Modality Switching for Mitigation of Sensory Adaptation and Habituation in Personal Navigation Systems

Kyle Kotowick
Massachusetts Institute of Technology
Department of Aeronautics and Astronautics
Computer Science and Artificial Intelligence Laboratory
Cambridge, MA, USA
kotowick@mit.edu

Julie Shah
Massachusetts Institute of Technology
Department of Aeronautics and Astronautics
Computer Science and Artificial Intelligence Laboratory
Cambridge, MA, USA
julie_a_shah@csail.mit.edu

ABSTRACT

When humans need to navigate across terrain accurately and quickly, they often use portable electronic navigation systems for directional guidance. Prior work in this field has focused on selecting either the visual or haptic sensory modality for providing such guidance and has indicated that either option may be preferable depending on the user's specific goals. However, basing the selection of visual or haptic guidance on static criteria of this type discounts important time-varying effects, primarily stimulus-specific adaptation (SSA) and habituation. Here, we propose a navigation system design that mitigates these detrimental effects by periodically switching between visual and haptic navigation guidance. While this is likely to incur an undesirable switching cost, we hypothesize that the long-term benefits of counteracting SSA and habituation will outweigh this cost. In this paper, we describe the design and results of a human-participant study intended to evaluate this hypothesis. Our findings indicate that modality switching results in a transient cost to performance, but also that switching modalities lessens the SSA and habituation effects over time as compared with single-modality systems. The results support the hypothesis that an alternating-modality system would outperform a single-modality system for long-duration navigation tasks.

Author Keywords

Multimodal; Sensory Modality; Navigation; Habituation; Adaptation.

INTRODUCTION

Assisting humans with navigational tasks is one of the most common uses for portable electronic devices. In particular, users in extreme environments — such as emergency first responders or military infantry on patrol — often make use of devices that aid them in locating and navigating to emergency scenes, victims, or enemy targets. For such users, high performance is of paramount importance and it is critical that these navigational devices provide directional guidance in the most effective manner possible.

Historically, navigation systems have been based on visual displays. For millennia, maps and compasses — both of which require visual attention from the user — were the primary navigational tools. In the last few decades, with the development of computerized audio systems, auditory directional guidance (i.e., verbalized directions) has also become available on many devices. Only in recent years, however, has a third major sensory modality been actively investigated for directional guidance: haptic feedback.[1]

Investigation into the use of haptic feedback for navigation systems began in the early 2000s, primarily within the military community. Multiple studies and research programs have demonstrated the merits of a haptic navigation belt: a belt with vibrating motors placed throughout which vibrate in the direction the user needs to move [11, 13, 19, 18, 17, 14]. One of the main outcomes of this prior work was determination of the relative advantages and disadvantages of visual vs. haptic directional guidance. Each performs better under specific circumstances; for example, in one study by the U.S. Army Research Laboratory, a visual GPS display allowed significantly faster traversal over terrain by a soldier with no other tasks to complete, while a haptic navigation system allowed a soldier to pay significantly more attention to visual search tasks, detection and avoidance of obstacles, and weapon control [13]. In related work to date, these advantages and disadvantages have formed the sole basis for selecting one modality over another: the optimal modality is that which is most compatible with the user's specific goals. These relative merits, however, are of a static nature: they only consider the present circumstances and do not allow for time-varying effects. We believe there are additional important, dynamic effects that must be consid-

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[1] Throughout related literature, the terms "haptic" and "tactile" are used interchangeably. Specifically, "haptic" refers to the overall sense of touch including kinesthetic (the sense of position and movement of muscles, tendons, and joints) and tactile (the sense of touch or vibration in the fingers or on the surface of the skin) sensory input. We use "haptic" throughout this paper for simplicity and consistency.

ered during modality selection: specifically, stimulus-specific adaptation and habituation.

Stimulus-specific adaptation (SSA) and habituation — physiological and behavioural (respectively) detrimental effects that result in decreased sensitivity to continuous stimulation over time [21, 48] — are likely to reduce a navigation system's effectiveness over time if it continues to incorporate a single directional guidance modality, regardless of whether the chosen modality is that which is most compatible with the user's specific goals. As the user continues to receive directional guidance in the same modality, he or she is naturally less likely to notice and respond to it. Both of these effects, however, can be "reset" by changing the modality of the stimulus, causing the user to regain full sensitivity to it [59, 48]. We hypothesize that by regularly changing the modality in which directional guidance is presented, we can counteract the effects of SSA and habituation in order to provide greater performance stability over long-duration navigation tasks.

In this paper, we describe the design and results of a 32-participant experiment intended to determine the impact of SSA and habituation on a visual/haptic navigation system, as well as to investigate whether that impact can be mitigated trough periodic switching between modalities. We conducted the experiment according to a within-participants design, with the navigation feedback modality as the controlled independent variable. The data was analyzed with linear mixed-effects models; the main and interaction effects of various factors on multiple performance metrics are presented and discussed here.

RELATED WORK

Haptic Navigation

Following from extensive prior research into use of the haptic modality to convey information in general, research into haptic directional guidance became quite active in the mid-2000s for both civilian and military applications.

