Exploring the Role of Haptic Feedback in Enabling Implicit HCI-Based Bookmarking

Matthew K.X.J. Pan, *Student Member, IEEE*, Joanna McGrenere, Elizabeth A. Croft, *Member, IEEE*, and Karon E. MacLean, *Senior Member, IEEE*

Abstract—We examine how haptic feedback could enable an implicit human-computer interaction, in the context of an audio stream listening use case where a device monitors a user's electrodermal activity for orienting responses to external interruptions. When such a response is detected, our previously developed system automatically places a bookmark in the audio stream for later resumption of listening. Here, we investigate two uses of haptic feedback to support this implicit interaction and mitigate effects of noisy (false-positive) bookmarking: (a) low-attention notification when a bookmark is placed, and (b) focused-attention display of bookmarks during resumptive navigation. Results show that haptic notification of bookmark placement, when paired with visual display of bookmark location, significant improves navigation time. Solely visual or haptic display of bookmarks elicited equivalent navigation time; however, only the inclusion of haptic display significantly increased accuracy. Participants preferred haptic notification over no notification at interruption time, and combined haptic and visual display of bookmarks to support navigation to their interrupted location at resumption time. Our contributions include an approach to handling noisy data in implicit HCI, an implementation of haptic notifications that signal implicit system behavior, and discussion of user mental models that may be active in this context.

Index Terms—Haptic I/O, human-centered computing, user/machine systems, low-attention interfaces, notifications, browsing, multimodal user interfaces

1 Introduction

In the past decade there has been a radical shift in the type of human-computer interfaces in prevalent use. Powerful handheld technologies allow users to supplement keyboard-enabled workstations with portable, anywhere-anytime devices, now widely accepted.

Typically these devices employ a traditional Human Computer Interaction (HCI) dialogue where information is exchanged *explicitly*: users provide commands to the device through deliberate physical gestures (e.g., finger swipes) or verbal commands (e.g., Apple iPhone Siri interface) and information is received from the device through vision or audition. Although the explicit interaction method is established and ever-evolving, by definition of demanding direct attention, it undermines a user's true cognitive multitasking [1]. Consequently, while *accessible* anywhere, performance of simultaneous activities such as walking, driving or even conversing may be impaired [2], [3], [4], [5]. Today's environments call for mechanisms to move an interaction between attentional foreground and background by quietly observing and adapting to our needs [5], [6]. Interfaces in which user behavior not aimed directly at the device is used as input have been described as *implicit*; and their design and study as implicit human computer interaction (iHCI) [7], [8].

Interactions are rarely purely explicit or implicit, but often lie on a continuous spectrum where multimodal sensing and feedback afford varying levels of implicitness [9]. Because implicit sensing may occur without a user's awareness, enabling an iHCI often requires supplying unobtrusive multimodal feedback to avoid confusion as to whether their own actions/behaviors were recognized and acted upon by the system. In this work, we present and test ways of enabling an iHCI interaction by providing feedback, as framed in a use case.

1.1 A Use-Case for Enabling Implicit Interaction

Audio stream listening [10] offers a multimodal framework in which to explore how implicit-sensing transparency could work. We begin with two scenarios illustrating ways that a user's attention could be undesirably demanded by an explicit interface, and possible outcomes.

A woman listens to an audiobook on her portable media player in a dentist's waiting room. Her name is called. Her focus shifts from the audiobook to the hygienist. She fumbles in her bag to pull out the device, and eventually finds the "pause" button. The hygienist waits. Or,

... her focus shifts. Reluctant to make the hygienist wait, she pulls out her earbuds and gets up, leaving her player running. Later, she iteratively scrolls and listens backwards through the audio stream, trying to find the last familiar point and estimating forwarding intervals when she overshoots.

The user is forced either to interact with the device at untimely moments, or be penalized. Consuming streaming media often breeds this situation—a ringing phone when

- M.K.X.J. Pan and E.A. Croft are with the Department of Mechanical Engineering, University of British Columbia, 6250 Applied Science Lane, Vancouver, BC V6T 1Z4, Canada. E-mail: mpan9@interchange.ubc.ca, elizabeth.croft@ubc.ca.
- J. McGrenere and K.E. MacLean are with the Department of Computer Science, University of British Columbia, 2366 Main Mall, Vancouver, BC V6T 1Z4, Canada. E-mail: {joanna, maclean}@cs.ubc.ca.

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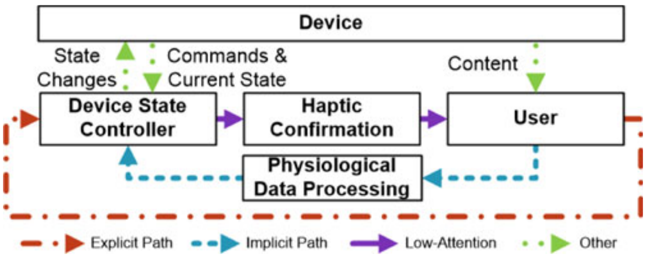

Fig. 1. Diagram of the multimodal feedback loop (interruption time): bookmarks are implicitly placed based on physiological data, which are rendered unobtrusively with haptic cues. A different feedback loop governs cues employed during explicit resumptive navigation.

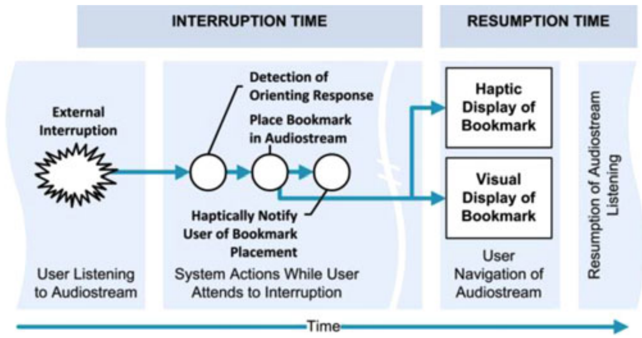

Fig. 2. Flowchart showing progression of events in the audio stream bookmarking use case.

watching TV, engaging music that distracts a driver during a difficult maneuver, or a neighbor stopping to chat while a gardener is listening to a podcast.

To address this, we proposed and explored the feasibility of an interaction model employing iHCI for this use case in [9], [10]. Our paradigm uses physiological signals in a device's control loop, generating a response to the user's inferred affective state. During design, we learned that users wanted to be informed of actions automatically taken. This guided us towards *unobtrusive feedback* of action information, to reduce the urge for volitional action at interruption time. This reassuring loop-closing (Fig. 1) is implicitly initiated and ambient rather than completely silent, thus *enabling* the iHCI component of the system.

