Haptic Navigation in Virtual Reality

Investigating and developing guidelines for vibrotactile feedback using multiple types of information simultaneously

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Investigating and developing guidelines for vibrotactile feedback using multiple types of information simultaneously

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ABSTRACT

Med hjälp av en taktil huvudmonterad enhet kallad Perman Hjälmen togs en rad funktioner ämnade för att navigera i en virtuell rymd fram. Dessa funktioner var kollisionsförebyggande system, målsökning samt kompassorientering. För varje funktion togs tre olika lösningar fram och utvärderades i en lämplig miljö. Efteråt utfördes ett andra experiment för att ta fram riktlinjer för hur olika lösningar för olika uppgifter bör kombineras för att presentera maximal mängd information utan att överbelasta användare. En ny anpassad testmiljö utvecklades och olika kombinationer av lösningar till de olika uppgifterna utvärderades. Även två specialkonfigurationer togs fram för att testa specifika faktorer.

Resultaten från experimenten visade att använda flera simultana vibrotaktiska informationsflöden var praktiskt möjligt med åtminstone tre distinkta typer av flöden. Utöver detta har olika tillvägagångssätt och kombinationer övervägts och jämförts. Baserat på detta har flera riktlinjer tagits fram för utveckling och vidareforskning av system med multipla simultana vibrotaktiska informationsflöden.

Dessa slutsatser kan komma att bidra till vidareutveckling av framtida kommersiella och industrianpassade vibrotaktiska enheter, vilket gör detta ett relevant forskningsområde.

Nyckelord
Vibrotaktik, Navigation, Simultana Informationsflöden, Virtuell rymd, Huvudmonterade Enheter
ABSTRACT
In recent years, progress has been made regarding the use of tactile devices such as belts and helmets for navigational tasks. As most of the devices and solutions so far have focused on presenting one type of information at a time, the potential for tactile devices for simultaneous multiple tasks have yet to be properly explored. Based on such research, this study investigates various methods of presenting multiple simultaneous information using a vibrotactile head-mounted device for navigational tasks in a virtual space. The goal is to determine if it is possible to effectively present various simultaneous navigational information with vibrotactile feedback in a virtual space, and if so, determine guidelines for doing so while avoiding cognitive overload.

Using a tactile head-mounted device known as the Perman Helmet various functions related to several navigational tasks in a virtual space were developed. These tasks were collision avoidance, object search and compass orientation. First a test was conducted to determine the most suitable solution for each given task. For each task three different types of solutions were developed, tested, and evaluated in an appropriate testing scenario.

Afterwards, a second test was conducted to determine guidelines for how to combine those various solutions to present as much information as possible while avoiding cognitive overload. A new testing environment was created that incorporated all three tasks and various combination of the solutions were tested, along with two special configurations to test other factors.

The results from the experiments shows that using several simultaneous vibrotactile signals representing different types of information is feasible and practical with at least 3 different types of signals. Furthermore, various types approaches and combinations have been considered and compared. Based on these findings, several guidelines when developing systems informing a user with multiple vibrotactile feedback signals have been proposed.

These findings could help hasten the development of commercial and industrial multiuse vibrotactile devices, making it a relevant field of study.

Keywords
Vibrotactile, Navigation, Simultaneous Multitype Information, Virtual Space, Head-mounted Device
1. INTRODUCTION

1.1 Background
When using personal computers, smartphones or similar devices, the most common way to represent information to a user has always been visual and auditory feedback. These types of feedback are well understood and devices and methods for presenting such information are well developed and can provide rich information in a manner that is easy for the average consumer to understand. However, feedback types that relies on the other human senses such as touch in the form of haptic feedback are not as well developed.

Haptic feedback can be divided into two groups, kinesthetic and tactile. Kinesthetic feedback is what one feels with the sensors in one’s muscles/joints/tendons such as weight and object size. Tactile feedback is related to what one feel with the surface of one’s skin, such as vibration, pressure, and texture. Furthermore, vibrotactile feedback explicitly refers to vibrations. Throughout the report the terms haptic feedback and tactile feedback might be used interchangeably, as kinesthetic feedback is not the focus of this report.

