Integrated Head-Tilt and Electromyographic Cursor Control

Jennifer M. Vojtech, Surbhi Hablani, Gabriel J. Cler, and Cara E. Stepp

***Abstract*— This study evaluated the performance of two alternate computer access methods that could be used for two-dimensional cursor control. The first method, ACC/sEMG, integrates head acceleration and facial surface electromyography. The second method, Camera Mouse, is a free-to-use, computer vision-based access method. Twenty-four healthy adults performed a target acquisition task using each computer access method across two lighting conditions and three computer orientations. Performance in the task was evaluated using metrics of target selection accuracy, movement time, and path efficiency. Using ACC/sEMG resulted in better mean path efficiency and target selection accuracy, whereas using Camera Mouse resulted in faster target selection. Moreover, performance in the task when using Camera Mouse depended on lighting conditions in the room. The findings of this study show that the ACC/sEMG system is an effective computer access method across different lighting conditions and computer orientations. However, there is a tradeoff between speed and accuracy: ACC/sEMG system provided higher target selection accuracy compared to Camera Mouse, while the latter provided faster target selection. Future development should focus on evaluating performance of each method in populations with limited motor abilities.**

***Index Terms*— Surface electromyography, head acceleration, human machine interface, Camera Mouse.**

I. Introduction

IN RECENT years, there has been widespread interest in developing alternative computer access methods for use by individuals with severe speech and motor disabilities. Currently, interacting with desktop computers typically relies on engaging the hands of the user; however, alternate access methods often aim to limit the physical connection between the user and the computer, and capitalize on subtle, simple movement cues to sufficiently control the computer. Head control has received significant attention as an input modality since it can be used across a wide range of individuals with minimal ability to perform volitional movements. For example, individuals with spinal cord injuries may retain the ability to control head movements since head movement via sternocleidomastoid is innervated by a cranial nerve rather than by cervical nerves (although other head movements are innervated by cervical nerves; as a result, high spinal cord injury may affect head movement). Several approaches have been proposed to enable head control for computer access, including computer vision techniques, accelerometer- and gyrosensor-based methods, and hybrid systems combining one or more of these approaches.

Computer vision-based head movement detection relies on image processing and/or pattern recognition techniques to estimate head pose from video data [1]–[5]. Many of these systems make use of an infrared optical sensor to track head movement: infrared light is emitted from an optical sensor and the light that is reflected back is processed and returned to the computer to control cursor position. To enable cursor movement, the user must wear a reflective target that can be tracked by the optical sensor. While these devices offer a solution for individuals who require hands-free computer access in numerous lighting environments (including sunlight and darkness), infrared optical sensors struggle with reflections. Thus, individuals who require glasses or are seated in front of mirrors or windows may experience issues using these systems. Non-infrared optical sensors are also an attractive computer vision-based method to enable computer access. Instead of tracking a reflective target worn by the user, the user's face or a specific facial feature is tracked via user selection [6], [7] or automated algorithms [5], [7]–[10] by means of a standard camera (e.g., built-in laptop camera, standard USB webcam). Although these devices are less affected by reflections, lighting conditions may instead cause issues. Using the system in the absence of natural or artificial light (or changing lighting conditions during use) may lead to cursor drifts that necessitate recalibration [6]. Accelerometer- and gyrosensor-based systems are favorable alternatives to computer vision-based methods since they are unaffected by environmental light. Accelerometer- and gyrosensor-based approaches directly translate head position into cursor

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movements via measures such as head tilt angle or velocity of head movement.

Regardless of the method used to detect head movement, a means of selecting targets is required. Many systems rely on a cursor dwell time (i.e., the cursor hovers over a location for a specified duration to make a selection), gesture selection, or a specific direction of head motion to access a selection. However, many of these systems require significant processing requirements to run in real-time, which can be expensive [4]. While dwell-based modalities are easy to navigate, the duration of the dwell time is crucial to optimize performance of the modality: shorter dwell time leads to faster target selection, but also unintentional, inaccurate selections. On the other hand, a longer dwell time may slow performance [11]–[13]. As such, there is speed-accuracy trade-off with dwell-based modalities.

Another solution for alternative computer access stems from combining one of the aforementioned input modalities with an adaptive switch (e.g., sip/puff switch or button-style switch), wherein the user must perform a separate action to emulate selections. However, access via adaptive switches can be extremely difficult for individuals with severe motor disabilities due to a limited range of movement (e.g., brainstem stroke) or uncontrollable movements (e.g., cerebral palsy). To address this, hybrid systems have been developed that combine different computer access methods to simplify cursor movement and selection. An example of this is using a gyroscope to control movement within an interface and optical sensors to recognize target selection based on user facial patterns [14]–[17]. The benefit of using these systems is that there is little-to-no physical connection between the user and the computer to be controlled; however, many of these systems are too bulky for practical use [15], and it is unclear how these systems perform in different lighting conditions.

Surface electromyography (sEMG) has been proposed as an alternative mechanism for enabling target selection capabilities. For example, Ancan *et al.* [18], Fall *et al.* [19] and Perez-Maldonado *et al.* [20] utilized sEMG signals in combination with accelerometer signals obtained via inertial measurement units for complete cursor control: head-tilt angle computed via accelerometer allowed for cursor movement, whereas muscle activations performed using spared facial musculature (e.g., hard blinks [5], teeth clenching [21], frowning [22], or smiling [23]) enabled target selection. This type of hybrid system is advantageous over many computer vision-based systems since it is insensitive to reflections and lighting conditions. Moreover, maintaining one body posture is difficult and specific positions are required for different tasks (e.g., eating) [24], thus when using systems that do not instrument equipment directly to the user, target selection accuracy may be affected by changes in the user's body posture (e.g., initiated by caregivers and attendants, or users themselves). Thus, an additional benefit of this type of system is that sEMG and accelerometer equipment is instrumented directly to the participant. Despite the theoretical advantages of this hybrid system, direct investigation into how user performance compares to computer vision-based access methods is warranted. Examining user performance across different lighting conditions and computer orientations will provide insight into the feasibility and versatility of using a hybrid system combining sEMG and accelerometry computer access.