We established the technical viability of the interrupted audio stream use case in [11], employing a user's electrodermal activity to drive an auto-bookmarking system for audio streams. Bookmarks are algorithmically placed when the system detects an orienting response (OR: a user's immediate response to a change in the environment) to an interruption. ORs suitable for bookmarking streaming media are available with reasonable reliability from conventional physiological sensors. Here, we explore the implementation and effect of (a) implicit-trigger notification and (b) resumption support via non-uniformly spaced haptic detents in our multimodal audio stream use case. The scenario now becomes:

. . . her focus shifts. A sensor embedded in her bracelet captures this, signaling the system to mark the audio stream that continues to play. She feels a small pulse on her wrist that signals a bookmark's placement. She follows the hygienist, pulling out the earbuds when it is convenient. Later when alone, she scrolls through the audio stream, feeling for discrete vibrations on her wrist indicating bookmarks. She jumps back through several automatically placed marks, locates the one placed just before the interruption, and resumes playback from there.

Physiological data is noisy, as is most contextual data. Its display must be an unobtrusive indication. Therefore, we designed the system to offer user 'suggestions' in the form of navigable breadcrumbs. A more direct action (e.g., stopping audio stream play) would likely frustrate the user in the case of false positive detections. In this use case, we notify the user of the breadcrumbs via haptic cues, to avoid interference with audio consumption and to facilitate eyes-free multi-tasking.

We posit that these cues will be useful at *interruption time*: ambient access to awareness that bookmarks have been placed can reassure users, allowing them to focus on the interruption. This awareness, as bookmarks are placed, may also facilitate later bookmark retrieval. For example, if the user notices that no cue is provided when there should have been (false negative), or extra bookmarks have been erroneously placed (false positives), the user can change later navigation strategy to minimize effects of such errors. Clearly perceptible haptic rendering of bookmarks delivered at resumptive listening time can further assist in re-finding the location, via tactile landmarks that echo the bookmarks' temporal spacing (Fig. 2).

This use case exemplifies a multimodal interaction loop and encompasses the main mechanisms and effects of an iHCI enabled by low attention feedback. It is one of many mobile applications that can benefit from communication existing on the spectrum between fully implicit or explicit, integrated with a haptic display. Its examination provides insight into how a class of interactions can work in the presence of noisy contextual sensing, as well as preliminary performance data. Other examples include in-vehicle information displays and workplace environments where attention fragmentation is common.

1.2 Research Questions and Contributions

The goal of the present research is to demonstrate an implementation of these two feedback paths supporting the proposed implicit interaction paradigm in terms of the audio stream bookmarking scenario; and to investigate its efficacy and viability. We conducted a user experiment to test the usability, appropriateness and perceived value of haptic feedback in the context of supplying: (a) notification of bookmark placement after an interruption has been detected, and (b) haptic breadcrumbs that later assist the user in navigating to the bookmark of interest.

Four research questions help illuminate how users utilize feedback in closing an iHCI loop; and whether and how haptic displays can be utilized and accepted in signaling physiologically-derived device state changes:

Q1. Do *auto-generated bookmarks* provide assistance to users in the context of interruption?
Q2. Does *haptic notification* of bookmark placement at interruption time provide value to users?
Q3. Does *haptic display* of non-uniformly spaced bookmarks during resumptive navigation provide value over visual or no display?

Q4. Do users find *combining* auto-bookmarking, haptic notification and navigation feedback useful?

This research contributes and explores:

- aspects of a physiologically-driven iHCI utilizing a haptic modality for user feedback;
- design of a cueing system enabling the larger scenario's (interruption/resumption) implicit component;
- data on the ability of haptic markers to assist users in traversing a media landscape; and
- non-uniformly spaced haptic detents depicting temporal events mapped to a spatial continuum.

This knowledge moves us towards a fundamentally different form of interaction employing iHCI enabled by low-attention haptic feedback.

2 Literature Review

2.1 Implicit Human-Computer Interaction

iHCI is built on the underlying notion that the participating computer system has a data-driven model of certain behaviors of a human participant (the user model). These are usually inferred by recognizing the user's physical gestures, facial expression, physiology or a combination thereof. Behaviors recognized through comparison to the user model can support automatic responses. However, context estimation is noisy—human behavior is non-deterministic, and the environment may not correlate well to the system model [12].

Event generation from sensed actions has yielded several iHCI schemas [5], [13], [14], [15]. Schmidt et al. facilitated 'real-world bookmarking' [8] with passive RFID tags in physical objects linked to an application: a user's ring-worn RFID tag reader instructed his smartphone to open a recipe website when he picked up a spoon, or display his stock portfolio when he opened his wallet.

Physiological signal processing has appeared in iHCI. Conati measured physiological responses in children playing educational games [16], then used a probabilistic affect model to generate interventions to optimize the child's learning and engagement. Startlecam, a wearable video camera, monitored electrodermal activity for physiologically arousing events [17] then recorded nearby images, capturing the startling event for an image diary.

These studies addressed technical challenges. In contrast, our first question (Q1) examines whether design can render such a system usable given the noisy nature of implicitly generated events, avoiding natural disorientation or frustration of interacting with a system that one does not directly control and is not fully transparent.

2.2 Multimodal UI and Haptic Notification

Prevalent mental model theories (multiple resources, dual-coding) posit that humans process information more effectively through coordinated multiple channels than through a single channel [18], [19]. In multitasking environments, where data may relate to different and competing percepts, audition and vision may already be in play: further demand may overload attentional resources and degrade performance [2], [20], [21].

Multimodal interaction has been used to mitigate task overload and to develop adaptive interfaces. Input data for has been obtained via affect [22], text/speech [23] and gestures [24], [25]; outputs can be rendered through heat, olfaction, audition, and tactility [21], [26] among others.

Haptic notification is appealing both as an underused channel, and for its potential for unobtrusive display given careful notification design and deployment [27]. It is clearly possible to present non-critical information about ambient events haptically without disturbing the user's primary interaction in another modality. This capacity is already exploited in mobile devices to signal events such as arriving text messages [28], [29], [30], [31], [32] and the passage of time [33]. [27], [34] provide a more comprehensive review.

Much of the work in multimodal UI explores the technological design of interface inputs and outputs rather than their application in a holistic interaction loop. Additionally, we are not aware of any study of haptic display in the context of implicitly observed events. Q2 explores the utility of feedback through haptic notification for events generated involuntarily by the user, particularly when the notification channel is peppered with false positive events.

2.3 Bookmarks and Temporal-Spatial Haptics

Implicit bookmarking has appeared previously, particularly in web browsing and e-reading [35], [36], [37]. Cockburn et al. developed a browser add-on that captures and records information on user-visited webpages, to organize bookmarks by importance [36]. More frequently visited bookmarks, assumed more important, are visually prominent. Yu et al. designed an algorithm to automatically generate document bookmarks based on user scrolling behavior, to support passage revisitation [37]. However, these and most of the bookmarking methods found in prior work display only in the visual channel [38], [39], [40]. We posit, based on prior research [26], [31], [41], [42], [43], that haptic cues can help a user to compose, access and navigate a temporal-spatial model of data or events.

Several systems have used belt- or back-worn displays for navigating through physical space [30], [41], [44], [45], [46]; or to assess ordinal data by coordinating movement in time and space [47]. While evidence of the utility of purely haptic feedback in mental model development is mixed, users can evidently perceive, learn and interpret icon data haptically in high workload multitasking, speeding reaction time and lowering mental effort [30], [42], [48], [49].