Traditionally, haptic feedback has seen some use in commercial products, usually in the form of vibrotactile feedback. Examples include message notifications from smartphones and force feedback from rumble packs in game controllers to enhance immersion. One notable example would be the recently released Nintendo Switch game console, with controllers which has a feature referred to as “HD Rumble”. This feature offers vibrotactile feedback with greater detail than what has traditionally been done, and can for instance present the user with haptic illusions such as of a box with balls rolling around as the controller is turned and twisted.

However, haptic feedback is often used as a secondary information channel using output devices with limited abilities to present rich information. This is despite the wide variety of information that touch can present such as movement, texture, and spatial information. Furthermore, haptic feedback can help offload other senses and prevent sensory overload, such as phone vibrating notifying a new message when in a dark or/and noisy environment. Haptic feedback is also discrete, as information presented to one user is usually not felt by people nearby, thus not disturbing them.

As such, recent research has focused on developing new tools and aids that utilizes tactile information to either substitute other senses such as mimicking visual information for blind people (Sensory substitution) or provide information that humans normally cannot naturally discern such as compass directions (Sensory Augmentation). One common field of research is navigation using haptic feedback. One example is a belt that helped a blind person navigate by signaling the direction of the magnetic north\(^1\). Another example is the CyARM, a device that allows a user to determine the distance of nearby objects\(^2\). This is done by letting the user actively scan an area using a handheld device. The distance

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\(^1\) Sensory augmentation for the blind, Silke M. Kärcher, Sandra Fenzlaff, Daniela Hartmann, Saskia K. Nagel, Peter König

\(^2\) FutureBody: Design of Perception Using the Human Body, Makoto Okamoto, Takanori Komatsu, Kiyohide Ito, Junichi Akita, Tetsuo Ono
should be used to determine rudimentary guidelines for future research on the subject.

- Make sure that the solutions and tools are practical and comfortable for average user. This includes evaluating how intuitive the messages are, how comfortable the experience is for the user, if they could process the information without confusion and if/what annoyance there are.

2. RELATED RESEARCH

2.1 The Perman Helmet
Recently at Hokkaido University, Japan, a device known as the Perman Helmet\(^3\) was developed to take advantage of vibrotactile feedback in a gaming environment. This helmet consists of several vibrotactile motors placed around the helmet to allow feedback on various spots of the head. This is to allow the helmet to present 3D spatial feedback to a user. Each motor’s frequency and intensity can be controlled individually. The helmet proved to be valuable in helping users not familiar with navigating a virtual 3D space to navigate a labyrinth. This resulted in completing the labyrinth quicker with no collisions with the walls in comparison when not using a helmet. Due to availability and ease of programming the helmet, it will be used for this paper’s investigation.

The version of the Perman Helmet that will be used consists of 15 coin-shaped vibrotactile motors placed around a half-spherical paper headwear. At any given moment the motors can only vibrate with one intensity and frequency. As such, to render more complex info, one must either use multiple motors simultaneously or change some variable such as intensity over time. The motors are connected to an Arduino board that accepts commands from a computer via a USB-cable and uses those commands to set the intensity of the individual motors. The arrangement of the vibration motor placement will be described using the following polar coordinate system.

\((\theta, \psi) \quad \theta : \text{Elevation}, \psi : \text{Azimuth}\)

For example, a motor placed facing forward with no elevation would be described as \((1,0,0)\) and a motor on the right side elevated halfway to the top would be described as \((\pi/4, 3\pi/4)\).

The motors are arranged in 3 elevation tiers, with the distributions as follows:

\[(0, n\pi/4) \quad (0 <= n <= 7)\]

\[(\pi/4, n\pi/4) \quad (0 <= n <= 5)\]

2.2 Similar tactile devices
The tactile helmet created by Craig Bertram and team\(^4\) is another helmet fitted with actuators with the intention to give the user long-distance sense of touch, much like mice uses whiskers to feel objects at a distance, thus providing sensory-augmentation. Such a device could potentially be used in search-and-rescue missions in dark settings or for partially-sighted people. Experiments have shown that blindfolded people have been more successful in navigating a corridor looking for an exit by using the helmet. This suggests that the tactile data can provide spatial information that can be intuitively used for navigation.