II. Current Investigation

We developed a head control-based system for two-dimensional cursor control, called "ACC/sEMG." ACC/sEMG combines a tri-axial accelerometer with a single sEMG sensor to control cursor movements and target selection, respectively. The purpose of developing and evaluating ACC/sEMG is two-fold: (1) to create a user-borne system that could be used in a variety of environments (e.g., different room lighting conditions), and (2) to overcome limitations presented by other accelerometer- and sEMG-based systems, including noisy and inaccurate accelerometer signals [18], patient- discomfort from sensors [18], lack of commercial accessibility [18]–[20], and lack of comparisons against other head control-based access methods [18]–[20]. Instead, the sensors used in the ACC/sEMG system are commercially available from Delsys, Inc. (Natick, MA), and, as a result, have been validated for consistency, repeatability, and data quality. Head tilt angle is calculated from the tri-axial accelerometer, which is in contrast to other accelerometer-based systems that use two-dimensional acceleration force [1], [25], [26]. As opposed to pressing the sensors against the skin using a headband [18] or using conductive-adhesive gel [20] to improve electrode contact, the sensors are applied with medical-grade adhesive stickers to minimize participant discomfort and enhance skin-electrode contact.

In the current study, we aim to validate the usability of ACC/sEMG for two-dimensional cursor by comparing it to another head control-based access method. The method, Camera Mouse, is a free computer vision-based input modality. We compare ACC/sEMG and Camera Mouse in a target acquisition paradigm. The paradigm was designed to assess psychomotor performance when using each computer access method under two lighting conditions (light and dark) and three computer orientations to emulate everyday use of a computer for communication. Performance in the task was evaluated using metrics of target selection accuracy, movement time between targets, and path efficiency. The following hypotheses were proposed:

- Due to potential effects of drift and dependence on environmental lighting conditions, user performance (via all three outcome measures) will be worse when using Camera Mouse in a dark room.
- User performance (via all three outcome measures) will not significantly differ when using the ACC/sEMG system across different lighting conditions since accelerometry and sEMG are insensitive to light.
- User performance (via all three outcome measures) will be significantly better when using the ACC/sEMG system across different computer orientations since the equipment is directly instrumented at the user.

III. Methods

A. Participants

Twenty-four healthy adults (12 female, 12 male; M = 21.3 years, SD = 2.7 years) with no history of

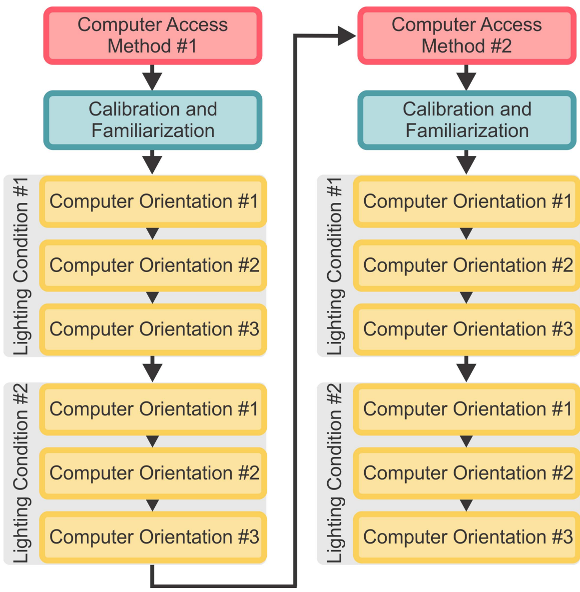

Fig. 1. Schematic of the experimental design, wherein participants were pseudorandomized to the order in which they experienced each computer access method (ACC/sEMG, Camera Mouse), lighting condition (Lights On, Lights Off), and computer orientation (No Rotation, Base Rotation, Screen Rotation). The order of lighting conditions and computer orientations was kept consistent across the two computer access methods. All orders were counterbalanced across participants.

motor impairments or experience with human-machine interface research participated in the study. All participants completed written consent in compliance with the Boston University Institutional Review Board and were compensated for their participation.

B. Experimental Design

1) Overview: All participants completed one experimental session that lasted 1.5 hours. Participants were instructed to complete a target acquisition task using the two access methods (ACC/sEMG, Camera Mouse) under two lighting conditions (Lights On, Lights Off) and three computer orientations (No Rotation, Base Rotation, Screen Rotation). Presentation of the access methods, lighting conditions, and computer orientations were counterbalanced across participants. Fig. 1 shows a schematic of the experimental design, described in detail below. For each computer access method, participants first underwent an automated system calibration with the lights in the room turned on, followed by two minutes of free play to gain familiarity with the access method. Prior to the start of this brief familiarization task, participants were informed that their performance in this familiarization task would not be evaluated. Then, a screen with several black targets appeared and participants could practice navigating to and selecting targets.