Research for civilian applications of haptic directional guidance has been conducted independently by numerous research groups. A study by Tsukada and Yasumura examined the feasibility of a prototype haptic navigation belt, finding that it was able to assist users in accurately navigating through waypoints [57]. Pielot and Boll conducted similar work by comparing the effectiveness of their prototype haptic navigation belt with conventional visual navigation systems, finding that the haptic system required less attention but was not as effective in helping the user reach the waypoint [42]. That same research group conducted another study to evaluate the use of haptic vibration patterns on a mobile phone to convey navigation information, finding that it required less attention while having no significant navigation performance differences compared to a visual system [43]; they then incorporated these results into a prototype haptic navigation system and conducted a large-scale study of its use in an urban environment and confirmed these results [44]. Several studies have investigated the design and use of haptic directional guidance for blind users, all showing encouraging results [1, 34, 67, 45]. Many additional, similar studies on haptic directional guidance for pedestrian use have demonstrated positive effects [36, 30, 33, 47].

Research for military applications has been conducted primarily by the U.S. Army Research Laboratory. This research program included four major experiments on the use of haptic directional guidance for soldiers in the field using a "personal tactile navigator" (PTN), i.e. a haptic belt that vibrates in the direction the soldier needs to move. A series of four experiments all demonstrated potential benefits and detriments of haptic guidance compared to visual guidance: the visual modality allowed faster navigation when there were no additional tasks, while the haptic modality was less likely to interfere with secondary visual-based tasks such as target identification [16, 11, 13, 14]. Other publications have included details of improvements to the navigation system [15] and a summary of the first three experiments [18].

Overall, prior work on haptic directional guidance has demonstrated that it is a worthwhile technology to develop and integrate into modern navigation systems, thereby motivating the research described in this paper.

Modality Switching Cost

One of the potential disadvantages of any system that switches between modalities for conveying information, as would be the case with this proposed navigation system, is that an effect known as "switching cost" may be introduced. Switching cost is when a user experiences a worsened response time or sensitivity to a stimulus due to having to switch attention from one sensory modality to another. The specific type of switching cost that is relevant to this study is known as a "within-task switching cost."

A within-task switching cost occurs when information from a given source/task is presented to the user in a sensory modality other than the one it was expected in, e.g. if a user expects an alert to be provided auditorily as an alarm, but instead it is presented visually as a warning light. While the body of research assessing this effect is smaller than that of other types of switching cost, numerous studies have shown its influence to be significant. In a study by Klein, participants exhibited slower response time when they received a simple stimulus in a modality different from that which they expected [32]. A later, similar study by Spence *et al.* yielded the same result for the detection of target locations [52]. Post and Chapman demonstrated that participants responded less quickly to simple stimuli when they did not know which modality to expect them in or when they expected them in the incorrect modality, compared to when their expectations were correct [46]. The results of these studies suggest that navigation performance while using a navigation device which switches between different modalities would drop after each switch before recovering as the user becomes accustomed to the new modality.

Sensory Adaptation

Sensory adaptation, also referred to as neural adaptation, is a physiological effect where continuous exposure to a stimulus causes changes in the response properties of the activated neurons, usually resulting in decreased sensitivity to that stimulus over time [64]. The body of work investigating this effect is extensive, beginning with research conducted by Herman von Helmholtz in the 19th century who investigated visual and auditory adaptation to abnormal stimuli [27]. Similar work was conducted in the field of psychology later that century [53]. In more recent years, research has focused on the specific mechanisms that cause this effect and the evolutionary process that lead to them. Various reasons for the evolution of this trait have been proposed, such as efficient coding of neurological signals (similar to a form of digital compression) and allowing for heightened response to rare or changing stimuli [35, 63, 12].

Stimulus-Specific Adaptation

Stimulus-specific adaptation (SSA) is sub-category of sensory adaptation and relates to adaptation to the history of a stimulus. As the neurological system receives the same stimulus continuously for an extended duration — or receives a brief stimulus frequently — the neural response to that stimulus decreases over time [3, 21]. SSA is most widely known for its relevance to the concept of change detection [23].

Although much of the research on this topic has been conducted on rats or primates due to the invasive procedures required to obtain measurements, the effect has also been found to exist in humans for both visual [39, 5, 8, 50, 38, 49, 51] and auditory [59, 58, 2, 37, 4, 54, 41, 40] stimuli. SSA has been shown to exist for stimuli with durations of 200ms (the same duration as the vibration pulses used in the Army Research Laboratory's haptic directional guidance experiments) and after only one occurrence of a stimulus [62]. Prior work has suggested that SSA may end after the stimulus has not been received for ~2 seconds [59]. Unfortunately, research into this phenomenon appears to have focused exclusively on visual or auditory stimuli and provides little information regarding how SSA relates to haptic stimuli. However, study results have indicated that auditory SSA occurs in the thalamus [2], and that the thalamus is also involved in the perception of touch [9]. It is likely, then, that SSA exists for haptic stimuli as well; if this is the case, repeated pulses of vibration used for haptic directional guidance (even if limited to a duration of 200 ms) may become less noticeable to the user over time.