2.3 Vibrotactile language
Previous research has been done on how developing various tactile devices for navigational purposes, and one relevant area of research has been developing a tactile language. This includes best practices for how to present tactile information in various scenarios. Yueqing Li and team\(^5\) investigated various parameters for tactile feedback and how it affected vibrotactile feedback when it was the primary information modality. This was done using a belt with vibrotactile tactors attached. During tests, subjects would have to remember several directions in succession using various configurations of parameters. These parameters included frequency, message duration and amplitude. Performance was evaluated based on annoyance level, completion time, user preference and number of errors. Based on the results, several guidelines were suggested. The test subject appeared to be most sensitive to frequencies around 250Hz during the tests. Furthermore, a correlation between duration and amplitude was observed. Duration for tactile messages were recommended to be kept under two seconds. Shorter durations required larger amplitudes, and vice versa. Amplitudes were also dependent on tactor size, spatial location, and individual users. The larger the amplitude, the higher risk that a user might perceive the message as annoying, though it improved readability.

A similar research done by F. Arab and team\(^6\) investigated the effect of repeating vibrotactile messages to elderly users. Using a vibrotactile watch, a number of directional

\[^3\] PerMan: Presentation of 3D Information and Game Experience with Helmet Device, Tetsuya Kaneko, Nagisa Munekata, Tetsuo Ono, Hokkaido University

\[^4\] Sensory Augmentation with Distal Touch: The Tactile Helmet Project Craig Bertram, Mathew H. Evans, Mahmood Javaid, Tom Stafford, and Tony Prescott

\[^5\] Navigation by vibration: Effects of vibrotactile feedback on a navigation task; Li, Yueqing

\[^6\] Haptic Patterns and Older Adults: to Repeat or not to Repeat? F. Arab, S. Panels, M. Anastassova, et al.
messages (move right/left/back) and informational messages (problem, point of interest and arrival at destination) could be presented. Parameters included amplitude, tactor positions, message duration, pause between tactor activation and repetition pattern. The test consisted of walking a predetermined route outdoors using the watch as a guide. During the test, message recognition was recorded and analyzed. Afterwards, a questionnaire to evaluate user experience was also administered. Based on the results, a few recommendations were proposed.

First, important messages should be as simple as possible. Strong continuous signals without much repetition proved to be the most successful in this regard. Second, messages should be task-specific based on user priorities. Messages considered crucial should be easy to distinguish from secondary information, as well as intuitive and easy to remember. Third, repetition of messages should be used with care, as it can cause confusion and adds additional cognitive load. Fourth, metaphor-based messages appeared to be promising, as they were perceived as intuitive to the test subjects. For instance, a message to turn around by making a tactile turning motion proved to be more successful than its more abstract counterpart. Finally, haptic aids’ acceptability should be considered as seriously as the language itself. This includes features such as the device’s esthetics, comfort, and portability.

3. METHODS

Before testing can commence a suitable task consisting of several subtasks should be defined. The task needs to be related to navigation in a virtual 3D space, and each subtask needs to be a distinct separate goal that can be individually measured and evaluated.

The proposed subtasks and how they are to be approached using vibrotactile feedback are as follows:

Navigating using a haptic compass: Using tactile information, a user should be able to navigate a 3D environment using a compass to determine the user’s orientation. Much like a real-life compass, this vibrotactile compass should by simple means give the user an intuitive idea as to where a universal focal point is located.

Finding targets: Hidden across the virtual space there will be targets that the user needs to find and collect by touching them. The feedback should give the user relevant information as to where these targets can be found, for instance by giving a direction and a distance.

Collision avoidance: The user should try to avoid colliding in walls and/or other obstacles scattered across the virtual environment. If a collision occurs, the user will be given a penalty. The feedback should let the user be able to tell where there are walls and how close they are to collide with them, as well as when a user collides with them.

Combining these subtasks together into one major task can thus be done as follows. A user needs to navigate a labyrinth with various targets scattered around. The labyrinth is largely featureless with same looking corridors. No overall information on the shape of the labyrinth will be given to the user. This is to encourage the user to rely on the compass. The user is to collect all the targets across the labyrinth in the shortest time possible while avoiding colliding with the walls. The completion time and error rate will be measured. Moreover, questionnaires will be handed out after each run to determine the user experience and opinions of the solutions. Examples of user experience would be how intuitive the solutions are, comfort, cognitive load as well as general thoughts and suggestions.

Before the main test is to be conducted, various solutions will be developed for each subtask and tested isolated from the other subtasks. Error rate and task completion time, as well as user experience will be measured. The most promising solution of the developed and tested solutions will then be selected for each subtask. These solutions will then be used in the main test where the subtasks are combined and tested together.