Following the two minutes of free play, the lights in the room were either turned off or left on. Participants then completed a center-out targeting task using the calibrated access method three times, which lasted approximately 30 minutes (10 minutes per task "set"). Across these three sets, the orientation of the laptop computer was altered in each one of the following ways: (a) The laptop computer was centered in front of the participant approximately 20 inches away from the nose, with pitch of the screen set parallel to the participant ("No Rotation"), (b) The laptop computer base was rotated 15° counterclockwise from the participant, with the pitch of the laptop screen set parallel to the participant ("Base Rotation"), and (c) The laptop computer was centered in front of the participant approximately 20-inch away from the nose, with the screen rotated 10–15° toward the user ("Screen Rotation").[1] Laptop base and screen rotations were performed to emulate shifts in equipment orientation by caregivers or attendants, which may occur in repositioning the participant's body in a care facility, or from repositioning the body or equipment by the users themselves. The three configurations for the laptop were pseudorandomized across participants, and, within each participant, the order of computer orientations was kept consistent across computer access systems and lighting conditions.

The lighting conditions in the room were then reversed from the previous three sets and participants completed the targeting task again under each computer orientation. After the six sets (i.e., two lighting conditions × three computer orientations per lighting condition), the participant then repeated this process—including calibration, familiarization, and the six targeting task sets—using the second computer access method.

2) Participant Setup: Participants were seated in a reclining chair with a laptop (Lenovo ThinkPad X1 Carbon; i7-6600 Intel processor; 16 GB RAM; running Windows 10) equipped with an integrated camera (HD Intel®Camera, 0.92 megapixels, 1280 × 720 resolution, 30 frames-per-second) centered on an adjustable overbed table (35"h × 31.75"w × 15.75"d; Improvements, Maple Heights, OH). The reclining chair was set to a semi-upright sitting condition of 60 degrees to simulate an appropriate patient position in a hospital or clinical setting [27], with the viewing distance between the computer screen and the participant approximated at 20 inches [28], [29] (see Fig. 2). The computer screen was set to be parallel with the participant's head when resting against the headrest of the reclining chair. Participants were instructed to keep their arms and legs as still as possible during the sets to minimize any additional movements that could affect the cursor movement.

3) Target Acquisition Task: The targeting task, schematized in Fig. 3, consisted of seven isometric, equidistant circles at a resolution of 1920 × 1080 pixels (see Fig. 3A). The cluster of targets was set to randomly appear in one of five locations on the computer screen: at the center, or in one of the four corners of the screen. To complete the task, the user was instructed to navigate to and select the active target (henceforth referred to as a "trial"). The active target was colored red, whereas the non-active targets were colored black (see Fig. 3B). Cursor selections produced a short "click" sound. When a target was unsuccessfully selected (i.e. unintentional or incorrect selection), the accuracy for that trial was set to 0%; otherwise,

[1] Screen rotation angle was empirically chosen as the maximum pitch angle that could be achieved where the participant could still see the entirety of the laptop screen. Rotations away from the user were not examined in the present study due to poor screen visibility during pilot testing.

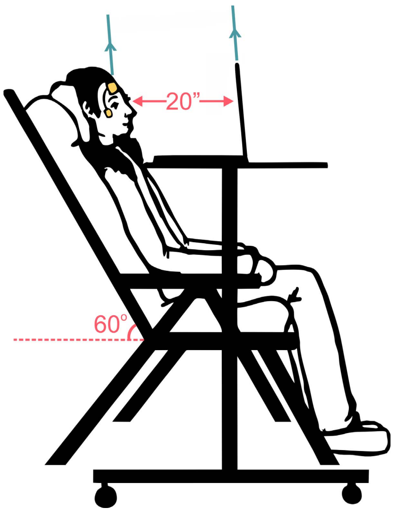

Fig. 2. Schematic of the participant setup, with participant sitting in a reclining chair. The chair was set in a semi-upright position at 60°, with a laptop placed approximately 20 inches away, centered on an adjustable overbed table. During initial participant setup, the laptop screen angle was set to be parallel with the participant's head, as shown by the teal lines with arrow marks. The placement of the sensors for the ACC/sEMG system is schematized in yellow, and is described in *ACC/sEMG System*.

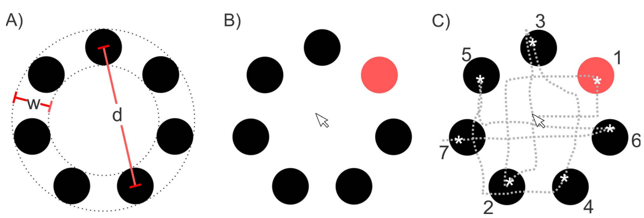

Fig. 3. Schematic of the center-out targeting task, with A) seven targets of equal width, *w*, and inter-target distance, *d*, surround the centroid of the computer monitor, B) start of the targeting task, with the active target shown in red, and C) example path a user may take to complete the round, with numbers denoting order of target selection and asterisks depicting the locations of cursor selections.

accuracy was set to 100%. Upon selection, a new target diametrically opposite to the active target would be designated as the new active target. Attempts at selecting all seven targets (one task "round") would reset the cluster of targets to appear in a different location on the computer screen. Participants were required to complete the task at each of the five cluster locations; after five rounds, one block of experiment was complete. The order of presentation of each of these target locations was randomized across participants, with the distance between targets and the width of the targets remaining consistent each time.