Menu scrolling and graphical widget targeting can play well with haptics. Vibrotactile feedback added to graphical icons on a touch screen interface made them more findable, especially when users were under cognitive strain [43]. Evenly-spaced detents in tilt-based list scrolling for navigation rate feedback netted a 22 percent task speed-up [50]. Other scrolling techniques exploit a sense of distance travelled or velocity generated based on constantly-spaced features [51], [52].

Q3 and Q4 delve into non-uniform detent spacing to locate temporal events (like bookmarks) mapped to a spatial dimension. Rather than giving rate or distance cues, they anchor a search task. We further consider the impact of false positive events on navigation usability and the impact of haptic notification of events prior to resumptive navigation,

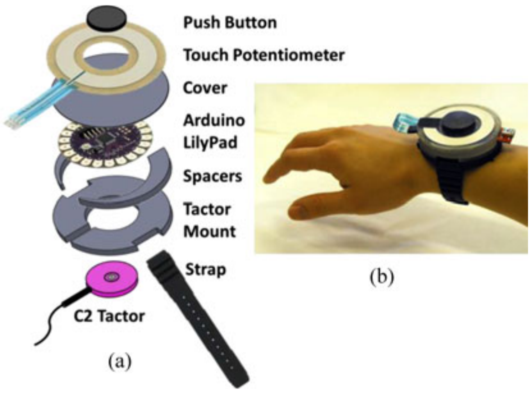

Fig. 3. (a) Exploded view and (b) photo of wrist-worn navigational device and haptic display.

marking a clear distinction in how we expect users to employ haptic information with this tool.

3 System Overview

3.1 System Overview

We previously developed an audio player system [10] where a user's galvanic skin response (GSR) is monitored for orienting responses to external interruptions. Bookmarks are automatically placed in the audio stream upon detection of an OR (interruption), and indicated with an unobtrusive haptic cue on a wrist-worn device. After attending to the interruption, the user can resume audiobook listening by navigating back to the bookmark, with the optional assistance of haptic resumption-time cues.

3.2 Orienting Response Detection

For experiment control, in the present work we replaced "live" GSR detection with a simulated setup based on our previously measured detection performance). However, for context we describe the system developed in [9], and relevant performance in Section 4.5. A GSR signal is collected using dry electrodes attached to the index and middle fingers of the non-dominant hand. The signal (measured micro-Siemens) is filtered and differentiated to obtain locations of GSR peaks. The magnitudes of peaks at these locations are then compared to a threshold: if the peak value exceeds the threshold, the system will assume an orienting response occurred.

3.3 Haptic Wrist Navigator and Haptic Display

We built a device to navigate an audio stream, worn on the wrist of the non-dominant hand (Fig. 3). Users press a button to start/pause, and advance by finger-swiping a rotary touch potentiometer in a circle: clockwise to fast-forward, counter-clockwise to back up. Swipe speed controls navigation rate (linear control/display ratio). Radial scrolling provides control that is independent of podcast length, performs well for short hops, and supports 'eyes-free' navigation [53]. We opted for scrolling over alternatives (e.g., direct-jump with a button press) where pilot users performed poorly if bookmarks were incorrectly placed.

An EA C-2 Tactor [54] (voice-coil transducer, i.e. signal frequency and amplitude independently controlled) was mounted on the device where it contacts the skin. An Arduino LilyPad drove the tactor and communicated with custom audio player on a nearby laptop via USB. This level of control could also be implemented on a commodity handheld device.

3.4 Haptic Signal Design

Our haptic cues needed to (1) signal bookmark placement, and (2) facilitate later search of correctly-placed bookmarks amongst plentiful false positives.

3.4.1 Notification at Interruption Time

Imagine a user is at least peripherally aware of a cue that a bookmark was placed at the beginning of an actual interruption, and then of another felt a minute or two later. At resumption of audio stream listening, the user would know to navigate directly to the first (desired) bookmark skipping the second (extraneous) one. Additionally, we posited that users could utilize haptic feedback on notification (has a bookmark been created?) to inform their navigation strategy. For example, if users receive haptic notification of bookmark placement, they may look for bookmarks, else perform a manual search from the beginning.

As a highly tangible haptic signal may disrupt attention to an interrupter when this is undesirable (i.e., interlocutor in a conversation), the stimulus used at interruption time should remain unobtrusive, leaving the user's attention to be directed at the interruption. Past work indicated users perceived slow, sinusoidal haptic signals as 'relaxed' and 'reassuring' [55], so we chose a sinusoidal pulse (vibration frequency varied within a sinusoidal envelope) for bookmark placement notification. We use a 200 Hz sine wave signal (sufficiently distant from 250 Hz peak sensitivity of the Pacinian corpuscle while still allowing the user to detect the range of tactor displacement [56]), substantively blunted by envelopment in a slower 1.3 Hz sinusoid with a peak displacement of 1mm and lasting 0.75 s. Pilot testing (four users) indicated a good compromise between noticeability and unobtrusiveness.

3.4.2 Display of Bookmarks at Resumptive Navigation

In contrast to interruption time, in navigation the user's attention is fully focused on controlling the audio player; thus, we designed the haptic stimulus for bookmark display during resumptive navigation to be attention-catching, and restricted tactor vibration to a single frequency for salience. In pilots, users found a steady, peak-sensitivity 250 Hz, 1 mm $\times$ 0.75 s sine wave unpleasantly strong. We decreased it to 230 Hz, 1 mm $\times$ 0.5 s, which was acceptable. Although similar in frequency, this attention-catching signal differs from the one used at interruption time in that it is not enveloped by a slower sinusoid.

3.5 Visual Display

We developed a custom audio player based on the freeware cross-platform irrKlang library, with the ability to display GSR-based bookmarks as visual and haptic icons [57] (distinct from the media player we presented in [10]). Its graphical user interface (Fig. 4) simulated typical mobile smartphone functionality, in choice of audio player viewable area and by using a simplistic design with only a start/pause button, current track position and time, and

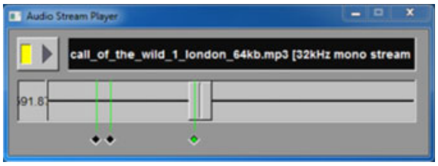

Fig. 4. A screen capture of the media player displayed to participants. The scroll bar represents the current location in the audio stream with respect to the current track. Automatically placed bookmarks are shown as green lines above diamonds. Green diamonds signify that the user has navigated to that bookmark.

the name of current track. The player window displayed bookmarks as solid lines directly on the track-progress scroll bar (Fig. 4). An icon below the bookmark line lighted up when a user navigates to a particular bookmark.

4 Experiment Methodology

We conducted a controlled user experiment to study the impact of auto-generated bookmarks, haptic notification at interruption time, and haptic display of bookmarks during resumptive navigation.

