AirTouch: Synchronizing in-air hand gesture and on-body tactile feedback to augment mobile gesture interaction

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Abstract

We present the design and evaluation of AirTouch, a wristwatch interface that enables mobile gesture interaction through tactile feedback during limited visual attention conditions. Unlike its predecessor, the Gesture Watch, AirTouch is supported by a push-to-gesture mechanism (PTG) where the user performs a gesture and then confirms it afterward with a trigger gesture. The Gesture Watch, in contrast, requires the user to hold a trigger gesture while performing an interaction, and its PTG method does not allow the user to preview nor reverse the action. The effect of the new PTG mechanism and tactile feedback are evaluated through two experiments. The first experiment compares AirTouch's PTG mechanism to that of the Gesture Watch both with and without visual access to the watch. The second experiment examines mobile gesture interaction with the new PTG mechanism in four conditions (with and without tactile feedback and with and without visual restriction). We found that the new PTG mechanic enabled more accurate and faster interaction in the fully visible condition. Additionally, tactile feedback in the limited visual access condition successfully compensated for the lack of visual feedback, enabling similar performance times and perceived difficulties as in the fully visible condition without tactile feedback.

1 Introduction and motivation

Gesture-based interaction is gaining attention in the consumer electronics market (e.g., Nintendo Wii and Microsoft Kinect) as a viable mode of interaction to control devices in a more natural and intuitive way. Mobile gesture interaction is a logical next step for future investigation. In a mobile interaction, users are often on-the-go interacting with their mobile device as they navigate the physical environment. When mobile, users need to split their visual attention between their device and the environment to ensure accurate hand-eye coordination while avoiding obstacles in their path. However, interacting with a mobile device while in motion raises concerns for safety [16, 19, 22].

When developing our first wristwatch user interface (UI) for mobile gesture interaction, the Gesture Watch [9], we observed similar problems. The Gesture Watch captured in-air hand gesture through wrist-mounted IR sensors and sent the gesture patterns to a recognizer. With the Gesture Watch, users could control electronic devices (e.g., MP3 player) while on-the-go.

AirTouch pairs each proximity sensor with a vibration motor pressed against the user's wrist. When the proximity sensor detects a hand above it, the corresponding motor buzzes. We designed a new push-to-gesture mechanism (PTG) for AirTouch which takes advantage of this tactile feedback. The mechanism follows two design principles of *direct manipulation: representation of the object of interest* (in this case, the tactile representation of hand movement in relation to the device) and *reversible operations* [21]. With AirTouch, a gestural command is implicitly canceled to reverse the action when the user does not commit the command with a trigger gesture. Unlike the PTG mechanism of the Gesture Watch, the new PTG of AirTouch provides an eyes-free representation of what the sensors are perceiving and allows the user to cancel the interaction implicitly in case the gesture was made in error or the system's perception of the gesture seems likely to be wrong (as judged by the user). We hypothesize that tactile feedback and the new PTG of AirTouch will assist eyes-free mobile gesture interaction when a user's vision is limited.

In this paper we present the results of two experiments that investigate mobile gesture input and vibrotactile feedback in conditions of limited visibility. The rest of the paper reports related work in mobile gesture interaction and tactile perception space, the introduction of the AirTouch system and pilot test for PTG design, and two experiments. Our first experiment evaluates the appropriateness of the new PTG technique while the second experiment evaluates the effect of tactile feedback on participants' use of AirTouch.

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2 Related work

As a design principle, direct manipulation has shaped graphical user interfaces (GUIs) and even physical UIs [8, 21]. For example, a text label or tooltip box that changes color or appears upon a mouse-over event in a GUI visually represents the *object of interest* and enables *reversible actions* as suggested by direct manipulation. By using capacitive sensing integrated with physical keys, Rekimoto and colleagues created keyboards which would display what action a given button would perform when a user touched the button but had not yet pressed it [15]. In this manner, users could interact with the physical buttons in smaller steps and retreat from an action before committing it.