4) Lighting Conditions: The brightness of the room was controlled to replicate lighting conditions in a hospital or care facility. In the "Lights On" condition, the brightness of the room was maintained at approximately 100 lux, as is the suggested brightness level in the general ward of a hospital [30], [31]. In the "Lights Off" condition, the brightness of the room was set at 0 lux. The brightness of the laptop was evaluated 20 inches away from the screen for both lighting conditions (i.e., the distance from the computer screen to the tip of the participant's nose when sitting in a chair). Pilot testing was conducted to choose the optimum laptop brightness to be used across the different lighting conditions, wherein the authors adjusted the laptop brightness based on their comfort level in a room with brightness level of 100 lux, and 0 lux. The average across participants and lighting conditions was chosen as the laptop brightness for the experiments, which was set at 60% for both room lighting conditions; this corresponded to a brightness level of 57.6 lux at the eye level for the Lights On condition and 10.8 lux for the Lights Off condition.

5) Data Acquisition: Two computer access methods were implemented in the current study. The first, Camera Mouse, relies on camera-based head tracking for access, whereas the second, ACC/sEMG system, uses head-tilt and sEMG. Each participant underwent a separate setup and automated calibration process for the two computer access methods prior to engaging in familiarization and target acquisition tasks. Regardless of lighting condition order in the targeting task, setup, calibration, and familiarization were performed with the lights on.

a) Camera mouse system:

(1) System overview: Camera Mouse is a free software that was designed to enable computer access for individuals with severe speech and motor abilities. The Camera Mouse system uses a built-in camera or standard USB webcam to track and translate head movements into cursor movement [6], [7].

(2) Head tracking setup: Camera Mouse 2018 (v.1.1, released Jan 17, 2018) was downloaded and installed directly from the developers' website (http://www.cameramouse.org/). All cursor movement and selection settings in the software were set to default, wherein (1) target selection was enabled with a "normal" radius and 1-second dwell time, (2) sensitivity was set to "medium" for horizontal and vertical directions, and (3) smoothing was set to "very low." Participants were situated in front of the laptop screen as described in *Participant Setup*; the Camera Mouse software interacted with the integrated camera of the laptop to enable head tracking capabilities.

(3) Cursor movement: Full details of the algorithms for Camera Mouse may be found in publications by the developers (see Gips *et al.* [7] and Betke *et al.* [6]). However, a summary is included here. During calibration (see *Calibration*), automated feature selection was performed, wherein the software automatically selected the corner of the user's eye as the feature to track. A square appeared around the selected feature (see Fig. 4) to be used as a "template" for visual tracking. As the user moved their head, the template was shifted by a visual tracking algorithm to determine its position in the next image frame. The search window with the highest correlation with the template was chosen as the new coordinates of the tracked feature. The cursor then moved to correspond with the new coordinates, and the area around the new coordinates were adopted as the new template. The location of the tracked feature was directly mapped to an (x,y) coordinate on the computer screen. Sensitivity and smoothing settings in the software affected the location of the new (x,y) coordinate, as well as the path the cursor took to reach this coordinate. Specifically, cursor sensitivity affected how head movements were translated into cursor movements: high sensitivity translated

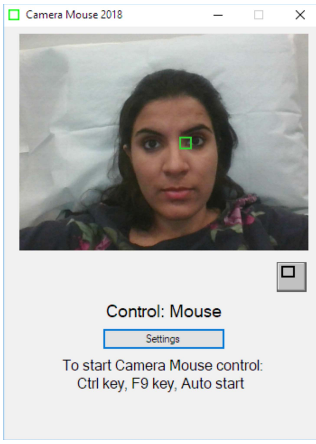

Fig. 4. Camera Mouse automated feature selection, with the green square indicating the tracked feature. Here, the inner corner of the left eye was selected to be tracked.

small head movements into large cursor movements, whereas low sensitivity translated small head movements into small cursor movements. In the current study, sensitivity was kept at the default level of "medium" so that users would not be required to produce excessively small or large head movements to reach the edges of the computer screen. On the other hand, cursor smoothing affected the user control in maneuvering the cursor between two points on the screen. By interpolating raw user movement data, high smoothing settings allowed users to smoothly move throughout the computer screen without experiencing cursor jerks. However, users were disadvantaged since greater data interpolation resulted in less control over the cursor. As such, smoothing was kept at the default setting of "very low" in the current study to ensure that users had maximum control over the cursor [32].

(4) Calibration: Upon software startup, a video screen containing the participant's face appeared on the monitor. Automated feature selection was enabled, and the corner of the eye was used as the prominent feature for tracking; the participant would see a green square appear on the video screen at this location (see Fig. 4). Following instructions by the developer, the participant was instructed to slowly move their head up, down, left, and right to determine if the software correctly tracked the feature. The software failed to recalibrate the template to the user's eye when changing lighting conditions and computer orientations. Because of this, the Camera Mouse software was restarted at the beginning of each trial. The automated calibrations required approximately 15 seconds at the beginning of each trial. The software failed to automatically track the intended feature in at least one trial for 13 out of 24 participants; in these cases, manual feature selection was required, extending the calibration process to approximately 30 seconds. In total, the automated calibration process successfully tracked the corner of the eye in 122 of 144 trials across all participants, with manual feature selection being required in 22 trials.

b) ACC/sEMG system:

(1) System overview: ACC/sEMG uses a combination of accelerometer- and sEMG-based inputs to enable cursor control. The system comprises a single Delsys Trigno™Mini sensor to capture head tilt angle (via accelerometry) and muscle activation (via sEMG), and custom Python software to translate this activity into cursor movements and clicks, respectively. Accelerometer and sEMG signals were recorded with the Delsys Trigno™Wireless EMG System (Delsys, Boston, MA) using factory default settings. Each sensor from the system comprises of a single differential Mini sensor (25 × 12 × 7 mm) and main sensor body (27 × 37 × 15 mm); the Mini sensor was used for EMG signal acquisition, whereas the main sensor body was used to 1) establish a local reference to the sEMG signals collected using the Mini and, 2) record a tri-axial accelerometer signal integrated in the Trigno™system. It is important to note that newer versions of the Trigno™Mini sensors include a six-channel inertial measurement unit (IMU) rather than a tri-axial accelerometer as employed in the current study. The accelerometer signals were recorded at 148 Hz, whereas the sEMG signals were recorded at 2000 Hz, band-pass filtered with roll-off frequencies of 20 and 450 Hz, and amplified by a gain of 300. Signal recording and processing was performed using a modified version of the open-source PyGesture [33] and custom Python software [34].