The most promising solution for each subtask will be used in the main test when the subtasks are combined and tested together.

During the main test, various configurations of the solutions will be tested. What impact different frequencies, rhythms and/or amplitudes for each solution will have on the results will be investigated. For instance, does having similar frequencies for all solutions have a negative impact on the results compared to when all solutions use different frequencies?

3.1 Testing solutions for each subtask

3.1.1 Haptic Compass

The first solution, called Point Pressure, aimed to be as simple as possible to keep cognitive load low. The direction of the compass point is given by continuously vibrating in the direction of the compass point, with the forward motor representing the facing direction of the first-person camera. The motor(s) currently closest to the compass point will vibrate, with the strength determined by how close the angle to the compass point is to the angle of the motor.

The second solution, called Turn Motion, attempted to use a motion metaphor to deliver information. In this case a vibration travelling around the head in a turning motion starting from the current facing direction moving towards the angle of the compass point was used.

The final solution called Focus Motion was another attempt at a motion metaphor. In this case, two vibrations would start at 90 degrees plus/minus from the compass point’s direction. These vibrations would then travel towards the compass point and eventually converge. As such, the intention would be to make it feel as if the two vibrations are focusing down towards the compass point’s direction.

3.1.2 Collision Avoidance

The first solution, Continuous Distance Pressure, vibrates motors corresponding to directions in which there are walls if they are close enough. The strength corresponds to
how close the walls are in a linear fashion. The closer the
wall is, the stronger the vibrations.
The second solution, Discrete Distance Pressure, works in
a similar fashion. However, instead of having strength
increase in a linear fashion, a few thresholds with distinct
strength levels are used. As such, there are more distinct
switches in vibration intensity to signify when a user is
getting too close.
The final solution, Rising Wall Pressure, works similar to
the Continuous Distance Pressure, but displays its data in
a different fashion. At first, the bottom tier of motors will
be used to represent how close the user is, much like the
first increasing in strength the closer the user is. Once close
enough, the second tier of motors are turned on, with the
first tier running at max strength. This simulates the feeling
of the helmet “filling up” with a rising vibration, and at full
strength the vibration reaches the top of the helmet.

3.1.3 Target Search
The first solutions, Closest Target, determines the closest
target and vibrates in the direction of said target. The
strength of the vibration is linearly dependent on the
distance to said target.
The second solution, Discrete Closest Target, works much
like the previous solution but discards the distance data
and vibrates with constant intensity.
The final solution, Close Targets works much like the first
solution. However, instead of displaying only the closest
target all targets within range are displayed.

3.1.5 Test Setup
For each task, a different test scenario was developed to
properly test the viability of the various solutions. The
development of the tests was done with regular input from
students otherwise not involved with the research. However, due to time issues proper pilot trials were not
possible to conduct.

A within-subject design approach was taken when
designing the test. Each subject tested every solution once
including control tests. The results were then compiled and
compared, making it possible to discern how each solution
affected each individual performance. This was deemed
necessary as skills related to navigating a virtual space
could vary greatly between subjects, making comparisons
between different groups testing different solutions less
practical. Afterwards, the results were compiled and
compared to find general patterns.

For testing the haptic compass solutions, the test subject
was put inside an enclosed box in a virtual space, in which
they could only turn around in. Using the various
solutions, the test subjects had to try to pinpoint the
direction of a randomized compass point that was
somewhere outside the box. Using the solutions, the test
subject had to try to face the direction of the compass point
and push a button once they thought they were facing the
compass point. This process was repeated 10 times.
Accuracy as well as completion time was measured.

For collision avoidance the test subject was placed in a
narrow corridor that twisted and turned numerous times.
The test subject had to run through the corridor as quickly
as possible to reach the end. Each time a collision with a
wall occurred a 5 second penalty was added to the total
completion time.

For target search, the test subject was placed inside a
labyrinth containing 5 targets. The subject had to search
and find said targets as quickly as possible using the
various solutions.

After each session, the test subject was handed a short
questionnaire to write down their general impressions
about the solution they just had tested as well as any free
comments. A pre/post-test questionnaire was also filled in
before and after the test.

Due to concerns that repeating the same test scenarios with
different solutions could lead to the test subjects getting
better results due to repeated attempts. For instance, a
solution always tested last could get better results than if it
always went first. To avoid such learning effects affecting
the results, the order of the solutions tested was
randomized.