Touch and sensor-based interactions in mobile and wearable computing often raise new concerns on motor performance. Proprioception [20] (perception of motion and position of body parts in accordance with joint and muscle control) is essential in motor performance [17] and highly affected by force feedback [18] and vision [14]. Even expert typists suffer performance difficulties when using touch-based soft keyboards due to the lack of force feedback [4]. This difficulty can be reduced by providing tactile or auditory feedback [12]. To reduce visual distraction in mobile interactions, researchers have explored the benefit of using haptics. Users can perceive tactile patterns on the wrist while visually distracted [11], receive tactile directional cues on the torso while driving [6], and navigate the environment helped by navigational cues on the waist [23].

Motor distraction in mobile computing (e.g., walking) can also limit human performance [2, 3]. To compensate for limited dexterity (and improve social appropriateness) while mobile, Whack Gestures [7] utilized gross gesture for inexact and inattentive interaction rather than fine gesture that requires precise hand-eye coordination. Ashbrook and colleagues tested the importance of device placement in mobile computing. They observed significantly faster interaction time on wrist-worn mobile devices than devices stored in pockets [1], suggesting that wrist-worn devices may require less motor distraction than devices placed elsewhere.

3 Apparatus and configuration

As with the Gesture Watch, AirTouch performs gesture recognition using the Gesture and Activity Recognition toolkit (GART) [13], which utilizes hidden Markov models (HMMs). GART links the patterns of hand gesture to corresponding commands that can be sent to electronic devices.

3.1 Wristwatch interface and GART

The Air Touch consists of two parts, the sensors in a wristwatch UI and a tactile display which are fastened by

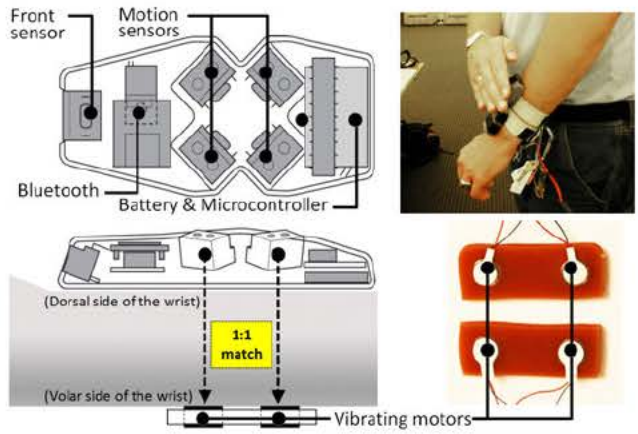

Figure 1. AirTouch wristwatch interface

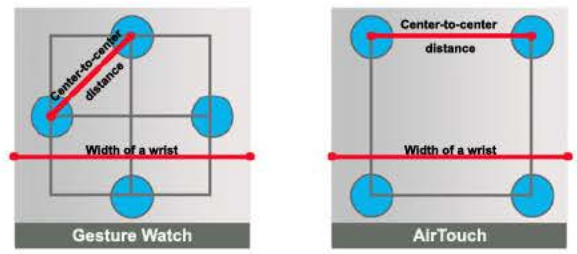

Figure 2. Sensor layout comparison

an elastic strap and worn on the dorsal and volar sides of the wrist, respectively (Figure 1). Since we observed user difficulty in localizing vibrators on the dorsal side of the wrist in our previous studies [5], we located the tactile display on the volar side, where high perception accuracy has been shown previously [10, 11]. The size of the wristwatch UI is 109mm x 20.5mm x 49.5mm (L x H x W).

We use four SHARP GP2Y0D340K IR proximity sensors to capture in-air hand gestures between 10 - 60 cm above the wrist. Four vibrating motors (Precision Microdrives #301-101, 200Hz, d = 10 mm, h = 3.4 mm) are arranged in a square with 30 mm center-to-center distances. A rubber housing ensures constant center-to-center distance between the motors. Unlike the cardinal layout of the Gesture Watch, AirTouch sensors are arranged in an orthogonal layout (Figure 2) to assist easier perception of tactile feedback. The orthogonal motor layout that is synchronous with sensor layout enables longer center-to-center distances between motors compared to the cardinal layout. We believe that the longer center-to-center distances and the simpler grid of AirTouch enable easier perception.

