



Evaluation of Multi-sensory Feedback in Virtual and Real Remote Environments in a USAR Robot Teleoperation Scenario

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Good afternoon everyone

I appreciate the presence of all of you today.

As you might well know I am here to present the findings of my dissertation research and to discuss these not only with my committee members but also with all of you.

Multi-sensory Feedback

- Feedback for multiple senses
- Data
 - Is spatialized
 - Come from all directions
 - User does not have to look to notice it
- Leverages more human senses
- Make feedback easier to understand



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- 1) First, let me introduce you to the concept of multisensory feedback. Simply, put, it is the idea that the user of an interactive system can now receive feedback from multiple senses, not only through vision.
- 2) Data can now be spatialized and perceived by the user from around him, not being limited to the area available on a computer screen.
- 3) Moreover, because the user is now making use of other senses to perceive the data, he doesn't need to look at that data in order to perceive it. He is not limited by the directional nature of vision, but can now perceive data omni-directionally, that is, coming from all directions.
- 4) Last, if well designed, presenting data in consonance to match physical feedback the user is accustomed to receiving from the real world, multi-sensory feedback can lead to more natural types of displays to the user.

Urban Search-and-rescue (USAR) Robotics

- When: after a catastrophic event (building collapsed)
- Who: a team of experts and a robot
- Where: building debris area
- What: search for victims



<http://web.cs.wpi.edu/~hive/>

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Let's now talk about urban search-and-rescue (USAR) robotics. The idea behind USAR robotics is the following:

- 1) When there is catastrophic event involving assets that need to be recovered, be that human lives or not, and there are locations that are inaccessible to humans due to either physical constraints or hazardous conditions,
- 2) a team of rescue experts
- 3) remotely approach the location with a robot where the catastrophe has occurred
- 4) and attempt to find and recover as much as the assets lost as possible

Most of the focus is on locating human lives in either mine, building collapses or wilderness. However, lately, as was the case of the Fukushima disaster in Japan, we have seen robots used to also evaluate the overall safety of the plant before humans could actually come and attempt to fix the situation.

World trade Center (Murphy, 2004)

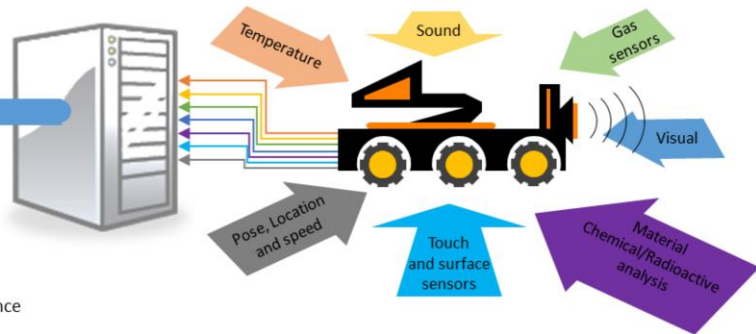
Current Situation of USAR Displays

Mono-sensory directional human data perception

Multi-sensory Omni-directional robot data sensing



- Too much data on screen
 - Visually cluttered
 - Cognitively demanding
- Directional nature of vision
 - User cannot pay attention to everything at once



But how do these two concepts relate to the research presented here. Well, let us start with the USAR robot (or rover) side.

Currently, the robot can potentially have multiple types sensors to capture a variety of types of data from the environment. The data is captured from all around the robot, not just from where it is looking at. The robot captures visual information, sound, temperature, detect object surfaces around itself, chemicals and gas levels, and also sends feedback about the robot state, such as its speed, position, orientation and pose.