4.1 Participants

Sixteen participants were recruited through on-campus advertising (six female), aged 20-28 ($\overline{x} = 24.5, \sigma = 2.03$), and were compensated with refreshments.

4.2 Factors

Our experiment was designed to clarify the impact of three factors on user performance. These relate to the time of interruption (N):

1. Haptic notification of bookmark placement (2): [haptic notification given (N_H), not given (N_{None})], and to display during resumptive navigation (D):
2. Visual display (2): [available (D_V), not avail]
3. Haptic display (2): [available (D_H), not avail].

Factors 2 and 3 cross to give four display conditions during resumptive navigation:

- no bookmarks displayed (D_{None})
- visual display of bookmarks only (D_V)
- haptic display of bookmarks only (D_H); and,
- both bookmark displays $(D_V + D_H)$.

4.3 Apparatus

The study was conducted using the system and equipment described in Section 4. The software was run on a laptop with 4 GB RAM, Microsoft Windows 7, and a 17″ LCD Monitor at $1,280 \times 1,024$ resolution. An interface provided the experimenter with the ability to artificially generate bookmarks (necessary for experiment condition control, described further in Section 4.5) and control over bookmark notification/display factors. When the experimenter selected the visual bookmark display option, the user's audio player window displayed bookmarks visually as described in Section 3.4.

4.4 Participant Task

A single trial consisted of listening to an audio stream (podcast) segment and then navigating back through the audio stream following an experimenter-generated interruption. Participants were instructed to attend to the once-per-trial interruption by the experimenter, diverting attention away from the audio stream. Half of the participants received haptic notification of a bookmark being recorded at the time of interruption. Following the interruption, participants navigated back through the audio stream with the goal of locating the point they were listening to prior to the interruption to resume the listening task. Navigation was done in one of the four display conditions, which always included audio stream playback.

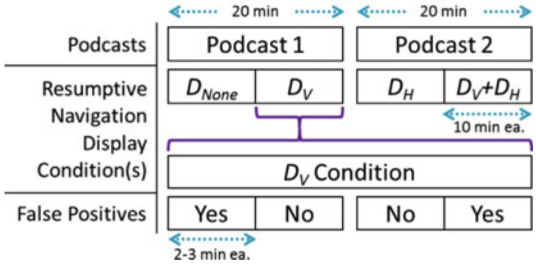

Fig. 5. Representative timeline for data collection portion of experiment, for one participant. Factor levels shown are for the within-subject navigation display conditions only; haptic notification at time of interruption is between-subjects.

4.5 Procedure

4.5.1 *Briefing*

A full session took 1.5 hours. Participants were trained to use the audio player software and equipment, and were informed that the experiment objective was to compare an automatic bookmarking system with haptic notification/navigation, to current media players (e.g., Apple iPod). Participants were directed to pay attention to information presented in the audio stream, as they would be tested on the content at the end of the experiment; but that when experimenters engaged them in conversation (i.e., the interruption), answering these questions was the priority. They were instructed not to pause or stop the audio stream, but instead to let playback continue while speaking, as they would be able to scroll back to listen to any content they might have missed immediately afterwards. In conditions where bookmarks were displayed during resumptive navigation, participants were informed that if they did not recognize content at a bookmark, they should scroll to an earlier bookmark.

4.5.2 *Experiment Session*

Participants were then asked to sit in a silent experiment room facing a computer monitor and to don the wrist-worn navigation device, headphones and GSR sensor (used as a prop only and not to record data or generate bookmarks for use in the experiment). Sessions were video recorded for post-hoc analysis to measure navigation times. Participants were asked to start listening to the preloaded audio tracks: two engaging 20-min fictional narratives from the podcast, 'The Vinyl Café' [58] entitled: 'Dave and the Dentist' and 'Sam the Athlete'.

Each session consisted of 16 trials; Fig. 5 shows an example timeline. Four trials per bookmark display condition were presented with a 5-min break in between the second and third (i.e., between narratives) to mitigate fatigue. In each trial, the experimenter interrupted the participant once and engaged in a 50-60 s conversation where the participant answered questions. Participants removed their headphones ensuring that the experimenter had taken their full attention away from the podcast. Pre-arranged conversation 'scripts' were used ensuring conversations subject matter was the same across all subjects; however, ordering of these scripts was randomized.

4.5.3 Bookmark Placement

All bookmarks were artificially generated and placed by the experimenter to ensure a bookmark was placed at the start of each interruption. To simulate semi-realistic performance of the automated bookmarking, we also provided *false positive* bookmarks and their associated notifications and representations: two extra false positive bookmarks were inserted at random times in two of the four trials for each of the D_H, D_V, and $D_V + D_H$ conditions. Thus, *precision*—the ratio of correctly-placed bookmarks to the total number of bookmarks placed— was 50 percent for a full session. This frequency of false positives was set at a level chosen conservatively relative to levels found in experiments described in [10], where we found that it was possible to obtain simultaneous bookmark placement precision and sensitivity of approximately 60-70 percent.

To keep the time required for a user to complete a full experiment session under a maximum of 90 min (to ensure participants were not fatigued and did not lose interest) we triaged the effects we wished to study. We thus de-prioritized (did not include) *false negative* errors in conditions where bookmarks were displayed. Our rationale was to assume that bookmarking algorithms would generally be tuned towards higher sensitivity, because there are more options for dealing with false positives than false negatives. As such, examining the effect of correct and false positive bookmark placements based on a noisy signal would be more beneficial and have higher priority in the design of our low-attention loop, than would the effect of false negatives (less likely to occur).

With the inclusion of the D_{None} condition, bookmark placement *sensitivity*—the ratio of correctly-placed bookmarks to total interruptions—was 75 percent for a full session (100 percent for D_H, D_V, and $D_V + D_H$; 0 percent for D_{None}). This ratio is consistent with the middle range of precision versus sensitivity tradeoff obtainable by our bookmarking algorithm [10].

4.5.4 Debriefing

At session closing, participants were asked to fill out a structured questionnaire regarding the interruptions and device interactions, providing qualitative feedback on the interaction experienced during the study.

4.5.5 Formal Design

We used a 2 (haptic notifications) × 2 (visual display) × 2 (haptic display) design. Haptic notifications were between-subjects to meet experiment duration constraints, and both display factors were within-subjects (four trials per display per subject as shown in Fig. 5). To minimize order effects, we counterbalanced the order of presentation of conditions through a balanced Latin square, producing four configurations. Ordering of the podcasts and the false positives were both randomized.

4.6 Quantitative and Qualitative Measures

For each trial we collected the time required for a participant to acquire a listening location following an interruption and the acquisition accuracy—the distance in the audio stream between the final navigated position and the 'true' position corresponding to the start of the interruption. For accuracy, we also recorded and tallied if a participant didn't scroll back enough, signifying that they had missed listening to a segment of the audio stream.

The post-experiment questionnaire asked participants to evaluate disruptiveness and usefulness of the haptic notification of bookmark placement, and annoyance and usefulness of the haptic display for bookmark navigation on Likert scales (1-10). Participant preference for each of the four display conditions was tallied.