The microcontroller synchronizes sensors and motors by turning on and off vibration motors based on the sensors' input. Users can mentally synchronize the in-air hand gesture with on-body tactile feedback. Power is supplied by a 3.7

Petitioner Ex-1039, 0002

Figure 3. Gestures tested in the user study.

Figure 4. GART GUI: training (left), recognition (right)

V Lithium-ion battery. A power regulator is used to guarantee a stable 3.3 V power supply. The front sensor is placed at the side of the watch facing toward the user's hand. To avoid false triggering caused by the hand, the front sensor is tilted 20 degrees upward.

A remote computer receives sensor data from AirTouch through Bluetooth and processes the gestures. The GART GUI is implemented in Java, and it assists visual training of new gestures and recognizes trained gestures during experiments (Figure 4).

3.2 Push-to-gesture mechanism (PTG)

Once captured, data from the sensors are passed to an ATmega 168 microcontroller. The microcontroller stores sensor data, turns on and off motors, and waits for user confirmation rather than immediately sending the gesture to GART. This storage function of the microcontroller is added to AirTouch to support our new PTG. The new PTG in AirTouch has a time-out period for user confirmation in the interaction. Within the time-out period, users can make a decision to confirm or abort the gesture (Figure 5). If the tactile sensation of the hand gesture does not match user's intention ('3-1.Receive tactile feedback' in Figure 5), the user can cancel the incorrect gesture by not triggering the confirmation sensor within the time-out period ('4. Confirm or abort' in Figure 5). The microcontroller will send data to GART only when the user confirms the gesture by quickly tilting up and down his wrist within the time-out period. Stored sensor data is discarded after the time-out. Following the principles of *direct manipulation* [21], the on-off status of the motor indicates the state change of the *object of interest* (sensors) and the time-out period that waits for user confirmation enables *reversible user operations*.

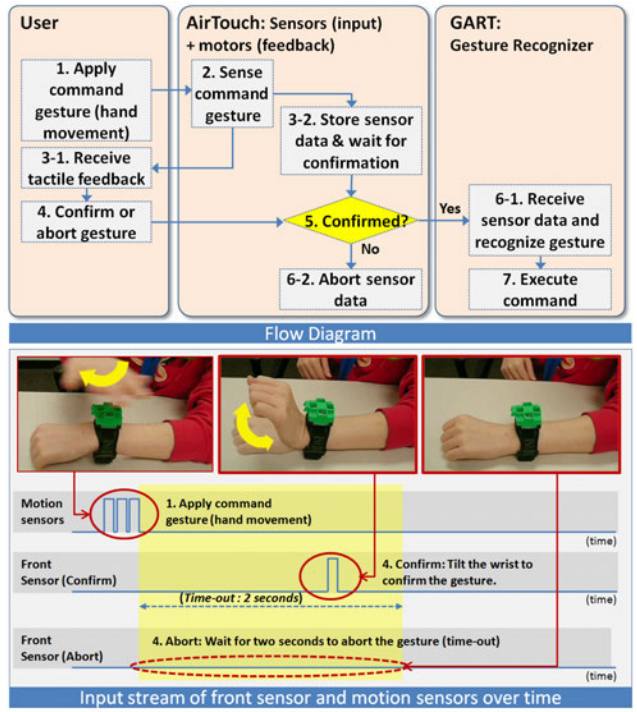

Figure 5. AirTouch interactions.

Unlike the PTG of the Gesture Watch which required a pair of wrist tilting gestures for segmenting the gesture to be recognized (Figure 6), the time-out period of AirTouch enables automatic segmentation of the gesture by taking advantage of the 'idle period.' With this PTG, the semi-automatic gesture segmentation in AirTouch is simpler than the 'do-while' type interaction of the Gesture Watch (i.e., hold segmentation gesture while applying command gesture).