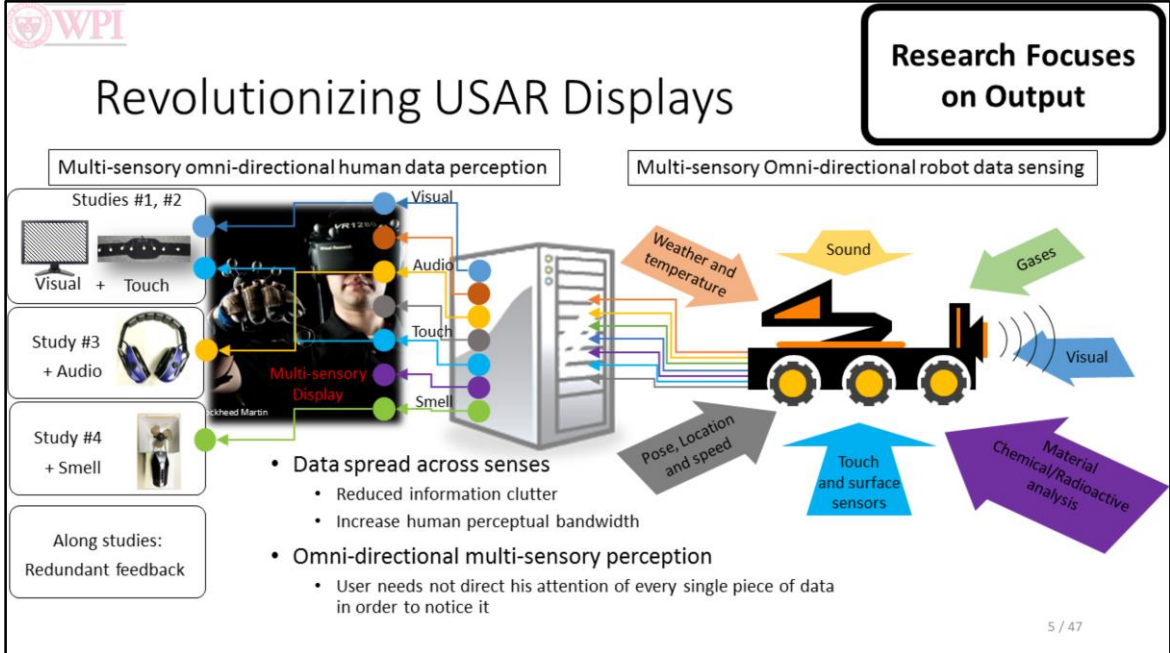
The raw data captured by the sensors is then received and analyzed by one or more computers. These can be located within the robot itself or remotely in the operator computer.

What is interesting about this situation however is when the data gets to the end user. Initially you have all this data that is sensed omni-directionally by the robot. However, when it gets to the user interface, everything is displayed together on a visual-only display interface.

Let's evaluate this situation from the perspective of flow. There are seven pipes coming in, each with its own flow of data and only one coming out. Considering all these pipes are the same diameter, it is easy to see that the flow coming out is going to behave differently than if we had the same pipe configuration coming out as the one coming in. With only one pipe coming out, the data flow might burst extremely fast and, even if it does so, it may still not be able to keep up with the incoming flow. Now, if this was a water flow situation, the computer would explode because of that. Fortunately, we are dealing with only data here.

One solution to the problem would be increasing the diameter of the out-coming pipe. A way of achieving that in reality would be having a visual display with larger area and resolution where more information could be displayed. This is almost as bad as having a rapid flow of data in a small display. Because of the directional nature of the human vision, the user (or operator) will not be able to monitor all data flowing and keep up with the flow of information. The result is loss of information and user awareness of the situation of the robot and remote environment.

But what other options do we have here, apart from using a display that leverages only mono-sensory and directional visual perception?



The research we present here takes an approach that has been used successfully applied in other areas of computer science, but that has not yet been fully explored in HRI, specifically in USAR.

The idea is to keep the multi-sensory and omni-directional sensing side of the robot as is. On the user side however, the idea is to attempt to recreate a similar multi-sensory and omni-directional situation for the human perception. Obviously, we should reproduce with complete fidelity the remote situation, otherwise using the robot interface will lead to the same hazardous or physically constraining situation with which, by using the robot, we are trying avoid direct interaction with in the first place.

The plan is to use a subset of the human senses to spread the flow of robot-sensed data. The motivation behind this approach is that, by adding other senses to perceive data will lead to:

- 1) A reduction in information clutter on screen,
- 2) An increase in the user perceptual bandwidth, since now he has not only the visual, but also other sensory channels to process information. It would be the equivalent of having more than one outgoing pipe coming out of the computer. This situation would

lead to higher flow without necessarily increasing the speed with which data should flow. A rather strange metaphor would be the human, instead of having only one mouth to drink the water coming out of the pipe, he would now have three or four mouths to do that, and can now drink a lot more water per gulp(s).

3) What is also interesting about this approach is that human perception is no longer restricted to where the user is looking. The user can perceive spatialized data coming from all directions. Therefore, we have shifted from an interface that displays data in a mono-sensory directional fashion to a display that leverages the multi-sensory omnidirectional human perception.

But how is this research going to accomplish that? The plan is to evaluate the impact of incrementally increasing the amount of multi-sensory feedback on a USAR robot interface.