4.7 Hypotheses

Performance refers to resumptive navigation time and accuracy. We hypothesized that users would:

H1. Perform better when bookmarks are displayed during resumptive navigation (D_H, D_V or $D_V + D_H$).
H2. Perform at least as well with D_H as with D_V.
H3. Perform better with $D_V + D_H$ over D_H and D_V.
H4. Prefer $D_V + D_H$ over D_H and D_V.
H5. At resumption time, perform better during navigation with bookmarks (D_H, D_V, or $D_V + D_H$), if notifications are experienced at interruption time (N_H).

5 Results

A $2 \times 2 \times 2 \times 4$ (haptic notification × visual bookmark display × haptic bookmark display × presentation order) repeated measures (RM) ANOVA was conducted for each dependent measure. No significant effects of presentation order were detected; thus, we simplify our results by examining only the three main factors. Significance is reported at $p < 0.05$. Mauchley's Test of Sphericity confirmed that the data analyzed did not violate the assumption of sphericity. Pairwise comparisons are protected against Type I error using a Bonferroni adjustment. We also report partial eta-squared (η_p^2), a measure of effect size that can be interpreted using the following rule of thumb: .01 as a small effect, .06 as medium, and .14 as large [59]. Results are organized by main findings.

5.1 Effect of Display on Resumptive Navigation

5.1.1 Navigation Time

Any bookmark display is better than no display for decreasing navigation time. Our overall RM ANOVA for navigation time revealed an interaction between visual and haptic displays of bookmarks during resumptive navigation ($F_{1,14} = 10.443,\ p = 0.006, \eta_p^2 = .427$). We therefore conducted a

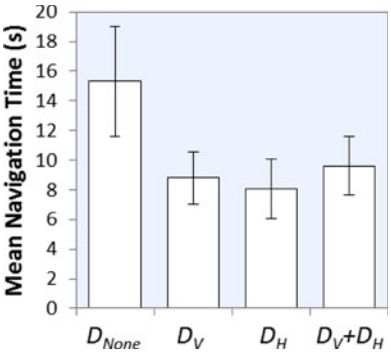

Fig. 6. Mean navigation times for each bookmark display condition. Error bars represent 95 percent confidence intervals. $(N = 16)$.

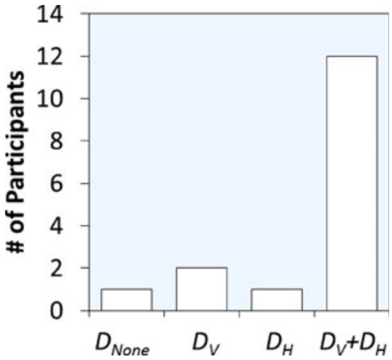

Fig. 7. Participant preference for bookmark display during resumptive navigation. $(N = 16)$.

follow-up one-way ANOVA on the four display conditions to test the interaction, revealing that the conditions had no additive effect. Tukey's HSD test shows that D_V ($\overline{x} = 8.8$, $\sigma = 3.41$), D_H ($\overline{x} = 8.07, \sigma = 3.68$), and $D_V + D_H$ ($\overline{x} = 9.62$, $\sigma = 3.90$) were all significantly faster than D_{None} ($\overline{x} = 15.30$, $\sigma = 6.94$) (Fig. 6), but that there were no other significant differences. This result supports our hypothesis that users perform better when bookmarks are displayed during navigation (H1).

D_V, D_H and $D_V + D_H$ bookmark display techniques were all helpful, but none offered a clear benefit over the other. Differences in resumptive navigation time between D_V and D_H *were non-significant, offering some support to* H2. In particular, navigation time for $D_V + D_H$ was not the fastest. This, in combination with the main effects described above, may signify that D_V and D_H both perform equally better than D_{None}, but that combining them $(D_V + D_H)$ may not offer an additional performance benefit in terms of navigation time, offering no support to H3.

5.1.2 Navigation Accuracy

Conditions rendering bookmarks *haptically (D_H and $D_V + D_H$) significantly increased navigation accuracy*. A significant main effect of haptic display on our overall RM ANOVA for navigation accuracy $(F_{1,14} = 5.4, p = 0.024, \eta_p^2 = .080)$ revealed that trials where there was a haptic display had higher accuracy ($\overline{x} = 13.85, \sigma = 5.68$) in resumptive navigation when compared to all other trials ($\overline{x} = 17.42$, $\sigma = 9.84$); trials with a visual display by contrast did not significantly impact accuracy. Altogether, this result for accuracy adds additional partial support for H1 and H2. Table 1 shows accuracy means and standard deviations for each condition.

5.1.3 Self-Reported Measures and Comments

Haptic display of bookmarks *was perceived as useful and not annoying*. On a scale of 1 (not annoying at all) to 10 (very annoying), participants reported a mean annoyance of $2.3 (SD = 1.9)$. On a scale of 1 (not useful at all) to 10 (very useful), participants also reported that they found the haptic display to be useful ($\overline{x} = 7.6, \sigma = 2.3$). Data on the annoyance or usefulness of D_V was not collected as it was considered obvious.

TABLE 1
Means and Std Dev. for Navigational Accuracy

	D_{None}	D_V	D_H	D_V+D_H
$\bar{x}$	17.5	17.3	14.8	12.5
σ	16.38	9.35	8.94	6.50

$D_V + D_H$ was preferred over all other display conditions during resumptive navigation. From 16 responses, we analyzed the frequency with which a display condition was preferred. This was done by calculating the one-dimensional Chi-square statistic to determine if the actual frequency was significantly different from the case where all frequencies were equal. As shown in Fig. 7, 75 percent of participants reported that they preferred using $D_V + D_H$ $(n = 16$, $\chi^2(2, 15) = 21.5, p < 0.001)$, supporting H4. In the post-experiment survey, a few participants mentioned that they liked the $D_V + D_H$ condition due to its affordance for ballistic yet accurate navigation trajectories. As one participant stated, "*Visual confirmation with haptics allows me to be much sloppier when scrolling to a bookmark without overshooting*." [P1]

5.2 Effect of Haptic Notification

5.2.1 Navigation Time

Haptic notification of bookmarks at interruption time (N_H) significantly reduced navigation time if bookmarks were displayed visually during resumptive navigation, but did not do so if they were displayed haptically. From our overall RM ANOVA on navigation time, there was a significant interaction effect between haptic notification of bookmark placement at interruption time and visual display of bookmarks during resumptive navigation $(F_{1,62} = 7.0, p = 0.019, \eta_p^2 = .334)$ (Fig. 8). Two-sample t-tests were conducted to examine the interaction. The first t-test revealed that when a notification was provided at interruption time, it resulted in faster resumptive navigation, but only when the bookmarks were displayed visually at resumption $(t(30) = 2.2, p = 0.03$, $d = .8)$, as shown in the right side of Fig. 8. The second t-test revealed that when there was no notification provided at interruption time, there was no significant difference in resumption speed based on presence of a visual display, as shown in the left side of Fig. 8.