To find the appropriate length of the time-out period, we performed a pilot test with seven participants. During the pilot test, participants were asked to apply four gestures (Figure 3) six times (4 gestures x 6 times = 24 trials) in random order while wearing the AirTouch system on their non-dominant wrist. Participants listened to voice commands from a computer and applied the gesture with the new PTG (Figure 5). We measured the time lapse between the last data input from the motion sensor and the front sensor activation. The result calculated from 168 data points showed that the maximum time between the hand gesture and confirmation was 1.3 seconds. Thus, we decided to set the time-out period for two seconds in our formal experiment.

4 Study design overview

To investigate the possible benefits of tactile feedback with respect to visual attention in mobile gesture interac-

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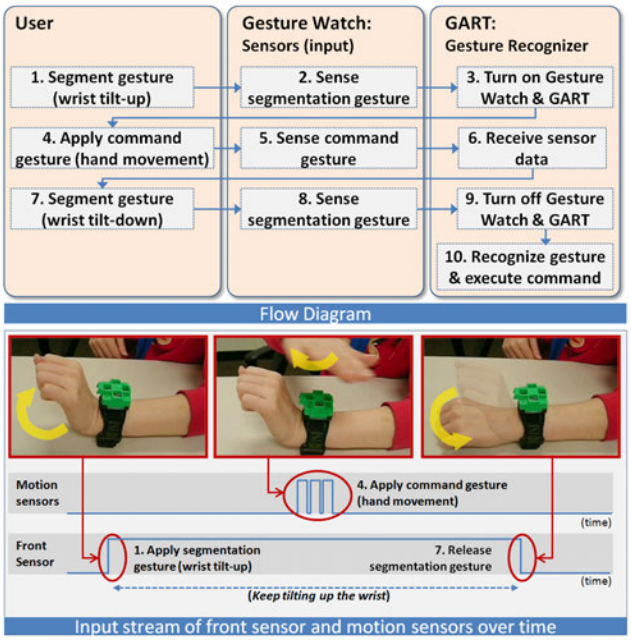

Figure 6. Gesture Watch interactions.

Table 1. Conditions for experiments 1 and 2

	Experiment 1 (old PTG vs. new PTG)		Experiment 2 (effect of tactile feedback)	
	old PTG	new PTG	no feedback	has feedback
full vision	Old-full	New-full	nT-full	T-full
limited vision	Old-limited	New-limited	nT-limited	T-limited

tions, we conducted two experiments involving limited and full visual access to the interface. Experiments addressed the following research questions: how are the two PTG mechanisms different and what is the impact of the new PTG on user performance compared to the previous PTG? (experiment 1) and does tactile feedback during gestural interaction compensate for limited visual access while the user walks (experiment 2)? The study design for each experiment is composed of 2x2 conditions (Table 1). Tasks in all conditions are performed while the participants walk in a designated path (Figure 7-right). The walking path is set in a quiet lab setting. A pair of orange flags visually mark each 'gate' in the walking path to guide the user. All participants were recruited from the Georgia Institute of Technology.

5 Experiment 1

Fourteen participants volunteered for the experiment (mean age = 22.36, eleven male). The mean width and circumference of their wrists were 54.53 mm and 162.93 mm, respectively. All participants were right-handed except one. 50% of the participants wore a wristwatch daily. During the experiment, we measured accuracy and amount of time required to gesture (4 gestures x 6 times x 2 conditions x 2 groups x 14 participants = 1344 trials). Participants completed a NASA Task Load Index (TLX) for each condition and a survey on their impressions of the interfaces.

5.1 Task and procedure

The experiment was conducted with a mixed between-within subject method in a balanced order. We selected this method because interactions with different PTG mechanisms is likely to cause confusion when used consecutively by one person. Seven participants (five male) controlled the watch with the old PTG method (Figure 6), whereas the other seven participants (six male) used the new PTG mechanism (Figure 5). No tactile feedback was provided in this experiment. Participants in each group had two conditions, full or limited vision. To simulate limited visual access to the watch, participants wore half-blocked goggles. The goggles limited the wearer's sight below the eye level when interacting with the wristwatch interface. However, the goggles allowed full vision for walking.