3.1.5 Hypothesis
Solutions that provide short simple messages are believed
to be easier to learn and understand than more elaborate
and complex solutions.

Furthermore, messages that can provide more granularity
are believed to provide better results. For instance,
discrete systems that can only provide data regarding if a
wall is close or not will not be as effective as a system
that also provides an abstraction of the distance.

3.2 Testing simultaneous multitype
feedback for the main task
Some minor edits to the chosen solutions from the first test
were made to make it easier to distinguish between the
solutions. The compass function’s intensity was given a
sine-wave patterned, with the intensity increasing and
decreasing rhythmically over time. The collision
avoidance function was given an exponential intensity
curve instead of a linear, so the power was lessened when
far away and increased more sharply when getting close to
the wall. Finally, the search function was giving a
rhythmic beat, instead of a continuous vibration.

Six configurations where chosen for the experiment.
All functions on (Compass/Collision Avoidance/Target
Search)
Compass/Collision Avoidance on
Compass/Target Search on
Collision/Target Search on
Compass/Target Search with similar messages (That is, without previously mentioned edits)

Compass/Target Search with only one tier of motors (While other configurations will use different tiers of motors to separate their functions this configuration will not.)

3.2.1 Test Setup

The test subject is put inside a virtual narrow labyrinth viewed from a first-person perspective. The test subject is then tasked with finding at least five out of six targets hidden inside the labyrinth. Once the targets have been found, the test subject must go to the exit. Once there, the test will be over and the time that it took to complete the task will be measured. Furthermore, for every time the test subject collides with one of the labyrinth walls, a 5 second time penalty is added.

![Figure 2- Picture of the labyrinth with one of the targets](image)

Much like the first test, the test subjects answered questionnaires between each session, as well as pre/post-test questionnaires. The order of the configurations tested were randomized to avoid a potential learning effect, much like the first test. Furthermore, the starting position was also randomized, as to make it harder to memorize the layout of the maze. The within-subject design used in the previous test remained the same.

3.2.2 Hypothesis

As the number of different simultaneous messages increases, so too will the amount focus required to comprehend the messages rise.

Messages that are differentiated in various ways (amplitude, signal pattern, spatial location, etc.) will be easier to tell apart than messages that are similar.

A user will focus mostly on the currently most important messages while trying other messages. If one type of message is currently not necessary/very useful, this will likely result in more cognitive load and annoyance.

4. RESULTS

For both tests, ten test subjects participated. Both times, 9 males and 1 female test subject participated. 3 test subjects participated in both tests. The average age was 23 and 25 respectively. None had problem with using their sense of touch. In both cases, 9 out of 10 considered themselves experienced with navigating a 3D virtual space in a first-person view, with roughly half the test subjects doing it on a regular basis (At least monthly). When asked about if the test subjects have trouble navigation in first-person settings, the response was negative.

4.1 Solutions for each subtask

Regarding the Haptic Compass solutions, the Point Pressure solution proved to be both the most effective and the most popular one. Completion time was consistently the lowest for most of the test subjects (Fig 4) with a mean time of 70.9 seconds. The solution also scored the highest (Fig 3), with a mean value of 7.5 points. Do note that test subject number 2 had to abort the Point Pressure test due to complications.

These results are also reflected in the questionnaire. A scale with values from 1 to 5 was used, with 1 being strongly agree and 5 being strongly disagree. On the question regarding if the test subjects found the solution to be easy to understand, the Point Pressure solution got an average of 1.5, Turn Motion 2.4 and Focus Motion 2.8. Regarding the question if the task was easy to perform using the solution, the Point Pressure got an average of 1.7, the Turn Motion got 2.5 and the Focus Motion got 3.3.

![Figure 3 - Haptic Compass Test Results: Score Distribution](image)
For the Collision Avoidance solutions, the results were mixed. A significant number of test subjects seemed to have little trouble navigating the corridor, colliding rarely or never, no matter if they were using one of the solutions or not (Fig 5). Likewise, the completion time did not differ greatly between the tests for a majority of the test subjects (Fig 6), with the control tests having slightly higher mean completion time (114.6 sec) than the other solutions (110.3, 113.8 and 98.9 sec). According to several test subjects, the act of repeatedly performing the tests in the same corridor had an effect on their performance, as they got used to the layout and the controls.

