The Effectiveness of Haptic Cues as an Assistive Technology for Human Memory

Stacey Kuznetsov, Anind K. Dey, and Scott E. Hudson

Human Computer Interaction Institute, Carnegie Mellon University,
5000 Forbes Avenue, Pittsburgh, PA 15213
{stace,anind,scott.hudson}@cs.cmu.edu

Abstract. Many people experience difficulty recalling and recognizing information during everyday tasks. Prior assistive technology has leveraged audio and video cues, but this approach is often disruptive and inappropriate in socially-sensitive situations. Our work explores vibro-tactile feedback as an alternative that unobtrusively aids human memory. We conducted several user studies comparing within-participant performance on memory tasks without haptic cues (control) and tasks augmented with tactile stimuli (intervention). Our studies employed a bracelet prototype that emits vibratory pulses, which are uniquely mapped to audio and visual information. Results show interaction between performance on control and intervention conditions. Poor performers on unaided tasks improve recognition by more than 20% ($p<0.05$) when haptic cues are employed. Thus, we suggest vibro-tactile feedback as an effective memory aid for users with impaired memory, and offer several design recommendations for integrating haptic cues into wearable devices.

Keywords: Wearable computing, haptic interfaces, memory cues.

1 Introduction

Memory recall and recognition continue to pose a challenge for a variety of people during routine activity. Numerous wearable devices aid human memory retrieval with context-aware audio and video cues (e.g., [1, 2, 3]). However, these cues are disruptive in environments that require acute visual or audio focus, and are often inappropriate in socially-sensitive situations. Haptic feedback is a discreet and unobtrusive alternative - it can be conveyed by a bracelet or anklet, minimizing audio and visual disruptions. Since interaction with haptic feedback as well as the device itself may be entirely concealed, tactile cues can be leveraged to assist users suffering from amnesia, Alzheimer's disease, dementia and other functional memory impairments, without drawing social attention to their condition.

We hypothesize that tactile cues can aid recall and recognition of visual or audio information. We present 4 studies which employ a wearable device that maps distinct haptic pulses to new concepts. When these concepts are re-encountered at a later time, corresponding cues are replayed. We find that high-performers on non-haptic tasks perform neutral or worse when assisted by cues. However, low-performers significantly improve on recognition tasks when haptic cues are employed.

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2 Prior Work

Prior research has explored cross-modal priming for visual and haptic stimuli, where information was presented in one modality (e.g., haptically) and tested in another (e.g., visually). Ballesteros et al. have shown that people remember haptically presented stimuli after *repetitive* tactile exploration. Reliable haptic priming has been shown for adults, as well as healthy elderly and Alzheimer's patients [4, 5]. Piateski et al. compared human recognition of vibro-tactile patterns applied to the hand and the torso, and concluded that torso-recognition is superior [6]. Since people are adept at retrieving haptic memories, we propose to explore multimodal priming where retrieval of video and audio concepts is assisted with haptic cues.

Several user interfaces have leveraged haptic stimuli to direct attention and aid memory [7, 8]. Young et al. employed haptic cues ("taps") to orient users' visual attention to different quadrants on a screen [9], implying the possibility of cross-modal links between haptic and visual attention. Wall, Brewster and Kildal have employed haptic feedback as memory "beacons", enabling visually impaired users to mark points of interest on tactile displays and navigate by recognizing the 'beacon' pulses [10]. The Multimodal Collaboration Environment for Inclusion of Visually Impaired Children (MICOLE) project employed 'tactons' in memory games where visually impaired users were presented with vibro-tactile pulses and, at a later time, asked to identify which pulses they have experienced before [11]. While prior work leveraged haptic feedback in the context of attention, navigation or memory games for visually impaired users, we hope to explore the effectiveness of vibro-tactile cues as a memory aid for people who experience memory difficulties during everyday tasks.

3 Wearable Haptic Feedback Device

We envision a context-aware wearable device that augments human memory with haptic cues. To this effect, a prototype of the wearable device has been implemented using a small vibratory motor. This motor is integrated into a bracelet (Fig. 1), powered by an external Atmel AVR microcontroller [12] board, although the final instantiation of the device would be controlled wirelessly. Distinct pulse signatures are produced by varying the motor speed, pulse length, and frequency. Each pulse is encoded by analogue signals, ranging from 0-255, with perceptible motor speeds starting at 120 (effectively, no pulse below the analogue signal of 120).