The experimental procedure was composed of four sessions: training, walking practice, main test, and survey session. During the training session, participants wore the watch UI on the non-dominant wrist, stood in front of the computer, and attempted four gestures three times (4 gestures x 3 times = 12 trials) guided by the researcher. The training GUI (Figure 4-left) and a synthetic voice on the computer presented the name and direction of the gesture. Once the participants heard the voice command for the gesture, they applied the gesture to the watch UI. This procedure is identical to the full vision condition in the main session except for the absence of the visual guide (gesture direction and name) and additional mobility condition (standing instead of walking). After finishing the training session, participants practiced walking twice along the designated path. The researcher led the participant for the first trial and followed the participant for the second trial (Figure 7-right).

In the main test session, participants wore headphones and carried a laptop in a backpack (Figure 7-left). On the laptop computer, the GART test GUI (Figure 4-right) was played to provide tasks for the user. This GUI was also remotely shared to another computer in the lab so that the researchers could monitor the live status of the performance. The voice command from the headphones prompted the study by saying 'Welcome to the user study. Please start walking.' Within 5 seconds, the first task was given by a voice command. The name of the gesture was played twice to ensure clear delivrey of the voice command (e.g., "Forward gesture. Forward."). Then the participant applied a hand gesture to the wristwatch UI. For the first group that used the old PTG mechanism, no feedback for confirmation or failure of the gesture was provided as the old system was

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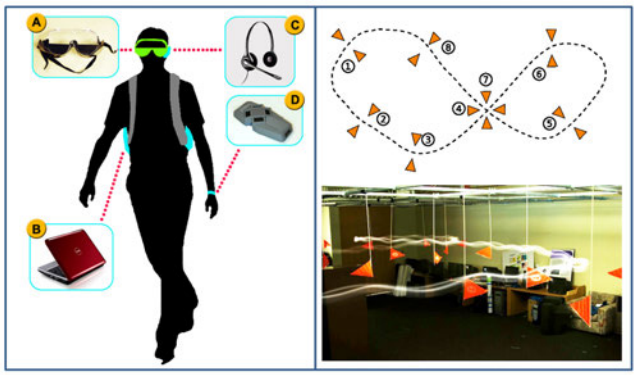

Figure 7. Test setting (left, A: Half-blocked goggle, B: Laptop computer, C: Headphone, D: AirTouch), walking track (right).

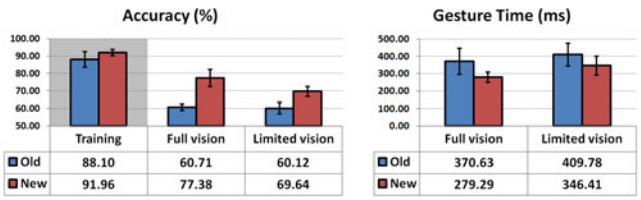

Figure 8. Experiment1: accuracy and time.

not designed to support it. On the other hand, for the second group that used the new PTG method, voice feedback was provided to indicate the user's decision (e.g., "Confirmed" or "Aborted, please try again"). The result of the gesture performance (correct or incorrect) was not provided for either groups. After a random interval that ranged between 10 and 20 seconds, another voice command was played to guide the next trial.

While participants walked and performed the task, researchers sat on the desk next to the walking path. One researcher controlled the GART GUI, and another researcher observed the participants to take notes or help them upon request. A subjective rating survey and the NASA-TLX was administrated after the main test session.