Thus, our hypothesis that users will navigate bookmarks better with N_H (H5) is partially supported. Haptic notification significantly impacted navigation time only when navigation bookmarks were visually displayed.

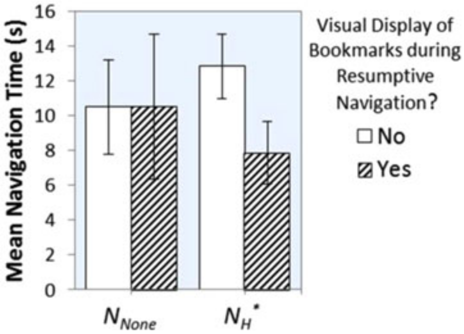

Fig. 8. Mean navigation times for haptic notification of bookmark placement at interruption time and visual display of bookmarks during resumptive navigation. Error bars represent 95 percent confidence intervals. *represents a significant difference between navigation times for trials with and without visual display of bookmarks. $(N = 16)$.

5.2.2 Navigation Accuracy

No significant effects of haptic notification at interruption time for resumptive navigation-time accuracy were observed, providing no support for H5.

5.2.3 Self-Reported Measures and Comments

Haptic notification of bookmark placement (N_H) was deemed useful and not disruptive. Participants receiving N_H reported the level of disruptiveness and usefulness of N_H on 10-point Likert scales. From 1 (not disruptive at all) to 10 (very disruptive), participants rated disruptiveness of N_H as low$(\overline{x} = 2.9, \sigma = 2.1)$. From 1 (not useful at all) to 10 (very useful), participants also reported that they found haptic notification to be useful $(\overline{x} = 8.4, \sigma = 1.1)$. One participant commented: "*Although [the notification was] noticeable enough, it was not so much that it distracted me from answering [the experimenter's] questions.*" [P10] Another said, "*It is good to use vibrations as it helps signal where I left off without worrying if a mark was placed or not.*" [P11]

5.3 Secondary Analyses

5.3.1 False Positives

Introducing false positives into trials increased navigation time. We ran a paired-sample t-test to determine the effect of

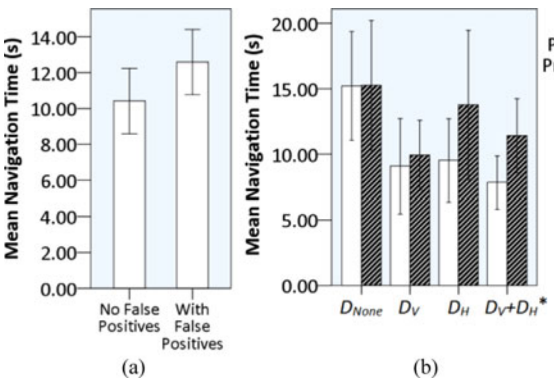

Fig. 9. (a) Mean resumptive navigation time for trials with and without false positive bookmarks. (b) Mean resumptive navigation time for each condition. Error bars represent 95 percent confidence intervals. *represents a significant difference between navigation times for trials with and without false positive bookmarks within a condition (this distinction is meaningless for the D_{None} condition). $(N = 16)$.

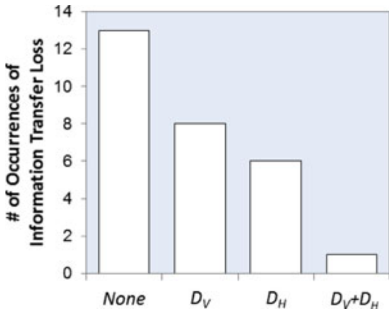

Fig. 10. The number of occurrences where information was missed due to improper navigation across experiment conditions. $(N = 16)$.

false positives on navigation performance. Results confirmed a significant difference in mean navigation time between trials *with* $(\overline{x} = 12.59, \sigma = 5.03)$ and *without* $(\overline{x} = 10.42, \sigma = 5.07)$ false positives $(t(31) = 2.06,\ p = 0.047,\ d = 0.365)$ (Fig. 9a). Paired t-tests were conducted to determine which conditions exhibited a significant difference in navigation time; $D_V + D_H$ was the only condition showing a distinction between trials *with* $(\overline{x} = 11.41, \sigma = 7.87)$ and *without* $(\overline{x} = 7.84,\ \sigma = 5.61)$ false positive bookmarks $(t(31) = 2.05, p = 0.049, d = 0.362)$. A trend (Fig. 9b) shows that false positives slowed navigation time in conditions where D_H was present, whereas this effect does not appear for D_V. One interpretation is that it is harder for participants to ignore false positives when they are rendered haptically, rather than visually. No significant effect was observed in navigation accuracy for trials *with* versus *without* false positives.

5.3.2 Information Transmission Loss

Visual + haptic display of bookmarks during resumptive navigation reduced the number of times that audio stream information was lost. While all participants scored perfectly on a multiple choice exam on the podcast's subject material, in some cases, participants did not scroll far enough back in the audio stream to reach the point where they were interrupted, 'skipping over' a segment of the audio stream as reported in interviews. In most cases, this caused participants to be disoriented, lacking contextual awareness of new information presented in the audio stream. Fig. 10 shows that the D_{None} condition produced the most occurrences (13) where information had been skipped following an interruption. A reduction in occurrences of 38 and 53 percent were observed in the D_V and D_H conditions, respectively; $D_V + D_H$ resulted in the least number of occurrences, providing some evidence that users perform better on this measure with $D_V + D_H$ (H3).

5.4 Summary

We summarize our main findings according to our hypotheses:

H1. Users perform better when bookmarks are displayed. SUPPORTED.
$D_H, D_V, D_V + D_H$ all resulted in faster navigation time than D_{None} and D_H and $D_V + D_H$ improved accuracy over D_{None}.

H2. Users perform no worse with the haptic display of bookmarks than the visual display. SUPPORTED.

No significant difference between D_H, $D_V, D_V + D_H$ in navigation time. In terms of accuracy, having a haptic display resulted in the best accuracy.

H3. Users perform better with $D_V + D_H$ over D_H and D_V alone. NOT SUPPORTED.
No difference in navigation time or accuracy.

H4. Users prefer $D_V + D_H$ over D_H and D_V alone. SUPPORTED.
$D_V + D_H$ was preferred by 75 percent of participants.

H5. Users perform better with N_H during navigation so long as bookmarks are displayed. PARTIALLY SUPPORTED.
N_H improved navigation time when bookmarks were displayed visually. There was no impact for haptically displayed bookmarks, or on accuracy.

Secondary analysis indicates that false positives may slow time required for navigation when *haptic display of bookmarks* is present. Additionally, users perform best with $D_V + D_H$ in terms of information transmission loss.

6 Discussion

6.1 Research Questions

Q1. Do auto-generated bookmarks provide assistance to users in the context of interruption recovery?