(2) Sensor preparation & configuration: A single Trigno™wireless sensor was used for computer access. Prior to sensor placement, the surface of each participant's skin was abraded using alcohol wipes, then exfoliated with scotch tape to remove excess skin and oils [35]–[37]. Following, the single differential MiniHead sensor was configured over the orbicularis oculi, with the side of the face (left or right) determined by participant preference (see Fig. 2). The sensor was placed parallel to underlying muscle fibers and centered on isolated muscle tissue. The main sensor body was attached to the glabella such that the y-axis of the accelerometer in the sensor was parallel to the sagittal plane of the user.

(3) Cursor movement: Participants were able to move the cursor by tilting their head in the direction of intended cursor movement. Specifically, tilt angle—which relates the angle of head tilt in the xy-plane to the acceleration in each axis—was calculated by converting the triaxial acceleration signals from rectangular (x,y,z) to spherical (ρ, θ, φ) coordinates [38]. Thus, head roll (i.e., head antero-posterior; see **Eq. 1**) was mapped to moving the cursor up or down and head pitch (i.e., head medio-lateral; see **Eq. 2**) was mapped to moving the cursor left or right. Combinations of these gestures enabled 360° movements within the two-dimensional onscreen interface.

$$\text{Head Roll}\,(\theta, \text{deg}) = \frac{360}{2\pi} \times \text{atan2}\left(\frac{y}{z}\right) \quad (1)$$

$$\text{Head Pitch}(\rho, \text{deg}) = \frac{360}{2\pi} \times \text{atan2}\left(\frac{-x}{\sqrt{y^2 + z^2}}\right) \quad (2)$$

To determine direction of movement, the root-mean-square (RMS) values corresponding to head roll and pitch tilt acceleration were evaluated over 54-ms windows. All RMS values were normalized by mean RMS values obtained in the calibration task (see *Calibration*). The sign of the movement was evaluated to determine if the intended direction was negative (i.e., left or down) or positive (i.e., right or up).

The magnitude of the head tilt was used to determine the speed of cursor movement. Minimum, maximum, and mean RMS values were extracted from head roll and pitch accelerometer signals during a calibration task (see *Calibration*). The magnitude of the head tilt was then normalized by mean RMS value, and either minimum (i.e., for left or down movements) or maximum (i.e., for right or up movements) RMS values extracted from the calibration task. This produced a scalar multiplier from -1 to 1 to be multiplied by the RMS of the accelerometer signal. As a result, small head tilts produced slow cursor movements in the intended direction, whereas larger head tilts near the maximum calibrated value would produce fast cursor movements. Movements with RMS values exceeding those obtained during calibration were automatically scaled to the maximum magnitude defined during calibration for the direction of interest.

In addition to moving the cursor using head tilts, participants were able to emulate cursor clicks using a hard wink or blink. The maximum RMS from the sEMG signal captured during the calibration task (see *Calibration*) was calculated over 54-ms windows, and was used to discern intentional muscle activation via hysteresis thresholding. Specifically, the system recognized a muscle activation as a deliberate cursor click if the RMS of the sEMG signal exceeded a first threshold; however, the cursor would remain in a "selected" position until the RMS of the sEMG signal fell past a second threshold. These thresholds were determined by multiplying the maximum RMS of the calibration signal by scalar factors: the first threshold multiplier was 0.7, as adopted from Cler and Stepp [39], and the second threshold multiplier was 0.4, as determined during pilot testing.

(4) Calibration: The ACC/sEMG system was calibrated once per participant with the lighting in the room turned on. Participants were instructed to produce a hard wink or blink and to tilt their head along the roll and pitch axes. This calibration process lasted 15 seconds. The maximum RMS value of the sEMG signal was extracted to determine a threshold discerning intentional cursor clicks and the minimum, maximum, and mean RMS values were extracted from head tilt accelerometer signals to determine direction and speed of cursor movements. To ensure that the ACC/sEMG system was calibrated for sufficient cursor control, a brief cursor test was performed: a target appeared in one corner of the computer screen and the participant was instructed to guide the cursor to the target and select it. Upon selection, the target changed location to another corner of the computer screen until targets within each of the four corners of the computer screen were selected. If the participant failed to select a target in under 20 seconds, the ACC/sEMG system was recalibrated. More than one calibration was required in 18 of 24 participants (M = 3.8 calibrations, SD = 2.7 calibrations). On average, calibration took approximately five minutes.

6) Data Analysis:

a) Performance metrics: Outcome measures of target selection accuracy, movement time between targets, and path efficiency were averaged across the five rounds for each of the [2 computer access methods × 2 lighting conditions × 3 computer orientations] 12 sessions. This resulted in 12 values of each outcome measure per participant.

Target selection accuracy was a binary parameter that was equal to one when participants successfully selected the active target and zero when the participants were not able to select the active target. Accuracy was set to 0% for a trial if a target was not successfully selected i.e. when it was incorrectly or unintentionally selected.

Movement time was the amount of time the user took to navigate to and select the active target. Trials for which accuracy was 0% were excluded from the analysis for target selection accuracy and movement time since the participant did not successfully select the intended target.