5.2 Result

The mean accuracy of the training session for the new and old PTG methods was 91.96% and 88.10%, respectively. In the main test, we measured performance accuracy (Figure 8-left) and gesture time (Figure 8-right), which is the time difference between the first and last incoming sensor data captured. The mean accuracy of the new PTG system was higher than the old system with statistical significance in the full vision condition (paired t-test with Bonferroni correction, $p < .05$), but not in the limited vision condition. The effect of visual restriction (full vs. limited vision) was not statistically significant in either PTG types (old and new).

Gesturing using the new PTG method was faster than the old PTG method with statistical significance in the full vision condition (paired t-test, Bonferroni correction, $p < .05$), but not in the limited vision condition. The effect of the visual condition (full vs. limited vision) was statistically significant only in the new PTG method (paired t-test, Bonferroni correction, $p < .05$).

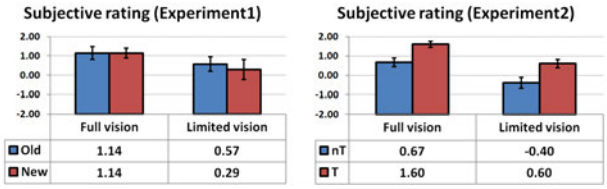

Figure 9. Subjective rating (-2.0 = very difficult, -1.0 = difficult, 0.0 = neutral, 1.0 = easy, 2.0 = very easy.

5.3 Subjective rating and workload

The difficulty (Figure 9-left) of all conditions was perceived as easy to neutral. The subjective rating of each condition indicated that the performance with full vision was perceived as easy (≈ 1.0) both with the old and new PTG methds. The limited vision condition was rated slightly lower as neutral to easy (0.0 - 1.0).

Results from the participants' self reports that were collected with the NASA-TLX assessment indicated that the design of the gestures was simple and easy, but using the system required a bit of familiarization time. Although the gesture (command, segmentation, and confirmation gesture) was awkward at first for some participants, soon they felt that the gestures became natural. Additionally, some participants reported needing extra effort while applying the L-shaped gesture. We will discuss the learnability of command gestures and PTG interactions later.

Ten out of fourteen participants mentioned that they could not coordinate hand and sensor correctly in the limited vision condition (which indicates the visual attention needed during the interaction). This difficulty was consistently observed both with the old and the new PTG mechanisms. Increased confidence was frequently mentioned in the full vision conditions. Some old PTG participants reported that holding the tilted non-dominant wrist for segmentation was obtrusive because they put extra effort in to avoid hitting the wrist during a dominant hand gesture.

Petitioner Ex-1039, 0005

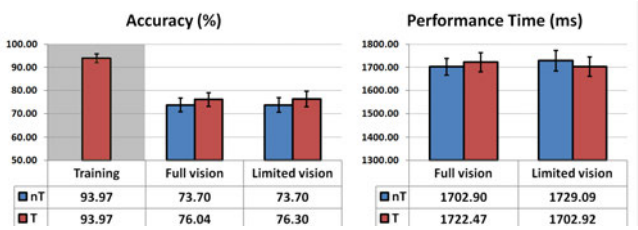

Figure 10. Experiment2: accuracy and time.

6 Experiment 2

Sixteen participants volunteered for the experiment (mean age = 24.25, thirteen male). The mean width and circumference of their wrists were 56.26 mm and 165.81 mm, respectively. All participants were right-handed except one. 37.5% of participants wore a wristwatch daily. During the experiment, we measured accuracy and performance time (4 gestures x 6 times x 4 conditions x 16 participants = 1536 trials) and recorded subjective feedback from the NASA-TLX and our survey.

6.1 Task and procedure

The experiment employed a within subject design in a balanced order. All participants had four conditions that were composed of 24 trials (4 gestures x 6 times). The 2x2 conditions of this experiment was determined by the presence or absence of tactile feedback (with tactile feedback = T, without tactile feedback = nT) and visual restriction (full vision, limited vision) (Table 1). The equipment and procedure of experiment 2 was identical to experiment 1.