1. On studies 1 and 2 we are going to evaluate adding feedback to the sense of touch by using a vibro-tactile belt;
2. On study 3 we are going to measure the effect of adding audio feedback to the previous visual and vibro-tactile interface;
3. On study 4 we are going to experiment smell feedback to the previous audio-visual and vibro-tactile interface.
4. Along the studies we are also going to evaluate the effect of redundant feedback, that is, if providing the same type of data through feedback using different senses is beneficial or not.

Please, notice that the focus of this research is not on input but on output methods.

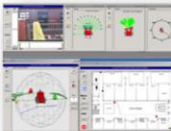
But, before going to the user studies, let me present what has been done so far in that regard by other research groups.

Related Work: Visual Feedback

Multi-out Multi-in Fusion Era!



Yanco *et al.*, 2004



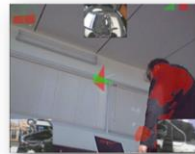
Johnson *et al.*, 2004

- Multiple windows
- Multiple data
- Potentially overlapping

Mono-out Pre-Fusion Era



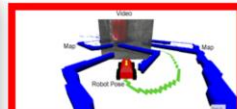
Yanco *et al.*, 2011



Kadous *et al.*, 2006



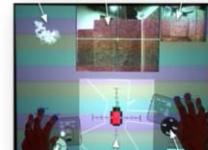
Desai *et al.*, 2013



Nielsen & Goodrich, 2006

- Data fused
- Data around (on top of) video and virtual robot
- Single window multiple panels

<http://> Mono-out Fusion Era



Micire *et al.*, 2011



Correa *et al.*, 2010

- Input interactions fused on screen

Mono-out Mono-in Fusion Era

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During my research on USAR interfaces, I have noticed most (if not all) interfaces displayed all data visually. In addition to that, I have also noticed that there was some kind of evolution in their design. I have divided such evolution here into three stages that I found easily distinguishable:

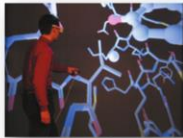
- 1) The Mono-out pre-fusion era: where data is spread across the visual display in multiple windows that can potentially overlap. In this era, a few attempts have already been made to fuse information into a single display as was the case of the Sensory Egosphere at the bottom, but overall, the design was multi-window, single display.
- 2) The Mono-out fusion era: where data is presented in a single window, but in potentially multiple panels that generally overlap. The fusion consists in actually performing the overlap but in an intuitive and non-obtrusive manner. Two good examples of this are the two interfaces on the right. The interfaces in this era allow for all important or more frequently accessed information to be located around the users center of attention. This facilitates the perception to such data.
- 3) Mono-out mono-in era: this the latest development in USAR interface design. The idea is to fuse the input interactions with the visual display itself. Much like the previous era, the input is done closer to the users visual point of focus and can therefore be handled or disambiguated more effectively and efficiently.

Much as the interface has improved, little effort has been put into using more than one sense for either input and output. And this is the motivation of our work, to bring the USAR interfaces to the next era, the era of Multi-out Multi-in data fusion.

To achieve that, however we need to start with small steps. The plan here is to use a fused visual interface (based on the work of Nielsen and Goodrich) as a control case and investigate what happens when it is enhanced with multi-sensory feedback.

Related Work: Audio feedback

Users studies:
Metonymic and cartoonified audio feedback

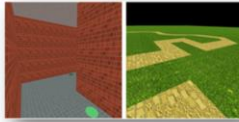


Gröhn *et al.*, 2005

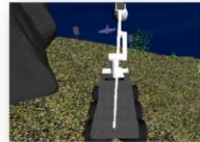


Gunther *et al.*, 2004

- Audio helped search task



Blom & Beckhaus., 2010

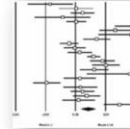


Kaber *et al.*, 2006

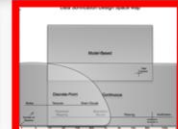
- Improve realism
- Improve Situation Awareness (SA)



Nehme & Cummings., 2004



Burke *et al.*, 2006



De Campo *et al.*, 2006

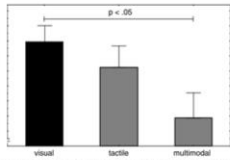
- Audio studies meta-analyses:
- Improvements in search and collision avoidance
- Data sonification techniques

In terms of audio feedback, many other researcher claim that adding it has:

1. Helped in search tasks;
2. Improved the realism and user situation awareness in virtual scenes. Situation awareness simply means how aware the user is of the current state of the robot or system and its surrounding environment.
3. And reduce collision levels in navigation tasks.