According to the questionnaire, all solutions were considered to be easy to understand, with an average of 1.5 for Distance Pressure, 1.6 for Discrete Distance Pressure and 1.5 for Rising Wall Pressure. Regarding how easy the task was to perform using the solutions, Distance Pressure scored 1.6, Discrete Distance Pressure scored 1.8 and Rising Wall Pressure scored 1.5, suggesting all systems were easy to use. Finally, all systems were considered by the test subjects to improve their performance, scoring 1.6 for Distance Pressure, 1.9 for Discrete Distance Pressure and 2.2 for Rising Wall Pressure. According to several test subjects, this was due to the fact that having signals for several targets was more confusing than having one at a time.

All Target Search solutions provided clear improvements over using no vibrotactile solutions (Fig 7). In particular, two test subjects (Number 2 and 9) were unable to even finish the control test, taking over 10 minutes before giving up. Meanwhile, using any of the solutions resulted in completion times under 100 seconds, something nobody managed during the control test. The Closest Target and Discrete Closest Target solutions performed about equally, with a mean completion time of 70.1 sec and 71.9 sec respectively. The Close Targets solution performed slightly worse, with a mean completion time of 80.2 sec. According to several test subjects, this was due to the fact that having signals for several targets was more confusing than having one at a time.

When asked if the task was easy to perform without a helmet, the response was negative with an average score of 4.6. In contrast, when asked if using the solutions improved their performance, all solutions got a positive response of a 1.1 average score. When asked if the solutions were easy to understand, all solutions got a positive response, with a mean of 1.4 for Closest Target, 1.1 for Discrete Closest Target and 1.8 for Close Targets.
4.2 Testing simultaneous multitype feedback for the main task

In general, tests that included the Target Search system proved to be useful with the two configurations lacking it, the control test and the Compass/Collision configurations having the worst average completion times, 508.7 sec and 335.6 sec respectively. In comparison, all other configurations had averages below 200 seconds. They also had the highest average collision values, 45.5 and 14.6 collisions respectively. This is noteworthy in the latter case as that configuration included a system to avoid collisions.

The best performing configuration was Compass/Search with a mean value of 5.3 collisions and 144.2 seconds mean completion time. The Same Tier, Similar Messages and All Systems configurations had similar results with each other, with mean values of 6.4 collisions/158.1 sec, 7.1 collisions/160.5 sec and 5.8 collisions/162.7 sec respectively. Finally, the Collision/Search had mean values of 7.7 collisions/183.8 sec.

When asked about if the test subjects found the task to be easy to perform without the helmet, the general response was either slight disagreement or disagreement, scoring an average of 3.8. When asked if the task was easy to perform using the configurations, the general response was agreement, with the various configurations scoring an average from 1.2 to 1.9. The exception was the Compass/Collision configuration, which scored a mixed reception of 2.9. As for if the configurations various system messages were easy to understand, the general response was positive with averages ranging between 1.3 and 1.7.

When asked if the various systems in each configuration were easy to differentiate, the Compass/Search and Collision/Search scored a positive response with 1.9 and 2-point average score respectively. Meanwhile the other configurations got a moderate to mixed responses with averages ranging from 2.5 to 2.9 points. When asked about if the configurations improved their performance, almost all configurations got positive responses with averages between 1.2-1.8 points. The exception is the Compass/Collision configuration, scoring a 2.7 score average. Regarding if the test subjects often had to stop for extended periods of time to understand the various messages from the configurations’ systems’, the responses varied between the configurations. Same Tier had a negative response with an average score of 4. Compass/Collision and All Systems scored 2.9 and 2.6 respectively, making people stop the most. The rest of the configurations scored on average between 3.3-3.4.

When asked about if the configurations were uncomfortable during the tests, the response was generally negative, with averages between 4.25 to 3.7. In other words, the configurations were generally perceived as comfortable. The exception is once again the Compass/Collision configuration, scoring a 2.8 average.

4.3 Post-test questionnaire results

For both tests, when asked if the helmet was easy to use in general, the response was positive, scoring an average of 1.7-1.8. Likewise, questions such as “I found the helmet useful during the experiment” and “I think the helmet can be useful for other navigational tasks” got positive responses (Average of 1.1-1.4 and 1.6 respectively). Regarding if the helmet was intuitive and easy to learn, the response was also positive, scoring 1.7-1.8 on average.
during the tests, while the question “I believe the helmet is unnecessarily complex” got a negative response with an average of 4.4. Neither was the helmet found unreliable or inconsistent, scoring 4.1-4.4. When asked if they would like to use a similar device to the helmet, e.g. another helmet, a belt, etc. the response was positive to somewhat positive, scoring on average 2.1-2.5. As for recommending a similar device, the response was similarly positive, with an average score of 2-2.2.