The presence of this effect supports the idea that switching between modalities within a navigation system would yield a beneficial effect. Every time the modality (i.e., the stimulus) changes, the user would not be adapted to this new modality and should therefore not suffer from the detrimental effects of SSA.

Habituation

Habituation, although similar to sensory adaptation, is a behavioural learning effect (as opposed to a physiological one). While adaptation is a passive effect — i.e., a person has no direct control over it — habituation is an active effort by the brain to filter out background stimuli in order to allow more attention to be paid to irregular stimuli. Specifically, habituation is defined as "a behavioural response decrement that results from repeated stimulation and that does not involve sensory adaptation/sensory fatigue or motor fatigue" [48].

Research into habituation has a rich and extensive history. The term was already in widespread use by the beginning of the 20th century [31, 24], with a number of related terms used to describe the same concept, including "acclimatization" and "accommodation" [29]. Initially, habituation and adaptation were not clearly distinguished as separate effects. A landmark paper published in 1966 by Thompson and Spencer, however, reviewed definitive evidence that the decrease in sensitivity to repeated stimuli could not be entirely attributed to sensory adaptation, and that a separate effect must be present [56]. Further work by Groves and Thompson developed a more concrete theory of habituation [22].

Two elements of habituation are of particular importance in the context of this paper: *dishabituation* and *spontaneous recovery*, which are two of the characteristics of habituation originally specified by Thompson and Spencer [56] and later revised by Rankin *et al.* [48]. *Dishabituation* refers to a characteristic wherein "presentation of a different stimulus results in an increase of the decremented response to the original stimulus" [48]. In other words, if a person is habituated to a stimulus and therefore experiencing decreased sensitivity to it, providing him or her with an alternative stimulus will result in increased sensitivity to subsequent presentations of the original. *Spontaneous recovery* refers to a circumstance wherein "if the stimulus is withheld after response decrement, the response recovers at least partially over the observation time" [48]. This means that if a person is habituated to a stimulus and experiencing decreased sensitivity to it, withholding that stimulus for a duration of time will result in increased sensitivity to it upon its reintroduction. Results from various studies have indicated that the time required for spontaneous recovery can range from seconds to weeks depending on multiple factors [56, 65, 61, 68, 10, 20].

Both dishabituation and spontaneous recovery provide motivation for a navigation system that switches between modalities over time. If a user has become habituated to stimuli from a given directional guidance modality, be it visual or haptic, switching to the alternative modality would improve performance in multiple ways. This alternate modality would represent a new type of stimulus, thereby dishabituating the user from the prior modality and improving his or her sensitivity to it when it is reintroduced later. Switching to a new modality would also provide a break from the stimulus that the user has become habituated to, creating an opportunity for spontaneous recovery to occur.

HYPOTHESES

Our experiment evaluated a navigation system able to provide directional guidance in visual-only, haptic-only, or visual/haptic switching modes. Based on prior work regarding modality switching costs, SSA, and habituation, we designed this experiment to investigate the following two hypotheses:

Hypothesis 1: Switching directional guidance modalities during a navigation task will result in an immediate decrease in performance due to the associated modality switching cost, but performance will gradually recover over time. Specifically, this will be represented as a positive coefficent for the main effect of the amount of time since the last modality change on the

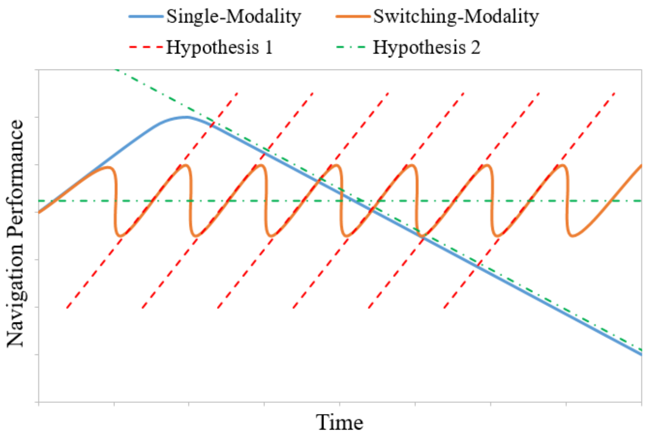

Figure 1. A graphical representation of the hypotheses. After the user becomes familiar with a single-modality navigation system, the performance gradually decreases over time due to SSA and habituation. For a switching-modality system, there is a decrease in performance after each switch, but no long-term SSA or habituation effects.

dependent performance variable (i.e. performance improves with time after each modality change).

Hypothesis 2: Switching directional guidance modalities periodically over the course of a navigation task will result in improved long-term navigation performance compared with visual- or haptic-only navigation systems by counteracting the effects of SSA and habituation. Specifically, this will be represented as a negative coefficient for the interaction effect between visual- or haptic-only modes (with the switching mode as the reference category) and the time since the navigation task began on the dependent performance variable (i.e., performance in visual- or haptic-only modes decreases with time compared with the switching–modality mode).

Figure 1 depicts a visual representation of the hypotheses. These hypotheses relate to overall navigation performance (the ability to reach a waypoint quickly); however, it is possible that individual components of performance may be affected differently. Therefore, we tested effects across multiple metrics including navigation speed, deviation from the shortest path (bearing error), and workload.