Fig. 1. Vibratory motor integrated into a bracelet to serve as a haptic feedback device

Table 1. Example pulse encodings, durations and descriptions

Encoding (100 ms segments)	Description	Duration (ms)
120,0,120	Short pulse, pause, short pulse	300
120,140,160,180,200,220,240	Continuously increasing long pulse	700
120,120,120,0,0,0,255,255,255	Soft pulse, pause, strong pulse	900

4 Methodology

We developed several user studies to validate our hypothesis that tactile cues can aid recall and recognition of visual and audio information. Our studies focused on 4 different challenges for human memory: blending (combining multiple distinct concepts into one) [13], auditory recognition, visual recognition, and free recall. Blending occurs when people confuse ("blend") aspects of different objects or locations into one seemingly familiar concept, most notably, during witness accounts in court proceedings. Poor auditory memory poses a challenge for a wide range of common tasks such as foreign language learning or following vocal instructions. Similarly, visual recognition is crucial, for example, in remembering faces or geographic locations. Finally, free recall ability influences retrieval of itemized information such as tasks from a to-do list, important dates, events, or phone numbers.

In order to evaluate the effects of a wearable haptic feedback device on the memory challenges outlined above, we conducted four user studies, each lasting for approximately 15 minutes. Each study consisted of three parts:

(I) *Training Phase*: Participants were presented with several distinct visual or audio stimuli, one at a time for five seconds each.

(II) *Pause*: Participants were given a distraction task of reading and rating three comic strips. This pause ensured that our experiments were not obscured by variance in short-term or working memory capacity.

(III) *Test Phase*: In this final phase, participants were asked to recall the concepts they were presented in phase I. Answers and response times were recorded.

Participants were asked to wear the haptic feedback device on their dominant hand. Participants in each study performed two versions of the tasks: control (without any haptic feedback), and intervention (with haptic feedback). To account for learning effects, the order of the control and intervention tasks were counterbalanced within and across participants. In the intervention tasks, a unique haptic pulse was played twice as each concept was presented in Phase I. During recognition tasks in Phase III, pulses were replayed when subjects were asked to recognize corresponding concepts. In recall tasks, participants had the option to replay the pulses multiple times.

Participants were recruited through the CMU Center for Behavioral Decision Research and compensated $10 upon completion of the study. Subjects (mostly graduate students) were not prescreened for memory impairments. The majority participated in all four studies, although several subjects skipped some studies due to time constraints and the non-Chinese language prerequisite for the audio study. Although the task order was randomized, and haptic cues were not reused between tasks, an interference effect is nonetheless possible among different haptic stimuli.

Haptic Cues and Blending
(24 participants, 15 male, 9 female, ages 21-65)
To determine whether haptic cues reduce blending, we implemented a shape-color recognition test. During phase I, subjects were shown 7 shapes of varying color, filled or hollow. The test phase presented 7 multiple-choice questions that showed three images - one familiar shape and two never-before-seen shape-color combinations. Participants were asked to identify which image they had seen before. During non-control tasks, haptic pulses associated with the familiar shapes were played.

Haptic Cues and Auditory Recognition
(20 participants: 12 male, 8 female, ages 21-65)
Non-Mandarin speaking participants listened to 5 Mandarin phrases, each repeated twice, while viewing the English translation. During the test phase, a Mandarin phrase was played while participants were shown an English translation and asked if it corresponded to the phrase. Each phrase was tested twice – once with a real translation and once with a translation that corresponded to another phrase in the set (10 total pairs).

Haptic Cues and Visual Recognition
(22 participants: 16 male, 6 female, ages 21-65)
Participants were shown 5 black and white portraits from the AT&T face database [14], and a name associated with each face. In phase III, subjects were shown a portrait-name pair, and asked if the name matched the face. Each picture was tested twice – once with the correct name, and once with a name belonging to a different face in the set (10 pairs total). For non-control tasks, haptic pulses corresponding to faces were played for both correctly and incorrectly matched name tasks.