6.2 Results

The mean accuracy of the training session was 93.97%. In the main test, we measured performance accuracy (Figure 10-left) and performance time (Figure 10-right). The performance time was broken down to two parts: gesture time and confirmation time. Gesture time indicates the time between the first and last sensor data captured, whereas confirmation time means the time between the last sensor data and the confirmation or rejection of the event.

The effect of tactile feedback (T vs. nT) on accuracy was not statistically significant (paired t-test, $p > .05$) regardless of the visual restriction. Similarly, the effect of visual restriction (full vs. limited vision) was not statistically significant regardless of tactile feedback ($p > .05$). When examining the accuracy to each gesture, the gesture type (e.g., backward, forward, inbound-L, outbound-L) affected the accuracy in all four conditions (one-way ANOVA, $p < .05$).

In performance time, the effect of tactile feedback was observed differently in full and limited vision conditions. In the full vision condition, the effect of tactile feedback (T vs. nT) was not statistically significant ($p > .05$). On the other hand, in the limited vision condition, tactile feedback enabled faster performance time with statistical significance (t-test, Bonferroni correction, $p < .05$). This result indicated that tactile feedback was more beneficial when the user's visual access to the interface was limited. The effect of visual restriction (full vs. limited vision) was statistically significant only in nT condition (t-test, Bonferroni correction, $p < .05$). This result indicated that the effect of visual restriction was significant when tactile feedback was not provided, yet not significant when the tactile feedback was provided.

6.3 Subjective rating and workload

The subjective rating showed that the full visual access condition consistently improved performance regardless of tactile feedback (Figure 9-right). Similarly, participants reported that tactile feedback made the task easier by increasing their confidence regardless of the visual condition. Although the accuracy result was not given to the participants during the test, most participants reported that the tactile feedback clearly represented their hand-sensor coordination. (i.e., "The tactile feedback tells where my hand is.") With tactile feedback, the perceived difficulty of limited vision condition (T-limited) was similar with that of full vision condition without tactile feedback (nT-full). This result indicated that the presence of tactile feedback compensated for the visual restriction. This compensation was consistently observed in the performance time as well as participants' self report.

Interestingly, all sixteen participants reported that tactile feedback was helpful even though none of the participants clearly felt the one-on-one matching of sensors and motors to localize the tactile stimulation. Instead of the localized buzz from each motor, all sixteen participants perceived the tactile clue as a binary alert that indicated presence and absence of the dominant hand on top of the sensors. With respect to the appropriate sensor-motor layout and gesture design, we will revisit the design implication of this finding later in the discussion.

7 Discussion and Future Work

In experiment 1, a difference in accuracy and time to gesture between the old and new PTG methods was observed only when the interface was fully visible. In the full vision condition, the new PTG method enabled higher accuracy and faster gestures. Participants using the old PTG method reported extra effort in performing the trigger gesture in parallel to the commmand gesture and in avoid hitting the tilted non-dominant wrist (trigger gesture) during the interaction. Since we did not observe such extra effort in the

Petitioner Ex-1039, 0006

new PTG method, we assume that the sequence of actions of the dominant hand (segmentation gesture) and the non-dominant hand (command gesture) in the new PTG method required less effort than the older method.

In experiment 2, we found slower performance for the limited vision situation only in the nT condition (no tactile feedback). This finding suggests that tactile feedback provides appropriate support when the user's visual attention is limited in mobile interactions. The similarity between T-limited condition and nT-full condition for the performance times (Figure 10-right) and subjective ratings (Figure 9-right) suggests that tactile feedback can compensate for limited visual attention in the AirTouch interaction. This result indicates that tactile feedback can successfully assist mobile gesture interaction when the user's visual attention for the interface is limited while walking.

The NASA-TLX result did not show a difference among conditions but revealed general guidelines for further improvement. For some participants, difficulties in matching the gesture name and hand movement (mental demand) and applying the L-shaped gesture correctly (physical demand) were observed. Since these difficulties are closely related to the the appropriateness in gesture design and learnability, we believe that a longitudinal study would be necessary to observe more accurate effects of tactile feedback in mobile gesture interaction.