EXPERIMENTAL DESIGN

The experiment, conducted according to a within-participants design, consisted of a navigation task performed on a desktop computer, with the navigation system "mode" (*visual*, *haptic*, or *switching*) serving as the controlled independent variable.

Equipment

We conducted the experiment using the ARMA 3 simulation software [7] on a custom-built computer.[2] ARMA 3 was selected due to its in-game scripting language that allows for programming of the experiment task, its open-world environment, and its external C++ extension callback capability for operating the haptic device and recording data to an external database. A custom-built wearable device consisting of an elastic belt containing eight tactors, evenly distributed around the waist, was used to convey information to the participant in the haptic modality. The tactors were C-2 models from Engineering Acoustics, Inc. Figure 2 depicts the experiment setup.

Figure 2. Experiment Setup

Navigation Task

The participant's only task during each experiment trial was to move his or her in-game avatar from its current position to a given waypoint. The participant controlled the avatar's movement using the "W" (forward), "A" (left strafe), "S" (backward), "D" (right strafe), and "SHIFT" (sprint) keys, while controlling the avatar's direction via the mouse. Participants received directional guidance through either a visual or haptic system, as described below. When participants reached the waypoint they would hear a chime and would be assigned a new waypoint. Trials lasted 8 minutes each, with participants continuing to receive new waypoints until time ran out.

Visual Navigation

When the navigation system was operating under the visual modality, participants were able to see a device attached to their avatar's chest that closely resembled a commercial GPS navigation display. The chest-mounted location was chosen in order to emulate the vest-mounted, flip-down GPS pouch utilized by the US Army as part of the Nett Warrior program (see Figure 3). The display showed a map centered on the avatar's current location and oriented such that the top of the map corresponded to the direction the avatar was presently facing. The display also included an arrow at the center that always pointed toward the current waypoint; to face directly toward the waypoint, the participant would turn the avatar until the arrow on the display pointed directly forward. The waypoint itself was not marked on the display, only the direction toward it — this was so that the visual modality would not provide additional information that was not also available

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[2] **OS:** Windows 10; **CPU:** Intel Core i7 6700K; **Memory:** 64GB Corsair DDR4-3200; **Motherboard:** ASUS Z170; **SSD:** 1TB Intel 600p M.2; **VGA:** 2x NVIDIA Titan X in SLI; **Audio:** Sennheiser HD 202 II headphones; **Mouse:** Logitech M500; **Keyboard:** Logitech G710+

Figure 3. Flip-down GPS pouch used by the US Army. Image reproduced from [60].

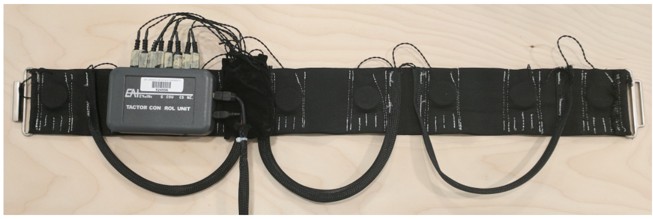
Figure 4. In-simulation visual navigation display.

in the haptic modality. Figure 4 depicts the visual navigation display.

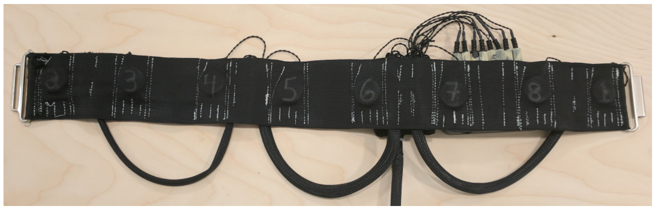
Haptic Navigation

When the navigation system was operating under the haptic modality, the GPS display was hidden, with directional guidance instead conveyed through the haptic belt around the participant's waist. The eight tactors in the belt were evenly spaced at the 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° positions with corresponding IDs of 1 – 8 respectively (the 0° position was located directly underneath the participant's navel). Figure 5 shows the haptic belt. The two tactors closest to the actual bearing of the waypoint relative to the avatar's current direction were vibrated at 250 Hz, with the gain of each tactor relative to its proportional representation of the actual bearing, according to the following equations:

$$G_{\lfloor B/45 \rfloor + 1} = ((45 - (B \bmod 45))/45)^{0.75} \tag{1}$$



(a) Outside



(b) Inside

(c) As worn by participants

Figure 5. Custom-built haptic navigation belt.

$$G_{\lfloor B/45 \rfloor + 2} = ((B \bmod 45)/45)^{0.75} \tag{2}$$

G_x is the gain level (0 to 1) of the tactor with ID equal to x and B is the bearing, in degrees, of the current waypoint relative to the avatar's current direction. For example, if the direction to the waypoint was at 80° relative to the avatar's current direction, the tactors at the 45° (ID = 1) and 90° (ID = 2) positions would vibrate with gain levels of 0.32 and 0.83, respectively. These non-linear equations were selected via pilot testing with the intention of providing an equal sensation of vibration strength regardless of direction.

