While her facial expressions and responsiveness did indicate some degree of fatigue in a few instances, she was adamant about her reported fatigue levels.

As for John, the mean time per item in the first and second baseline phases was 26.5 s and 43.8 s, respectively. His timing did not improve during the intervention phases and the mean time per item observed during the first and second interventions was 27.3 s and 46.6 s, respectively. Additionally, unlike Dorothy, John's error percentage increased during the intervention phases. The average percentage error observed during the first and second baseline phases were 12% and 16.9% percent, respectively. During the first and second intervention

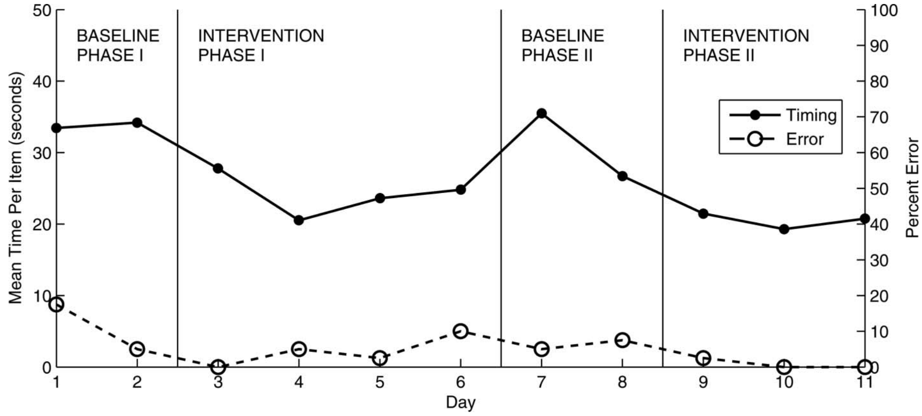

Figure 3. Baseline and intervention phase results for Dorothy. Solid circles represent mean time (seconds) per item and empty circles represent error percentage per day.

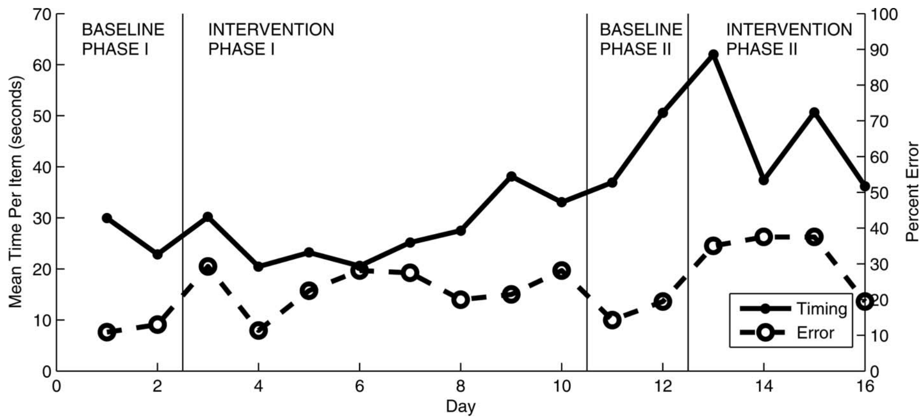

Figure 4. Baseline and intervention phase results for John. Solid circles represent mean time (seconds) per item and empty circles represent error percentage per day.

phases, in turn, the error percentage increased to 23.5% and 32.4%, respectively. While the changes in error percentage were not significant between baseline and intervention phases ($p > 0.05$, Kolmogorov–Smirnov test), they were substantial.

This drop in performance is attributed to John's limited endurance, which is known to limit his performance and concentration. For example, his caregiver reported a significant increase in fatigue levels during the course of the study, even before the experimental sessions started. This can be observed with the plot depicted by Figure 5 for initial tiredness levels as well as the relative tiredness measure described by Equation 1. John's caregiver attributed these unusual tiredness levels to a combination of illness (flu), stress from the large amounts of school work and the fast approaching year-end exams.

Discussion

This study described the development and evaluation of a dual-output throat vibration switch for individuals with complex communication needs who are able to produce controlled vocalizations. The results gathered from two participants extend previously reported claims [12] that improved communication (faster and more reliable) can be attained with a two-output access solution. With the case of the developed two-output solution, this improvement was observed for the individual who was able to control the duration of her vocalizations and not prone to premature fatigue. Notwithstanding, this study focused on using the developed switch for a scanning task only. Scanning tasks require numerous vocalizations, high levels of concentration, as well as fine control of vocalizations for timed responses. These task requirements may cause individuals to fatigue prematurely. For individuals such as John, the dual-output Hummer may be more suitable for less demanding applications, such as environmental control, where short- and long-duration vocalizations can be used to change TV channels/volume up or down, for example [14].