Path efficiency, a measure of the straightness of the cursor trajectory to the target, was calculated as the ratio of the ideal path between targets to the actual path (see example path in Fig. 2C) traveled by the participant. The coordinates in which the participant selected the previous target were designated as the origin, (x_0, y_0), whereas the coordinates corresponding to the position of the cursor when selecting the active target were defined as (x_n, y_n). The Euclidean distance between the coordinates corresponding to previous position of the cursor, and the end position of the cursor after moving was calculated and divided by the actual distance traveled, as described in Eq. 3. Trials for which accuracy was 0% were excluded.

$$\text{Path Efficiency} = \frac{\sqrt{(\mathrm{x_n} - \mathrm{x_0})^2 + (\mathrm{y_n} - \mathrm{y_0})^2}}{\sum_{\mathrm{i}=1}^{\mathrm{n}} \sqrt{(\mathrm{x_i} - \mathrm{x_{i-1}})^2 + (\mathrm{y_i} - \mathrm{y_{i-1}})^2}} \quad (3)$$

b) Statistical analysis: Data analysis was performed using Minitab 18 Statistical Software [40]. A repeated measures analysis of variance (ANOVA) test was performed on each outcome measure (target selection accuracy, movement time, and path efficiency) to examine the effects of computer access method, computer configuration, and lighting condition. Participant was included as a random factor in the model, with computer access method (ACC/sEMG, Camera Mouse), computer orientation (No Rotation, Base Rotation, Screen Rotation), lighting condition (Lights On, Lights Off), and their interactions as fixed effects. An alpha level of 0.05 was used for significance testing in each model. Effect sizes were estimated for fixed factors using squared partial curvilinear correlation (η_p^2) [41]. In analyses with significant main effects, Tukey *post hoc* tests were conducted to investigate differences among the means.

IV. Results

Table I displays the model summaries constructed for target selection accuracy, movement time and path efficiency.

A. Target Selection Accuracy

The model for target selection accuracy showed a significant, large main effect of the computer access method ($p < .001$, $\eta_p^2 = .25$), whereas lighting condition ($p < .001$, $\eta_p^2 = .05$) had a small, significant effect. Moreover, the

TABLE I

RESULTS OF ANOVA TEST TO EXAMINE THE EFFECTS OF COMPUTER ACCESS METHOD, LIGHTING CONDITIONS, AND COMPUTER ORIENTATION ON TARGET SELECTION ACCURACY, MOVEMENT TIME AND PATH EFFICIENCY

Model	Effect	*df*	η_p^2	*F*	*p*
Target Selection Accuracy	**Modality**	**1**	**.25**	**84.0**	**<.001**
	Light	**1**	**.05**	**12.9**	**<.001**
	Orientation	2	—	1.02	.36
	Modality × Light	**1**	**.04**	**11.3**	**.001**
	Modality × Orientation	2	—	0.36	.70
	Light × Orientation	2	—	0.04	.96
	Modality × Light × Orientation	2	—	1.52	.22
Movement Time	**Modality**	**1**	**.73**	**674**	**<.001**
	Light	1	—	0.36	.55
	Orientation	2	—	0.15	.86
	Modality × Light	1	—	3.92	.05
	Modality × Orientation	2	—	0.01	.99
	Light × Orientation	2	—	0.26	.77
	Modality × Light × Orientation	2	—	0.32	.73
Path Efficiency	**Modality**	**1**	**.03**	**5.53**	**.01**
	Light	1	—	6.60	.52
	Orientation	2	—	0.42	.24
	Modality × Light	**1**	**.02**	**0.93**	**.04**
	Modality × Orientation	2	—	4.23	.76
	Light × Orientation	2	—	0.28	.75
	Modality × Light × Orientation	2	—	0.29	.15

Note: "Modality" refers to computer access modality, "light" refers to lighting conditions, and "orientation" refers to computer orientation.zz

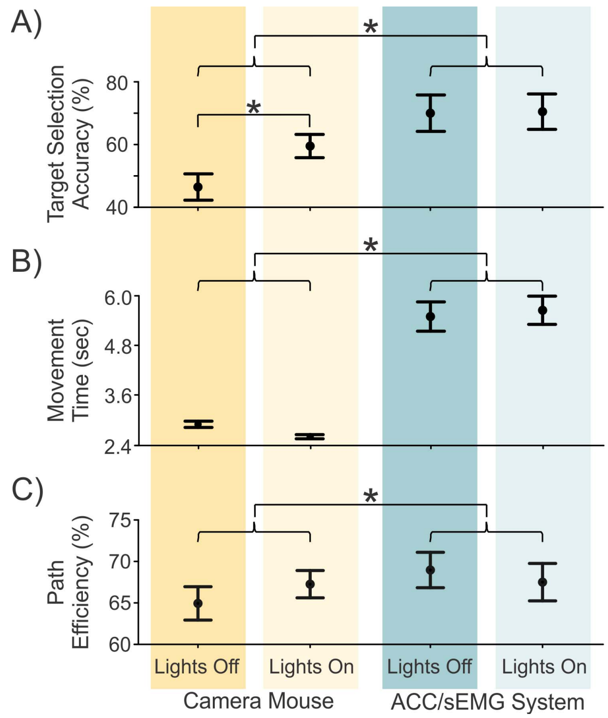

Fig. 5. Mean (A) target selection accuracy, (B) movement time between targets, and (C) path efficiency for computer access methods (Camera Mouse, ACC/sEMG system) across lighting conditions (Lights On, Lights Off). Mean performance in the Lights On condition is shown in pale yellow (Camera Mouse) and pale teal (ACC/sEMG), whereas performance in the Lights Off condition is shown in dark yellow (Camera Mouse) and dark teal (ACC/sEMG). Error bars represent 95% confidence intervals. $^*p < .05$.