Scoring

Participants received financial compensation based on a competitive structure, with the two highest-performing participants receiving bonus monetary prizes, as described in the Compensation section below. Therefore, it was necessary to implement a scoring system to motivate participants to maximize their performance. Every time a participant successfully reached a waypoint with his or her avatar, he or she received a number of points corresponding to the straight-line distance (in meters) between the last waypoint and the one that had just been reached. At the end of the trial, additional points were awarded for any progress made toward the final waypoint when time ran out.

Due to the open-world environment represented in the trials, it was possible for participants to cause their avatars to fall from heights or into open water. In order to prevent such behaviour — and the associated noise in the resulting data due to difficulty in extricating their avatar from its predicament — participants received a score penalty of -200 points if their avatar fell from a substantial height or into open water. Following such a fall, their avatar was then reset to its location 10 seconds prior to the event.

Procedure

The entire experiment took approximately 2 hours per participant. Participants began with a questionnaire to collect demographic information and ensure they met the requirements to participate, and were then gradually introduced to the navigation task, the visual and haptic navigation systems, and the scoring mechanisms through a training phase. This training also acted as a screening process, identifying participants who were unable to complete any individual task and therefore ineligible to continue. Upon completing the training phase, participants received three opportunities to complete a test trial and achieve the minimum overall performance level required to continue, which was set at the 25th percentile following a pilot study involving 11 participants. As the hypotheses tested in this experiment related to users in environments where a high level of performance is critical, this minimum threshold served to reduce the potential for low-performance outliers that did not represent the population the results would be applied to.

Participants who met the minimum performance level then began the main phase after a brief rest period. The participants completed eight trials, each of a different type, as shown in Table 1. Each trial took place in one of two environments: urban (Figure 6b) or jungle (Figure 6a). Within each environment, one trial was conducted in each of the following four navigation modes (depicted in Table 2):

- **Visual-only**: The entire trial is conducted using only the visual modality for directional guidance.
- **Haptic-only, continuous**: The entire trial is conducted using only the haptic modality for directional guidance, with the haptic belt providing continuous vibrations.[3]
- **Haptic-only, pulsed**: The entire trial is conducted using only the haptic modality for directional guidance, with the haptic belt providing 200 ms pulses of vibration with 800 ms pauses in between.
- **Switching**: The initial directional guidance modality alternatesx between visual and pulsed haptic at 60-second intervals (the modality used at the start of the trial is randomly selected).

(a) Jungle

(b) Urban

Figure 6. The two environments used throughout the experiment.

The order in which the trials were conducted was balanced between participants using a full Latin square design in order to compensate for learning effects. Four different Latin squares of eight rows each were concatenated to allow for balancing between all 32 participants. After each trial, participants responded to a NASA-TLX workload scale [26]. Following the first four trials, participants received a brief rest period. Upon completing the final four trials, the participants responded to an exit questionnaire in which they provided subjective opinions about which modes they felt allowed for the best performance, as well as which they preferred. Participants were also able to provide open-ended feedback regarding several aspects of the experiment.

Compensation

All participants who completed the training phase received $5 compensation; participants who met the minimum performance level after the training and completed the remainder of the experiment received an additional $15. In order to motivate participants to remain focused on the task and perform as well as possible, we also implemented a competitive score-based incentive structure as previously described, wherein the participants who achieved the highest and second-highest scores (as defined in the Scoring section above) received additional $85 and $40 prizes, respectively.

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[3] The "haptic-only, continuous" mode was included to simultaneously collect data for evaluating a hypothesis unrelated to this paper, and was not used in the analysis presented here.

Trial Type	Environment	Navigation Mode
1	Urban	Visual
2	Urban	Haptic (Continuous)
3	Urban	Haptic (Pulsed)
4	Urban	Switching
5	Jungle	Visual
6	Jungle	Haptic (Continuous)
7	Jungle	Haptic (Pulsed)
8	Jungle	Switching

Table 1. The trial types completed by each participant.

Time	Navigation Mode			
	Visual	Haptic (C)	Haptic (P)	Switching
0 - 60	V	HC	HP	V
60 - 120	V	HC	HP	HP
120 - 180	V	HC	HP	V
180 - 240	V	HC	HP	HP
240 - 300	V	HC	HP	V
300 - 360	V	HC	HP	HP
360 - 420	V	HC	HP	V
420 - 480	V	HC	HP	HP

Table 2. The directional guidance modalities used for each navigation mode.

Data Collection

The experiment began with a questionnaire designed to determine whether participants were eligible to complete the experiment (see the Participant Demographics section below), as well as to collect the following demographic information:

- The participant's age
- The participant's physiological birth sex
- Hours per day of computer use
- Hours per day of video game use
- Whether the participant had served in any first-responder role (military, police, fire, EMS)
- Whether the participant was a student

Over the course of each trial, the status of the participant's avatar and objective — including avatar position, waypoint position, avatar direction, and avatar speed — were recorded at 50 Hz. This, combined with the NASA-TLX workload scale conducted upon the completion of each trial, allowed for analysis of the following dependent variables:

- **Navigation Speed:** The rate, in meters per second, at which the participant's avatar progressed toward the waypoint. Note that this is different from the avatar's speed, as it only incorporates the component of the avatar's velocity vector occurring in the direction of the waypoint.
- **Bearing Error:** The difference between the bearing from the avatar's position to the waypoint and the avatar's current direction.
- **Workload:** This value was calculated according to the standard NASA-TLX workload scale instructions [26]. We analyzed the standard weighted single-value workload, as well as the individual "raw" rating scales (described in [25] and shown to potentially be more accurate in [6, 28]).