Haptic Cues and Free Recall
(24 participants: 16 male, 8 female, ages 21-65)
We implemented a free recall test based on the Ebbinghaus nonsense syllable experiment [15]. In the control phase, participants were shown 7 nonsense syllables for 4 seconds each, for example “hik” or “lup”. During the test phase, participants were asked to type in the syllables they could remember. In the test phase of the intervention study, subjects had the option to replay cues from the training phase.

5 Results

Tactile feedback led to a marginally significant 11% improvement in audio phrase recognition ($p = 0.0753$). There was no strong effect for face or shape recognition. Furthermore, haptic cues hurt free recall by an average of 20% ($p = 0.0094$).

Although haptic feedback did not have a strong positive main effect, our data shows significant interaction between subjects’ baseline performance and the effects of the intervention for the recognition tasks. To examine these effects, we label participants who perform above average on unaided control tasks as *high performers* and subjects who perform below average as *low performers*. Low performers were significantly better at all three recognition tasks when haptic cues were employed, while high performers did not show improvement or performed worse.

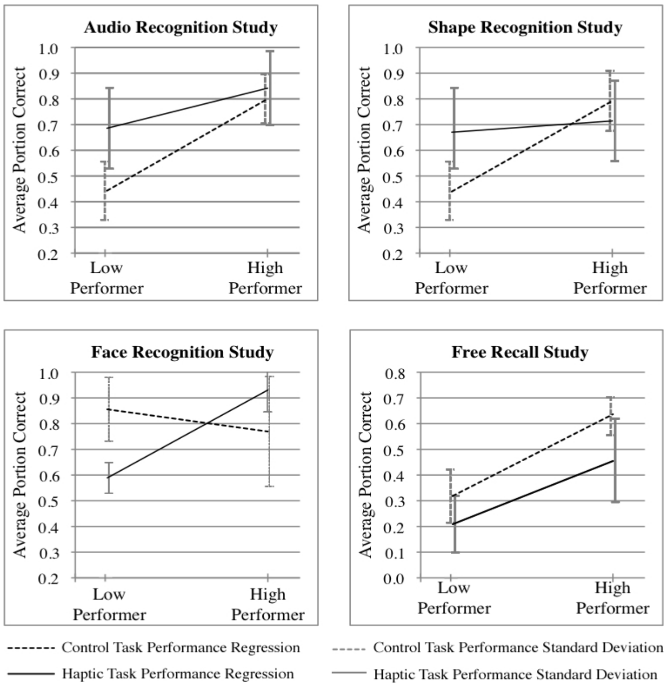

Fig. 2. Performance on shape, face, and audio recognition tasks with haptic cues interacts with performance on the control tasks ($p<0.001$, $p<0.001$, $p=0.0239$ respectively). Free recall shows no significant interaction, as both types of users performed consistently worse. with cues.

A 2-way Anova regression analysis was used to determine the interaction between control-level performance and performance on haptically-aided tasks. For each study, participants were classified as high or low performers based on the portion of control (non-haptic) memory tasks they completed correctly. Task condition (control or intervention) and performer type (high or low) were treated as independent factors. Significant interaction effects were found for all three recognition tasks (Fig. 2).

Fig. 3 juxtaposes the effects of haptic cues on low performers for each of the four memory tasks. Low performers showed an average improvement of 27% ($p<0.001$), 23% ($0<0.0064$), and 24% ($p=0.0062$) in face, shape and audio tasks respectively. Conversely, the average accuracy of high performers dropped by 16%, ($p=0.018$) and 18% ($p=0.02$) on the face-recognition and free recall tasks when haptic cues were employed. There was no significant difference in the audio and shape recognition studies for high performers, although the averages dropped by 4% and 10%.6 Discussion

High performers often performed worse on tasks that included haptic cues. Anecdotally, several participants felt that the haptic cues were ‘distracting’. It follows that some subjects were unable to concentrate on the memory tasks while attending to the haptic cues. In part, this cognitive overload stems from the crude nature of our prototype. The vibratory motor did not allow for fine-grain control of speed or frequency, making some pulses ‘too intense’. Furthermore, haptic feedback did not adapt to