An additional factor that may have caused the observed performance differences between the two

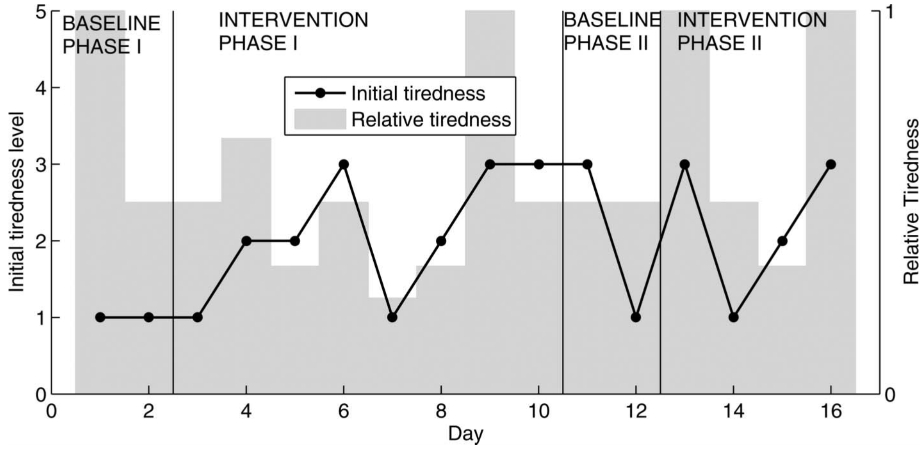

Figure 5. Baseline and intervention phase fatigue results for John. Solid circles represent the initial fatigue level (five-point modified Borg scale) and the bars represent the relative tiredness measure (Equation 1).

participants may have been the behavioural rigidity of "old habits" [15,16]. Aarts [16] mentions that 'when behaviour is performed repeatedly and becomes habitual, it is guided by automated cognitive processes, rather than being preceded by elaborate decision processes'. John had been using the single-output Hummer for automated row-column scanning, in both academic and non-academic settings, for over 1 year prior to this study [9]. Dorothy, on the other hand, had been using the single-output Hummer for only a couple of months and focused mostly on simple cause-and-effect games, thus had no exposure to scanning. Therefore, over the course of this study, Dorothy had the advantage of learning both scanning and vocal control from a clean slate, whereas John had to change previous habits and learn how to more precisely control his vocalizations. A third post-study intervention phase had been planned with John to test this hypothesis. However, due to personal reasons, John was unable to participate further.

In this study, the two-output Hummer was used to cycle between different keyboards in order to complete an image matching task. Commonly, two-output devices (or two distinct single-output switches) are used with two-switch step scanning applications where one output (or one switch) is used to scan through the different options available in the display/grid and the second output (or second switch) is used for selection [17]. The use of two-switch step scanning with a sound-based access solution, however, has some disadvantages, such as vocal strain and social distraction. One solution might be to develop a virtual keyboard that allows for one switch output (e.g. short duration hum) to control item selection and a second switch output to serve either as a backspace/undo keystroke, to cycle between different keyboard categories (e.g. numbers, symbols, predefined messages), or as requested by John, to generate a combination of two or more concurrent keystrokes for advanced video game playing.

The proposed dual-output extension developed for the Hummer relies on the user's ability to discriminate between short- and long-duration vocalizations. Previous studies have suggested that individuals with cerebral palsy and severe dysarthria can control the frequency of their vocal cord vibrations (commonly known as pitch control) [18]. The detection of two distinct pitch values (e.g. one low and one high) can be combined with the detection of two distinct vocalization durations to create access technologies with tertiary or possibly quaternary outputs. Having access to multiple outputs could also allow individuals with severe and multiple disabilities to independently control their wheelchair (e.g. low-pitch short-duration hum to move forward, high-pitch long-duration hum to move right), thus further improving their opportunities for independence and participation in life activities [19].

While special mounting is not required for the developed system, a major limitation lies in the current neckband and sensor design. For individuals with excessive contractions of the neck muscles, the neckband may loosen, thus, precluding the detection of targeted vibrations. Additionally, involuntary head movements in the chin-tuck position may shift the sensor away from the vocal fold region of the neck where the vibrations are most prominent. Improvements in neckband design, as well as the use of an array of sensors placed around the neck, will likely alleviate these issues.

Overall, the developed two-output solution was deemed to be a viable solution for Dorothy, who since the conclusion of this study has been using it for entertainment and classroom activities. For John, the system was not suitable, at least for the scanning application studied here. Further research is needed to assess the usability of the switch for less demanding applications such as environmental control [20].

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