Participant Demographics

Recruitment was limited to people between the ages of 18 and 50 years with a waist circumference between 71.1 cm (28in) and 101.6 cm (40in), which was the range compatible with the haptic belt. All participants were required to have vision in both eyes, hearing in both ears, and no disability that would prevent them from feeling vibrations from the haptic belt or interacting with the computer mouse and keyboard.

Thirty-two participants completed the primary experiment, including 20 men and 12 women. These participants ranged in age from 18 to 34 years (mean, 21.8 years; median, 21 years). Twenty-seven of the participants were students at the Massachusetts Institute of Technology, three were students at other universities, and two were not students.

Five additional participants began the experiment, but failed to meet the minimum performance level following training and were therefore excluded. Note that although the minimum overall performance level was set as the 25th percentile of post-training performance in the pilot study, suggesting that 25% of all participants in the main study should have failed to meet that minimum, the threshold was calculated using only the first post-training trial per pilot participant. In the main study, each participant was allowed three attempts to meet that threshold in order to accommodate those who took longer for the learning effect to subside, resulting in a much lower exclusion rate. Four additional participants voluntarily ended the experiment early for various reasons.

RESULTS

We conducted all modeling and analysis in MATLAB 2017b [55] using MATLAB's native linear mixed effects modeling capability (`fitlme`). Each model was either data point-based (incorporating individual data points collected at 50 Hz during the trials) or trial-based (incorporating aggregate data specific to a single trial). The models used the following independent variables:

- **Age:** The participant's age in years. Prior to analysis, **Age** values were centered using the mean age of all participants in order for the models' intercept values to represent the expected values at the average participant age.
- **Sex:** The participant's physiological sex. In the models, *female* was the reference category and *male* was the indicator variable.
- **Computer Use:** The average number of hours per day that the participant reported using computers.
- **Game Use:** The average number of hours per day that the participant reported playing video games.
- **Environment:** The simulated environment in which the trial was conducted. In the models, *jungle* was the reference category and *urban* was the indicator variable.
- **Trial Time:** The time, in minutes, since the start of the trial (only applicable for data point-based models).

- **Current Modality:** The directional guidance modality in use at the time the data point was recorded (only applicable for data point-based models). In the models, *Haptic* was the reference category and *Visual* was the indicator variable.
- **Modality Time:** The time, in minutes, since the last directional guidance modality switch (only applicable for data point-based models using the *switching* mode).
- **Mode:** The mode used for the given trial (*Visual*, *Haptic* (pulsed) or *Switching*). In the models, *Switching* was the reference category and *Haptic* and *Visual* were indicator variables.
- **Participant:** A unique ID number assigned to the participant.
- **Trial:** The chronological number of the trial for the given participant (i.e. 1 through 8, only applicable for data point-based models). Note that the trial number does not correlate with the trial environment or mode, as the order of trial types differed between participants according to the Latin square design.

Hypothesis 1

In order to determine whether there was a significant switching cost associated with changing directional guidance modality mid-task, we fit linear mixed-effects models to the set of all data points collected across all trials conducted in the *switching* mode. The models were formulated according to the following equation in Wilkinson notation [66]:

$$DV \sim Age + Sex + GameUse + ComputerUse + Environment + TrialTime + CurrentModality + ModalityTime + (1 \mid Participant) + (1 \mid Participant : Trial)$$

DV is the dependent variable in question. We fit this model for both the **Navigation Speed** and **Bearing Error** dependent variables. In order to test Hypothesis 1, we specifically evaluated the effect of *Modality Time* on the dependent variables.

Random Effects

Each of the linear mixed effects models testing Hypothesis 1 was fit using *Participant* as a grouping variable with a random intercept (baseline performance for each participant), as well as *Trial* as a nested grouping variable within *Participant* with a random intercept (baseline performance on each trial).

Analysis

The results of the Hypothesis 1 models are presented in Table 3. This table depicts the effect estimate for each factor on each dependent variable as as a percentage of the estimate for the model's intercept. As the intercept indicates a baseline value, representing each factor's effect size as a proportion of the intercept value allows for easier understanding of its relative size. The table also indicates which effects were statistically significant.

Hypothesis 2

In order to determine whether periodically switching directional guidance modalities prevented SSA and habituation, we fit linear mixed-effects models to the set of all data points collected across all trials. The models were formulated according to the following equation in Wilkinson notation [66]:

$$DV \sim Age + Sex + GameUse + ComputerUse + Environment + TrialTime * Mode + (1 \mid Participant) + (1 \mid Participant : Trial)$$

DV is the dependent variable in question. We fit this model for both the **Navigation Speed** and **Bearing Error** dependent variables. In addition to the main effects of each independent variable, we also included a two-way interaction effect between *Trial Time* and *Mode*, as determining the effect of this interaction term (and whether the effect is significant) is necessary in order to test Hypothesis 2.