interaction between computer access method and lighting conditions produced a significant, small effect ($p < .05$, $\eta_p^2 = .04$) on target selection accuracy. *Post-hoc* analysis showed that target selection accuracy was significantly higher for the ACC/sEMG system (M = 70.3%) than Camera Mouse (M = 53.0%). Additionally, target selection accuracy was greater when the target acquisition task was completed in the Lights On condition (M = 65.0%) as compared to the Lights Off condition (M = 58.2%). Target selection accuracy when using the ACC/sEMG system in the Lights On condition (M = 70.5%) was significantly higher compared to that of Camera Mouse in the Lights On condition (M = 59.5%; see Fig. 5A). Similarly, the target selection accuracy was significantly higher while using ACC/sEMG system in the Lights Off condition (M = 70.1%) than that of Camera Mouse in the Lights Off condition (M = 46.4%). No significant differences were found in the target accuracy selection of ACC/sEMG system across the two lighting conditions; however, the target selection accuracy of Camera Mouse in Lights On condition (M = 59.5%) was significantly higher than in the Lights Off condition (M = 46.4%). The main effect of computer orientation and its associated interactions did not significantly affect target selection accuracy.

B. Movement Time

Two trials using the ACC/sEMG system were removed prior to conducting statistical analyses on movement time due to a zero-target selection accuracy within the trials. For the remaining 144 trials for Camera Mouse and 142 trials for the ACC/sEMG system, computer access method had a significant, large main effect ($p < .001$, $\eta_p^2 = .73$) on movement time. The mean movement time for ACC/sEMG system (M = 5.55 s) was statistically significantly greater than the mean movement time for Camera Mouse (M = 2.76 s; see Fig. 5B). Neither lighting conditions nor the interactions between lighting conditions and computer access methods produced significant effects on movement times. Similarly, the main effect of computer orientation and its associated interactions did not significantly affect target selection accuracy.

C. Path Efficiency

As with movement time, two trials when using the ACC/sEMG system were removed prior to path efficiency analyses. Using the remaining 144 trials for Camera Mouse and 142 trials for the ACC/sEMG system, the model for path efficiency showed a significant albeit small main effect of the computer access method ($p < .05$, $\eta_p^2 = .03$; see Fig. 5C). The mean path efficiency for ACC/sEMG system (M = 68.3%) was significantly greater than that of Camera Mouse (M = 66.1%). Although there was no significant main effect of the lighting conditions, the interaction between the computer access method and lighting condition produced a significant, small effect ($p < .05$, $\eta_p^2 = .02$) on path efficiency:

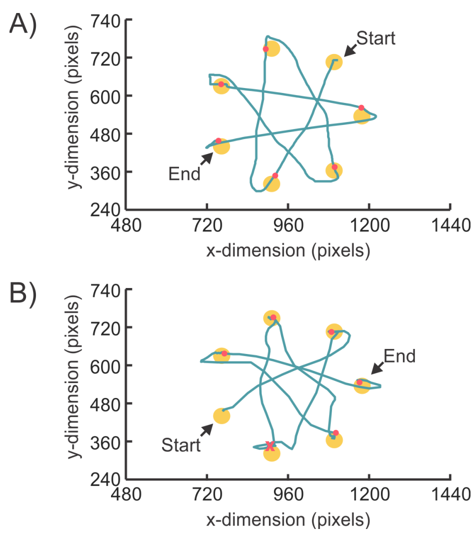

Fig. 6. Example cursor trajectories when using A) the ACC/sEMG system, and B) Camera Mouse. Starting targets ("Start") were not factored into outcome metric computation. Final targets ("End") marked the end of a trial. Inaccurate target selections are noted by a pink "X." Note that although cursor trajectories were recorded at a screen resolution of 1920 × 1080 pixels, the plots here were cropped for clarity.

the average path efficiency when using ACC/sEMG system in the Lights Off condition (M = 68.9%) was significantly greater than that of Camera Mouse in the Lights Off condition (M = 64.9%). No significant differences were found between path efficiency when using the ACC/sEMG system (M = 67.5%) versus Camera Mouse (M = 67.3%) in the Lights On condition. The main effect of computer orientation and its associated interactions did not significantly affect target selection accuracy.

D. Example Cursor Trajectories

Fig. 6 shows example movement trajectories from a single participant when using the ACC/sEMG system (Fig. 6A) and Camera Mouse (Fig. 6B). Trajectories are shown for the Lights Off condition to highlight differences between systems. When using the ACC/sEMG system, the participant successfully selected all targets (i.e., 100% target selection accuracy) at an average movement time of 4.04 seconds and path efficiency of 74.5%. The participant completed the trial using Camera Mouse at an average movement time of 2.78 seconds and path efficiency of 72.9%. In this trial, the participant inaccurately selected one target, resulting in an accuracy of 83.3%.

V. Discussion

In this study, two computer access methods were compared in a target acquisition paradigm using measures of target selection accuracy, movement time, and path efficiency. Room lighting conditions and computer orientations were altered to emulate everyday use of a computer for communication.