The biggest difference between the two tests were the comfort of the helmet. When asked if the helmet was uncomfortable, for the first test the response was mixed with an average of 2.9. For the second test average was a more negative value of 3.5, suggesting that the helmet and its systems were more comfortable for the second test.

5. ANALYSIS AND CONCLUSION

5.1 Solutions for each subtask

During both the compass test and the target search test, simpler solutions that delivered messages with a lighter cognitive load proved to be more effective than the alternative. For instance, the Point Pressure proved to be the preferred solution by the test subjects during the compass test, as well as the best scoring one. Likewise, the Close Targets solution which provided the most amount of information to the test subjects was perceived as the most confusing.

Interestingly, there was no major difference observed between discrete and continuous versions of solutions, such as Closest Target and Discrete Closest Targets. Perhaps the extra level of data provided was unnecessary for the current task or the test subjects made no real distinction between the two versions, and thus it was promptly ignored.

The collision avoidance results were inconclusive. On one hand, the results got slightly better when using the helmet, and the comments from the test subjects shows a perceived improvement. On the other hand, since the control test was always the first and several test subjects commented about getting used to the controls as well as learning the layout of the test area, it is very possible that the improvements are unrelated to the test solutions.

5.2 Testing simultaneous multitype feedback for the main task

Interestingly, using all systems at once performed comparably to many of the other configurations time and collision-wise, suggesting that the cognitive load was not as heavy as initially predicted. In general, the test subjects seemed to have little trouble to filter out currently unnecessary information.

The inclusion of Target Search system proved to be the most important factor for the task, with the two configurations lacking it (Control and Compass/Collision) performing the worst, both regarding the completion time and the number of collisions. However, in the latter configuration’s case the number are most likely an effect of the longer completion time and not because a lack of Target Search system causes more collisions.

When comparing the various configurations using the Compass/Search systems, Same Tier, Similar Messages and Compass/Search, the latter came out on top, having the least number of collisions, the shortest completion time and the most positive responses from the test subjects. This suggests that separating spatial location and making distinctly different signals are important. However, more tests would be necessary to verify this conclusion as the results vary between test subjects.

A complaint that came up several times during testing was that the Collision Avoidance was perceived as distracting to some degree, and that it did not provide as much help during testing as the other solutions.

Based on these findings the following conclusions have been drawn:

- People are capable of keeping track of at least 3 distinctly different types of information given through haptic feedback.
- Focus should be put on developing vibrotactile systems that individually contribute as much as possible to a given task and try to minimize the number of unnecessary systems.
- It seems that differentiating systems by using different types of signals, separating the signals spatial, etc. has a positive effect.
- When developing systems individually, simple signals with low cognitive loads tend to perform better. As such, providing only the most vital information regarding a task seems to be a good idea. Therefore, discrete data may be just as good as more granular continuous data in many cases.

5.3 Design of tests

During tests, the problem of learning effects was encountered. For instance, the problem was raised by several test subjects during the Collision Avoidance section during the first test who felt that they got more used to the controls or learned the layout of the test space. While measures were taken to combat this effect, the design effect of the test meant that the control tests were generally done first which could have affected the results to some degree. However, it is not believed that the effect is great enough to greatly change the conclusions drawn significantly.

Another potential issue was the gender imbalance amongst the test subjects. Most available test subjects either came from a male-only dormitory or from the lab which had a skewed gender-ratio. If there exist some potential difference between genders (E.g. experience with moving in a virtual environment, susceptibility to vibrotactile feedback) this can have potentially affected the results.

Finally, a concern regarding isolating the haptic modality was raised after the tests. During the tests, the subjects did not use earplugs. This could possibly mean that they were able to hear which vibrotactile motors were active. If that is the case, that means that the sound from the motors can have reinforced the subjects’ understanding of what motors were active and thus their abilities to navigate. In future research, isolating sound caused by motors should be a priority to better evaluate the actual contribution of the haptic modality.
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