	Navigation Speed	Bearing Error
(Intercept)	100%**	100%**
Age	0.452%	-0.834%
Sex (Male)	6.61%	-14.6%*
Computer Use	-2.00%*	2.82%
Game Use	4.64%*	-10.2%*
Environment (Urban)	-9.83%**	47.3%**
Trial Time	1.29%**	-3.14%**
Modality (Visual)	-1.57%**	-0.300%
Modality Time	6.52%**	-9.81%**

Table 3. Effects for Hypothesis 1 models. Blue cells indicate improved performance, red cells indicate reduced performance. *$p < 0.05$, **$p < 0.001$.

Random Effects

As with the modelling for Hypothesis 1, each of the linear mixed effects models testing Hypothesis 2 was fit using *Participant* as a grouping variable with a random intercept (baseline performance for each participant), as well as *Trial* as a nested grouping variable within *Participant*, also with a random intercept (baseline performance on each trial).

Analysis

The results of the Hypothesis 2 models for performance-based dependent variables are presented in Table 4. As with the results for Analysis, this table depicts the effect estimate for each factor on each dependent variable as a percentage of the estimate for the model's intercept, as well as which effects were statistically significant.

Subjective Workload

In order to determine whether periodically switching directional guidance modalities affected subjective workload levels, we fit linear mixed-effects models to the set of aggregate trial data (as workload values were only collected once per trial). The models were formulated according to the following equation in Wilkinson notation [66]:

$$DV \sim Age + Sex + GameUse + ComputerUse + Environment + Mode + (1 \mid Participant)$$

Again, *DV* represents the dependent variable in question. We fit this model for overall weighted workload, as well as individual ratings for each workload type.

	Navigation Speed	Bearing Error
(Intercept)	100%**	100%**
Age	-0.030%	-0.131%
Sex (Male)	9.13%*	-18.9%*
Computer Use	-1.65%*	2.04%
Game Use	3.43%*	-8.16%*
Environment (Urban)	-10.7%**	52.1%**
Trial Time	1.39%**	-3.31%**
Mode (Visual)	7.75%**	-14.9%**
Mode (Haptic)	8.86%**	-14.3%**
Trial Time : Mode (Visual)	-2.61%**	4.17%**
Trial Time : Mode (Haptic)	-1.53%**	3.09%**

Table 4. Effects for Hypothesis 2 models. Blue cells indicate improved performance, red cells indicate reduced performance. *$p < 0.05$, **$p < 0.001$.

Random Effects

Each of the linear mixed effects models testing Hypothesis 2 was fit using *Participant* as a grouping variable with a random intercept (baseline performance for each participant). Since workload values were only recorded once per trial, it was not necessary to include *Trial* as a nested grouping variable within *Participant*.

Analysis

The results of the Hypothesis 2 models for workload dependent variables are presented in Table 5. As with the results for Hypothesis 1, this table depicts the effect estimate for each factor on each dependent variable as a percentage of the estimate for the model's intercept, as well as which effects were statistically significant.

DISCUSSION

In this section, we present the evidence supporting our hypotheses, as well as the effects of other factors such as participant demographics. The names of dependent variables are bolded and the names of factors are italicized for clarity. "Significant" refers to $p < 0.05$, and "highly significant" refers to $p < 0.001$.

Hypothesis 1

In order for Hypothesis 1 to be true, the *Modality Time* factor must have a coefficient corresponding with improved performance. In other words, performance should improve with the amount of time since the modality last switched (as performance recovers after decreasing due to switching cost). As indicated by the data in Table 3, we found this hypothesized effect to be highly significant for **Navigation Speed** and **Bearing Error**, with per-minute effect sizes equivalent to approximately 6.5% and 9.8% of the model's intercept value, respectively. This model suggests that in our experiment, where the modality was switched every minute, there was a ~6.5% reduction in **Navigation Speed** and a ~9.8% increase in **Bearing Error** immediately following a modality switch.

As hypothesized, participants suffered a significant switching cost when the directional guidance modality was changed.

Hypothesis 2

In order for Hypothesis 2 to be true, the interaction effect between the *Trial Time* and *Mode* factors must have a coefficient corresponding with reduced performance for both the *Mode (Visual)* and *Mode (Haptic)* indicator variables. In other words, performance should drop over time when using either of the single-modality modes compared with the switching-modality mode. As the data in Table 4 indicates, we found this hypothesized effect to also be highly significant. While using the *haptic-only* or *visual-only* modes had highly significant effects on **Navigation Speed** and **Bearing Error** — suggesting that they allowed better average performance over the course of the entire trial compared to the *switching* mode — the *Trial Time : Mode (Visual)* and *Trial Time : Mode (Haptic)* interaction effects were both highly significant in the direction of reduced performance regarding the same dependent variables. The model had a crossover point (the *Trial Time* at which the expected performance of the *switching* mode exceeded that of the single-modality modes) of ~3 minutes (visual) and ~5.8 minutes (haptic) for **Navigation Speed**, and ~3.6 minutes (visual) and ~4.6 minutes (haptic) for **Bearing Error**. These results suggest that single-modality modes allow for better performance in the early stages of a navigation task, but performance in these modes will steadily decrease over time compared with the *switching* mode. As hypothesized, periodically switching modalities provides a more stable level of performance for long-duration navigation tasks.