We hypothesized that user performance would be worse when using Camera Mouse as compared to ACC/sEMG. Although path efficiency and target selection accuracy during the task were significantly higher when using ACC/sEMG, movement time was significantly longer. This increase in movement time may be the result of the interactions between features of the cursor systems (e.g., smoothing and sensitivity settings) and user compensatory responses during the task, and should be investigated in future work. Although participants made faster movements to reach their intended target when using Camera Mouse, it is apparent that users experienced the "Midas touch" problem when using this system. The Midas touch problem is a common issue with dwell time-based access methods. It is characterized by unintentional target selection as a result of short dwell times or by a user briefly resting while performing the task [42], [43]. Our results show a clear speed-accuracy trade-off: while Camera Mouse offered a faster mean navigation speed compared to ACC/sEMG, the latter resulted in higher mean target selection accuracy. Participants could increase their movement time by decreasing selection accuracy, and vice versa [44]. These findings suggest that movement speed and target selection accuracy are key factors to consider when assessing access method performance.

We hypothesized that user performance would decrease when using Camera Mouse in a dark room due to the potential effects of drift and a reliance of the video camera on high facial contrast to track features [32]. Conversely, we hypothesized that user performance would not significantly differ when using ACC/sEMG across lighting conditions since accelerometry and sEMG are light-insensitive [18]. No significant differences were found in mean path efficiency, movement time, or target selection accuracy for ACC/sEMG, whereas mean target selection accuracy was significantly different across lighting conditions while using Camera Mouse. Three participants wore eye glasses; when calibrating the system at the start of each trial, the automated feature selection functionality in the Lights Off condition tended to focus on the reflection of the laptop screen on the lens of the eye glasses instead of corner of the eye. The feature was thus manually selected for these participants.

While no significant differences were found in user performance across the three computer orientations, it was subjectively noted that the automated feature selection functionality of Camera Mouse properly identified the corner of the eye for each participant across the different computer orientations. Additionally, it has been reported that for the most optimal performance, Camera Mouse must be placed directly in front of the user in order for the laptop computer to track the feature. With different computer orientations, the alignment of the camera changes with respect to the user; hence, we expected the performance of Camera Mouse to worsen across different computer orientations. Zuniga and Magee (2017) subjectively reported that feature tracking began to drift from its original position, and ultimately caused a degradation in Camera Mouse performance such that the feature had to be manually reset [45]. Here, the Camera Mouse system was recalibrated at the start of each trial to minimize issues with feature tracking. ACC/sEMG was only calibrated prior to the familiarization task, with an average of four calibrations required to proceed to the task. Despite more trials being necessary to calibrate ACC/sEMG, the single, a successful calibration trial lasted throughout all sessions across lighting conditions and computer orientations.

Overall, differences in the performance of the two computer access methods shows that the efficacy of their use is also dependent on user ability and preference. For those who have difficulty in holding their head steady to activate the dwell-time selection mechanism using Camera Mouse, ACC/sEMG system's intentional selection mechanism provides a more reliable access method. This is in line with the findings of a study conducted by Magee *et al.* (2015) [42], which compared the performance of Camera Mouse to a single-muscle activation controlled selection cursor, and reported that participants found it difficult to hold the cursor steady in a small area for intentionally selection using Camera Mouse, and felt more in control with the sEMG cursor control method.

This research study offers a comprehensive comparison of two different computer access methods, each with its own advantages. It is important to note that ACC/sEMG requires cost-intensive sensors that need to be placed following proper skin preparation; conversely, Camera Mouse is a free-to-download software and does not require any user-borne accessories or preparation to use. Furthermore, a system combining accelerometry and sEMG may be prone to noisy accelerometer signals, and potential discomfort due to sEMG sensors. Additionally, ACC/sEMG target selection relies on the participant's ability to voluntarily perform a winking or blinking gesture. Although this method of interaction may not be ideal for a population that suffers from facial paralysis, a large majority of individuals with severe impairments that have spared facial musculature may still benefit from this computer access method. To this point, future work should evaluate ACC/sEMG in individuals with motor impairments.

The benefits of using ACC/sEMG are not only apparent for those with motor impairments, however. As the current study focuses on unimpaired individuals, it is necessary to discuss other applications for the system. One potential application includes emulating a typical computer mouse for basic computer use (e.g., accessing social media). Indeed, previous work in this domain demonstrated that a system leveraging head and eyelid movements could successfully be used to navigate the social network Facebook by unimpaired users [46]. Within a similar vein, our ACC/sEMG system may be a useful addition to augmented reality devices via supplementing eye-based target selection [47]. ACC/sEMG may also be useful in the realm of smartphone technology: Head- and eye-tracking have been proposed as promising modalities for smartphone device control (e.g., [48]–[52]), with prior work demonstrating that head-tracking was preferred over eye-tracking for smartphone-based gaming [53]. Abbaszadegan *et al.* [53] also evaluated the performance of tilt input derived from the smartphone's built-in accelerometer for device control; although our system uses tilt input derived from head movement instead of from the smartphone itself, it may be interesting to expand upon this work by examining the performance of the ACC/sEMG system for smartphone device control. Future work should thus investigate the ability of the ACC/sEMG system to be used for device control of smartphone and personal computer systems.

VI. Conclusion

In the current study, the performance of a computer access method that integrates head-tilt and facial electromyography for two-dimensional cursor control was evaluated. This system, called ACC/sEMG, was compared against the free computer vision-based access method, Camera Mouse, in a target acquisition paradigm. Results showed a tradeoff between speed and accuracy: ACC/sEMG led to higher target selection accuracy and more efficient paths traveled between targets, whereas Camera Mouse resulted in faster movement times between targets. Performance when using Camera Mouse varied across room lighting conditions as compared to ACC/sEMG. Overall, results show that the ACC/sEMG system is an effective method for computer access across different lighting conditions and laptop placements.

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