Participants perceived the tactile feedback as a binary signal rather than four localized sensations. This finding suggests that our efforts at providing clearly localized tactile sensations by changing the sensor layout (Figure 2) was not meaningful. Thus we decided to re-rotate the sensor layout to the cardinal arrangement (Figure 2-left). In the new arrangement, having a single motor would be sufficient. We assume that the 3x3 grid in the cardinal arrangement might enable more precise hand gesture sensing and more accurate recognition by utilizing a higher density of sensing points.

During the experiments, we observed three limitations of the study that were caused by the test setting, hardware, and gesture design. Since the test was performed in a lab setting, the walking task did not demonstrate the chaos of in-the-wild mobile interaction. In the fully visible condition that was also supported by tactile feedback (T-full), some participants reported that they used their vision only for the walking task but not for gesture interaction, whereas other participants shifted their visual attention between the walking path and the wrist. This result indicates that the user's vision was not as successfully controlled as we intended.

In addition, we found that the sensor range needed to be shortened. Occasionally, the system aborted the attempt soon after the voice command even before the participants applied a hand gesture to the motion sensors. Through real time observation, we found that the false triggering of the motion sensor was subject to body posture (e.g., pulling the forearm too close to the body or tilting the wrist and elbow toward the chest or face), which was less consistent while walking than while standing. When IR sensors accidentally captured data from chest or upper forearm of walking participants, the false data was considered as hand gestures and unintentionally started the clock to count the time-out period. Although the aborted trial did not directly affect performance accuracy, participants reported frustration whenever they heard the abort message from the system. To resolve this problem, we decided to use sensors with a much shorter detection range in our new design. The new wristwatch UI is smaller both in physical dimensions (46.5mm x 17mm x 45mm) and sensor range (Figure 11, black wristwatch UI). The proper detection range should be explored in future work.

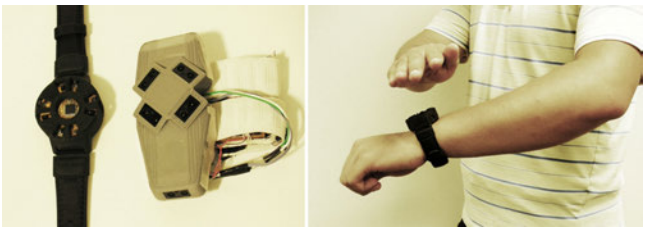

Figure 11. New AirTouch UI (black watch).

Although the new PTG method allows the canceling of a mistaken action upon user perception, none of the participants took advantage of this function. In experiment 2, all trials from the sixteen participants were confirmed without intentional abortion. We assume that this tendency was due to the easy set of gestures that we provided. To learn more about the benefit of the new PTG method in AirTouch with respect to the capability for reversible action across diverse gesture, testing the PTG with more sophisticated set of gestures would be required.

Compared to the training session ($\approx$ 90%), the accuracy is relatively low in the main sessions (60-80%). Given that the training session eased user performance by providing visual guidelines (gesture name and direction) in a less mobile condition (standing), we assume that the difference was caused by the combination of several factors: the walking task added additional workload; false triggering was caused by inconsistent body orientation while walking; novice users had learnability issues while memorizing and matching the gesture name and hand movement; the design and naming of the gesture might not be appropriate; and the interaction among all factors above with respect to complex gestures (e.g., L-shaped). Thus, further investigation is required to iterate on the design of hardware, gesture, and experiment in order to identify the effect of individual factors.

Petitioner Ex-1039, 0007

8 Conclusion

Our new push-to-gesture method, where the user commits a command gesture after performing it as opposed to holding a trigger posture while performing a command gesture, enables more accurate and faster mobile gesture interaction with less effort in conditions where the interface is visually accessible. Similar performance times and perceived difficulties were observed in a limited visual access condition with tactile feedback (T-limited) and a full visual access condition without tactile feedback (nT-full). Thus, we conclude that tactile feedback is beneficial for assisting mobile gesture interaction where visual access to the interface is limited.

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