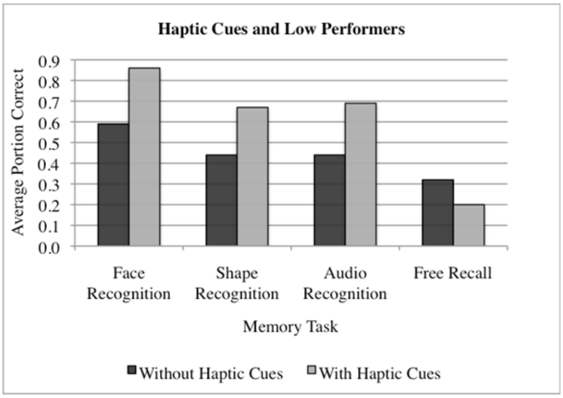

Fig. 3. Low performers showed improvement for all three recognition tasks with haptic cues

perceptual differences across participants, and consequently, some subjects were unable to accurately distinguish between pulses.

Free recall task performance was significantly lower with haptic cues, for most subjects. While recognition relies on perceptual memory where priming occurs subconsciously, free recall is influenced by declarative memory, which requires conscious, semantic processing [16, 17]. Hence, effective declarative memory cues must have semantic meaning that ties to the underlying concept. The haptic pulses employed in our study, however, were randomly assigned to nonsense syllables without semantic correlation. While non-semantic feedback successfully aided perceptual tasks such as visual and audio recognition, it failed for free recall, which hinges on explicit semantic memory. This explanation is consistent with participants' complaints about being unable to associate pulse frequencies and durations with specific letters of the syllables. Moreover, since participants were not screened by native language, semantic correlations between syllables may have been established based on subjects' linguistic backgrounds.

Our results suggest that high performers on non-haptic tasks perform differently from low performers on recognition tasks that are augmented with haptic cues. This interaction effect may be caused by a difference in cognitive processing and attention systems between high and low performers. Prior analysis of fMRI data implies that attention control systems vary between people with different working memory capacities [18]. Furthermore, people with good recognition of studied concepts show different event-related brain potentials (ERP's) than poor-recognizers [19]. Given this variance in attention and retrieval systems, the effectiveness of haptic cues may correlate with working memory capacity.

Since haptic cues benefitted participants with below-average performance on unassisted memory tasks, we propose haptic feedback as a memory aid for people with poor or impaired memory. It is not uncommon for memory-enhancing treatments to target poor performers while having neutral or negative effect on above-average subjects. For example, sabeluzole, a memory enhancing drug, has been shown to effectively improve consistent long-term retrieval in poor performers (below 50% long-term retrieval baseline), while having no effect on high-performers [20].

Furthermore, dextroamphetamine, a neurophysiologic inhibitor, has been shown to improve working-memory load only for participants with low baseline memory capacity, while worsening the performance of above-baseline participants [21]. Similarly, our data supports the use of haptic feedback as an assistive technology for low-performance participants.

Future Work – Improving Haptic Cues
We postulate that the adverse effects of haptic feedback can be attributed, in large, to a cognitive overload. Future work can focus on eliminating this effect through a refined implementation of the haptic feedback device. A more fine-grained motor or higher-resolution haptic display can offer more subtle cues. Moreover, an adaptive device can adjust intensity and frequency according to individual differences in perception. More importantly, however, the final wearable device must be context-aware and provide cues only in situations when the user is not suffering from cognitive overload. Since randomly assigned haptic cues proved detrimental for performance on free recall, an alternative approach could allow users to 'create' their own cues. That is, people may associate semantic meaning with different types of pulse signatures to aid personal recollection of declarative concepts.

6 Conclusion

We proposed haptic cues as an approach for improving human memory. While our user studies failed to validate haptic feedback as a universally effective aid for recall and recognition, we found significant interaction between performance on tasks with and without haptic cues. Poor performers improved by 20% or more on recognition tasks that were augmented with tactile pulses. It follows that vibro-tactile displays wield significant implications in the domain of assistive technology for memory-impaired users. As a ubiquitous, context-aware wearable device, haptic feedback has the potential to aid a multitude of people in overcoming memory challenges during everyday tasks.

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