Based on prior work, we were concerned that using an implicit method to generate bookmarks might cause user confusion [12]. Presenting false positives might also reduce the perception that bookmarks would be useful in resumptive navigation. However, in response to: 'Did you find the bookmarks helpful?' (de-briefing questionnaire), all participants stated that they felt that the bookmarks in and of themselves provided utility. There is also a measured performance benefit: bookmarks displayed to participants in any form reduced the average time required to navigate following an interruption and the number of occurrences of information transmission loss by at least 30 percent. We expected this for the D_V condition, but the similarity between all display types was surprising.

These results were obtained when overall precision and sensitivity of bookmark placement was 50 and 75 percent respectively; thus, these results indicate that the bookmarking algorithm appearing in [10] could be sufficient to provide value in bookmarking, offering a substantive performance and subjective improvement to the audio stream navigation experience.

Q2. Does haptic notification of bookmark placement at interruption time provide value to users?

The presence of N_H during interruption made no difference in either navigation time or accuracy when coupled with the *haptic* bookmark display in resumptive navigation. By contrast, N_H with *visual* bookmark display did produce a benefit over the D_V with N_{None} condition (Fig. 8).

One possible explanation relates to the types of mental models inculcated for the navigation task. We posit that displaying bookmarks visually during resumptive navigation may allow participants to develop a spatial mental map of where both useful and non-useful bookmarks have been placed, whereas participants lack such spatial information when working with only D_H. As N_H provides information that has direct correlation with a spatial mapping of bookmarks, the benefit of notification in terms of performance may only be apparent with the D_V and $D_V + D_H$ conditions, but not D_H alone. Thus, it may be that N_H provides a performance benefit to participants only when they are also provided with additional means to access or unlock that information; and in the conditions provided here, that extra key may have been best obtained through the visual sensory modality more broadly. More examination is required to substantiate this theory. We did not see any significant differences in terms of navigation accuracy between N_{None} and N_H trials; we infer that haptic notification did not provide enough navigation information to improve scrolling accuracy.

Subjectively, all participants except one of those receiving N_H reported it to be useful. As predicted by prior work in cognitive theories, our haptic cues were not perceived as disruptive to carrying out this primary task. Additionally, participant comments provided some evidence that N_H was able to reassure users that a bookmark had been placed; they could attend to the interruption without worry as stated in our hypothesis H2.

Q3. Does haptic display of bookmarks provide value to users over no display or visual display of bookmarks?

Only conditions with haptic display of bookmarks significantly increased navigation accuracy, which correlates well to results obtained in prior work [44], [45], [46]. D_V, D_H and $D_V + D_H$ produced significant reductions in navigation time over the control condition (D_{None}) but not over each other. Prior work has shown improved time performance for navigation tasks supplemented with haptic feedback [50], [52]; thus, this outcome was unexpected and is contrary to our hypothesis H3. However, we observe that most prior work is for navigation that is fully visually guided [26], [42], [43], [50], [51], [52].

On closer examination, we theorize that this outcome may be due to the different scrolling strategies afforded by the nature of the information provided haptically and visually respectively. A haptic bookmark display affords a ballistic trajectory, fast and less accurate—the feedback provides a 'safety net' that saliently informs users when to stop scrolling, but can occasionally require extra time to correct for an overshot target. Conversely, users reported that a visual display affords predictive finely-tuned scrolling with a smoother trajectory to the target; though compactness of the visual display causes errors in navigation accuracy. In this case, users may determine that high scrolling accuracy is difficult and choose not to attempt it, instead adopting a 'sufficing' navigation approach. In other words, we posit that a similar level of speedup was achieved in D_H and D_V, but through different mechanisms having different average accuracies, thus, pointing to a classic speed-accuracy tradeoff.

Interestingly, participants reported that both visual and haptic modalities can be used in parallel: they could benefit from the ballistic scrolling allowed by the haptic modality, and also use visual cues to predict when to start slowing down to prevent overshoot. Further work is required to see if greater familiarity allows users to integrate these strategies more effectively.

Generally, some participants felt that more could have been done to reduce the annoyance of the haptic cues indicating bookmark placement (e.g., shorter, weaker signal). This is in line with prior work suggesting that personalization is an important factor to consider in the design of haptic stimuli [33]. Some participants also suggested implementing a virtual haptic wall to prevent overshooting of bookmarks. In their present form, nevertheless, participants still found the haptic display of bookmarks useful. Their experience was, however, in a controlled environment, and the haptic signal's salience might be less adequate in more active surroundings. Another topic for further work (with very wide utility) is how to adjust haptic signal salience to accommodate ambient noise and activity levels.

Q4. Do users feel that auto-bookmarking with haptic notification and navigation feedback is useful?

Aside from some suggested improvements, the large majority of participants (88 percent) reported that they would use an auto-bookmarking system resembling the one presented to them. Several (5) participants were concerned with the system's usability due to the high number of false positive bookmarks in the experiment (50 percent precision); this shows that future work on this application should target increasing algorithm precision while maintaining or increasing sensitivity. Regardless, results showed that while inaccurate bookmarks do slow users down overall, the net effect of providing bookmarks is still better than the case where no bookmarks were provided. Although the occurrence of false positives should be reduced to increase usability, in general it may be a technically practical strategy to strive for an interaction style that 'lives with' substantial false positive rates and makes them tolerable, rather than trying to eliminate them. An example is to devise a method of distinguishing between bookmarks with lower statistical probabilities of being true positives from ones with higher probabilities, as judged by the physiological data processing block in Fig. 1. Thus, different haptic profiles could be assigned to each bookmark 'strength' category—i.e., lower probability bookmarks could feature lighter, less noticeable vibrations and higher probability bookmarks could use stronger vibrations.

As explained in Section 4.5, we did not study false negative errors in our D_V, D_H and $D_V + D_H$ conditions, instead taking the approach of assuming a tuning in which false negatives are rare. Assuming they could nevertheless occur, this does limit the generalizability of our results and perceived value of our system. For example, users might become even slower or more inaccurate than D_{None} as they attempt to search for a non-existent correct bookmark. Alternatively, the user may not peripherally detect haptic notification of bookmark placement, causing them *to* directly perform a manual search or to stop/pause the audiobook themselves, reducing time and increasing accuracy of the search. Thus, the effect of false negatives warrants further investigation.

6.2 Application of Results In and Beyond the Use Case

In this study, we explored the role which haptic feedback could play in enabling an iHCI for an audio stream bookmarking use case. However, many of the results obtained may be applicable to other iHCIs and systems which support/enable them. Here, we attempt to tease out what our findings may mean for such systems.

User mental models need to be considered in the design of interfaces supporting iHCI. As seen from discussion of *Q3*, users reported that through the combination of bookmark display types, they were able to achieve performance benefits. Additionally, through notification, users may be able to perceive usefulness or lack of certain bookmarks, improving performance. Thus, we suggest that mental models be carefully studied and considered when designing user feedback systems for the enabling of iHCI systems, especially when the implicit system is based upon noisy (i.e., physiological, contextual) signals.