Subjective Workload

Although not related to either of our initial hypotheses, we also evaluated the relative subjective workload levels associated with the *switching* mode compared with the single-modality modes. As shown in Table 5, we found that the *switching* mode did not result in significantly higher workload than either of the single-modality modes, i.e. neither the *Mode (Visual)* nor *Mode (Haptic)* indicator variables differed significantly from the *Mode (Switching)* reference category.

Other Factors

The effects of other factors not related to our hypotheses were evaluated with the same linear mixed models used for Hypothesis 2 (shown in Table 4), as those models included data from all trials and were not restricted to the *switching* mode alone.

Age

Age did not have a significant effect on any dependent variables in any analysis. We believe this is likely due to the relatively small age range of the study's participants (18 – 34 years).

Sex

All models were fit using "female" as the reference category and "male" as the indicator variable. *Sex (Male)* had a significant beneficial effect on **Navigation Speed** and **Bearing Error** over all trials, and also resulted in a significantly lower **Workload (Performance)** rating. These results suggest that men performed better in the navigation task than women, and that they had a higher self-evaluation of their performance.

	Overall	Mental	Physical	Temporal	Performance	Effort	Frustration
(Intercept)	100%**	100%*	100%	100%*	100%*	100%*	100%*
Age	0.897%	0.535%	-1.24%	1.01%	-0.851%	2.92%	4.98%
Sex (Male)	-11.6%	19.5%	14.0%	5.80%	-49.1%*	-7.36%	-19.8%
Computer Use	0.614%	1.19%	9.27%	-3.11%	7.80%	-2.39%	2.27%
Game Use	6.32%	-4.95%	42.4%	15.3%	-7.39%	10.2%	27.5%*
Environment (Urban)	7.01%*	27.5%**	-11.4%	9.68%*	4.51%	8.32%*	3.18%
Mode (Visual)	-1.34%	4.05%	-13.7%	-3.01%	3.89%	-1.26%	11.1%
Mode (Haptic)	-5.99%	-10.3%	-4.57%	-0.940%	-7.43%	-9.26%	-15.3%

Table 5. Effects for workload models. Blue cells indicate reduced workload, red cells indicate increased workload. *$p < 0.05$, **$p < 0.001$.

Computer Use

Computer use was self-reported by participants as the number of hours per day that they used computers. Increased computer use had a significant detrimental effect on **Navigation Speed**, for which we can offer no definitive explanation.

Game Use

Game use was self-reported by participants as the number of hours per day that they played video games. Increased game use had a significant beneficial effect on **Navigation Speed** and **Bearing Error**, as would be expected (more experienced video game players performed better within the experiment's video game environment). Additionally, participants who played video games more often exhibited significantly higher **Workload (Frustration)**, suggesting that they were accustomed to different or easier tasks in video games and were more frustrated by the experiment task.

Environment

All models were fit using "jungle" as the reference category and "urban" as the indicator variable. *Environment (Urban)* had a highly significant detrimental effect on **Navigation Speed** and **Bearing Error**, which was to be expected due to the requirement to navigate around large obstacles. *Environment (Urban)* also had a significant detrimental effect on **Workload (Overall)**, **Workload (Mental)**, **Workload (Temporal)**, and **Workload (Effort)**, likely due to the same reason.

Design Implications

The various significant effects observed throughout this study suggest a number of interesting design implications for personal navigation systems. As hypothesized, periodically switching the directional guidance modality of a navigation system results in a transient modality switching cost that dominates short-duration navigation tasks. However, it also appears to mitigate the detrimental effects of SSA and habituation associated with long-duration use of single-modality navigation systems. Together, these results suggest that if a navigation task is expected to have a short duration (less than ~5 minutes) before the user is expected to perform a different task, a single-modality navigation system is more appropriate. For longer navigation tasks that are unlikely to be interrupted, a switching-modality system will likely provide greater overall performance.

Limitations and Future Work

Due to limitations in how long participants were willing to engage in a study of this nature, combined with the numerous trial types that we asked each participant to complete, we were restricted to relatively short trials of 8 minutes each. Longer trials would have allowed us to better examine the effects of SSA and habituation on long-duration navigation tasks. Additionally, the experiment was carefully designed to maximize internal validity, which came at the cost of ecological validity. Participants had no additional tasks to complete while navigating, which is rarely the case in real-world applications. Further research is required to address these two limitations through the use of longer navigation tasks and additional secondary tasks.

CONCLUSION

In this paper, we describe the design and results of an experiment evaluating the effects of periodically switching the directional guidance modality of a personal navigation system in comparison to single-modality systems. Based on prior work across multiple fields, we hypothesized that periodically switching modalities would incur a transient switching cost to performance, but would also mitigate the potential stimulus-specific adaptation and habituation effects associated with a single-modality system. Linear mixed effects modelling of the results for the 32-participant experiment indicates that both these hypotheses are true, and that periodically switching directional guidance modalities over the course of a long-duration navigation task will lead to improved stability of navigation performance.

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