Haptic signaling which enables iHCI can be useful, and should be unobtrusive. As seen from the discussion of *Q2*, we see that haptic signaling can be useful for peripheral notification of iHCI-derived events or data. Such a haptic signal should be carefully designed for unobtrusiveness where it subtly informs or reassures the user of an event generated implicitly through contextual data.

Data generated via noisy signals should be presented as breadcrumbs. As user performance may be affected, false positive (and likely, false negative) outcomes from the implicit system should be minimized. However, evidence from user response to false positives suggests that when these errors are addressed through the system design (e.g., unobtrusive feedback), system errors could be accepted by the user to some degree before a decrease in system usefulness is perceived. Thus, we propose that users should be provided with carefully designed methods of 'optionally' interacting with data that is generated through implicit methods using noisy data. Users are thence not forced to use the data if they find it faulty or incorrect; rather, they can utilize or ignore the breadcrumbs. Additionally, our results confirm that users should be able to personalize the breadcrumb interaction and display (e.g., change the haptic signal used, and choice of either/both of visual and haptic display).

6.3 Limitations and Constraints of the Experiment

While a controlled lab setting was an appropriate first step, future research must confirm these results in more realistic settings (café, bus, etc.). This study did not specifically investigate the effects of false negative bookmark placements due to a triaging of effects that we wished to study. Although this choice was deliberate, based on the assumption that implicit signal detection algorithms are more easily tuned towards high false positive rates, some situations may still generate false negatives. Finally, it would be interesting to study a larger participant pool in less-structured environments. The task of returning to a location in the audio stream following an interruption inherently has considerable variation across participants in various environmental contexts, and a large experiment would be required to examine the full range of user types in a broad population, especially if it includes those without prior experience with circular scrolling devices.

7 Conclusions and Future Work

In this paper, we described and assessed a novel, multimodal interaction paradigm where an iHCI is supported by a haptic feedback mechanism. This feedback provides users with a notification that the application has acted in response to changes in the user's physiology. To examine the role of haptic feedback in implicit interaction, we have considered an automatic audio stream bookmarking use case based on a user's electrodermal activity. We tested two forms of feedback with an experiment in which bookmark placement was simulated rather than automated for purpose of experiment control: haptic notification of bookmark placement and haptic display of bookmarks during resumptive navigation.

Our results demonstrate the feasibility of using haptic feedback for this use case. We found that conditions providing haptic display of bookmarks during resumptive navigation significantly reduced navigation time and accuracy. Visual and haptic bookmark displays in resumptive navigation, alone and in combination, were all found to be faster than no bookmark display, although the combination of haptic and visual display provided the strongest statistical results. These findings confirm previous work regarding haptic augmentation of visual displays, and also show promising results regarding haptic-only interactions for simple eyes-free navigation tasks.

Although a high number of inaccurate bookmarks did negatively impact the time required to navigate an audio stream following an interruption (relative to completely accurate bookmark portrayal), this was outweighed by the benefit of providing bookmarks. This result confirms that using electrodermal activity as a system input is accurate enough to be used for interruption detection in an automatic bookmarking application. Additionally, user feedback suggest that users may tolerate detection errors in iHCI systems as long as the haptic notification is unobtrusive, assuming that the interaction does not force users to act on implicitly-generated data. False negative errors were not presented to users in conditions where bookmarks were displayed and remains a limitation of this study.

Several hypotheses have arisen in the course of the research inviting further investigation, including the premise that with haptic notification of bookmark placement at interruption time, users are able to develop a spatial mental map of where both useful and non-useful bookmarks have been placed. Thus, when provided with a visual-spatial mapping of these bookmarks during resumptive navigation, they are able to use this mental model to achieve a performance benefit in terms of navigation time and accuracy.

Reflecting on the larger context of this work, our results suggest that the iHCI model using haptic feedback to inform users of system state is viable; reactions from participants and performance data both indicate that feedback to support an iHCI framework is beneficial, and possibly necessary to introduce adequate interaction transparency. Aspects of this work, such as the knowledge of how different mental models can be used during navigation, effect of false positives on user perception of value of interaction, can be extended to other areas where interruption can severely impair primary task flow, and where managing task switchover and device behavior during the interruption would be valuable (e.g., distracted driving scenarios, sequential process flows within the workplace). We posit that haptic systems which aim to enable iHCIs should be designed with attention to user behavior, preference and mental models to be able to capitalize on performance benefits which may be afforded by the system.

Future work involves exploring application of this multimodal loop in other use cases such as gaming, media-playback, pedagogical systems, sport training, emotion-aware devices and in-vehicle systems operations.

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Matthew K.X.J. Pan received the BASc degree in 2009 from Waterloo in mechatronics engineering and the MASc degree in 2012, from UBC in mechanical engineering. He is currently working toward the PhD degree in the Department of Mechanical Engineering at the University of British Columbia. He currently holds a Natural Sciences and Engineering Research Council of Canada Postgraduate Scholarship. He is a student member of the IEEE.

Joanna McGrenere received the BSc degree in 1993, the MSc degree in 1996, and the PhD degree in 2002. She is an associate professor in the Department of Computer Science, the University of British Columbia. She is in the area of human-computer interaction, where she designs interactive technologies for older users. She received best paper awards at CHI, ASSETS, GI, and IUI. She is the inaugural winner of the Anita Borg Early Career Scholar award and was also a Peter Wall Institute for Advanced Studies Early Career Scholar. Recently, She received an Outstanding Young Computer Science Research Award from the Canadian Association of Computer Science. She is a regular participant on conference program committees, such as ACM SIGCHI, and is an associate editor for the *ACM Transactions on Accessible Computing*.

Elizabeth A. Croft received the BASc degree in 1988, Mech, UBC, the MASc degree in 1992, Mech, Waterloo, the PhD degree in 1995, Mech, Toronto, and the PEng, Fellow Eng. Canada. She is a professor and the NSERC chair for Women in Science and Engineering, BC-Yukon at the University of British Columbia. She teaches courses in dynamics, robotics, design, and engineering leadership. Her research investigates how robotic systems can behave, and be perceived to behave, in a safe, predictable, and helpful manner, and how people interact with and understand robotic systems. She is an author of more than 120 technical publications and applications of her work range from manufacturing assembly to healthcare and assistive technology. She is a fellow of the ASME, and a member of the IEEE.

Karon E. MacLean received the BSc degree in mechanical engineering and biology from Stanford in 1986 and the MSc and PhD degrees in mechanical engineering from MIT 1996. She is a professor of computer science at the University of British Columbia. Her research in ubiquitous haptic and multimodal interfaces brings together robotics, interaction, attentional, and affect design; using touch feedback as part of a multisensory HCI toolbox. Awards include: Peter Wall Early Career Scholar (2001); Izzak Walton Killam Memorial Faculty Research Fellowship (2007); and Charles A. McDowell Award, 2008. She was a founding associate editor of the *IEEE Transactions on Haptics*, founding member of several other editorial and advisory boards, and took the 2012 IEEE Haptics Symposium independent. She is a senior member of the IEEE.