The audio feedback we are going to use in our studies are metonymic and cartoonified audio sounds. Cartoonified means that they are exaggerated to make more explicit what the sound really means. This approach is commonly used in videogames and movies. Metonymic means that, even though the sound may not be made physically realistic, it is generally associated with the event occurring. An example of that would a kettle hiss increase being associated with a temperature increase.

Related Work: Vibro-tactile feedback

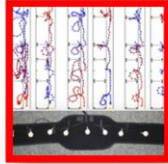


Van Erp & Van Veen, 2004

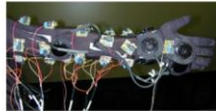


Van Erp *et al.*, 2006

- Better reaction time
- Lower mental workload
- Directional cue



Lindeman *et al.*, 2005



Bloomfield & Badler, 2007

- Completion time
- Task effectiveness



Elliott *et al.*, 2009

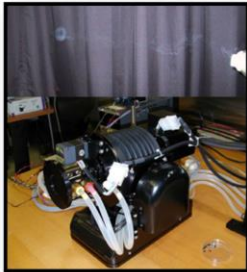


Arrabito *et al.*, 2009

- Helpful for alerts, directional cues and 3D information

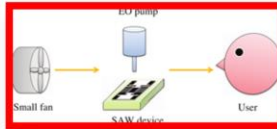
For touch feedback, I am going to cover here research in vibro-tactile feedback which is the main area of focus of this research work. Again, there has been a lot of research in that area, and vibro-tactile feedback has been associated with improved reaction and completion time, task effectiveness as well as claimed to be useful for providing directional cues, alerts and 3D information.

Related Work: Smell feedback

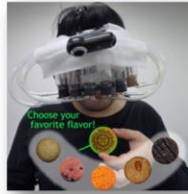


Yanagida *et al.*, 2004

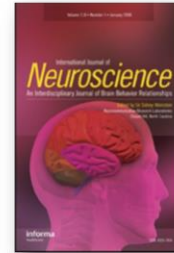
- Different devices
 - Smell projection
 - Fan + atomizer
 - Tube delivery system



Ariyakul and Nakamoto, 2011



Narumi *et al.*, 2011



Herz, 2009

- Some aromas may have psychological effects
- Rosemary:
 - Clears and alerts mind
 - Stimulates memory

In terms of smell feedback, many types of devices have been created and tested for providing smell feedback. Three approaches are commonly used among researchers:

1. Air cannon, where puff rings are directly or indirectly shot at the users nose;
2. Fans with atomizers where wind is constantly blown at the user, thus bringing him smell;
3. Transmission tubes that fuse the smell to a very close region to the user's nose in smaller amounts.

The current research has been directed towards creating the devices, but, to our knowledge, smell feedback has never been compared to other types of feedback in the performance of a task.

There are also aromatherapy studies that refrain the effect of different smells on the subjects mood and behavior. Some of these studies and results, however, are the cause of much contention among researchers.

The research presented here is going to use a fan+atomizer approach to display smell, and attempts to evaluate the benefits in performance and SA of using such feedback in a USAR task.

Questions To Answer

- Can multi-sensory displays also help improve USAR robot interfaces?
- What are the downsides of multi-sensory interfaces?
- How diverse can multi-sensory feedback become before cognitively overwhelming the user?
- Does redundantly providing the same type of feedback through different senses help the user?
- Is the usefulness of multi-sensory interfaces limited to certain types of task?
- Are there effects in user cognition when displays from different senses are put together?
- What methodologies can be used to evaluate multi-sensory displays?

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What questions are we trying to answer with this research.

- Can multi-sensory displays also help improve USAR robot interfaces?
- What are the downsides of multi-sensory interfaces?
- How diverse can multi-sensory feedback become before cognitively overwhelming the user?
- Does redundantly providing the same type of feedback through different senses help the user?
- Is the usefulness of multi-sensory interfaces limited to certain types of task?
- Are there effects in user cognition when displays from different senses are put together?
- What methodologies can be used to evaluate multi-sensory displays?

These are question that are not easy to answer, but our research work, rather ambitiously one might say, attempts to provide, if not an answer, at least a hint to what the answer to these questions should be.

Goal



- Running multi-sensory interface studies on a USAR robot scenario to answer these questions
- Expect that a better use of non-visual sensory channels will improve
 - Human data perception and cognition
 - Task performance
- Provide a set of instruments for assessing multi-sensory interface

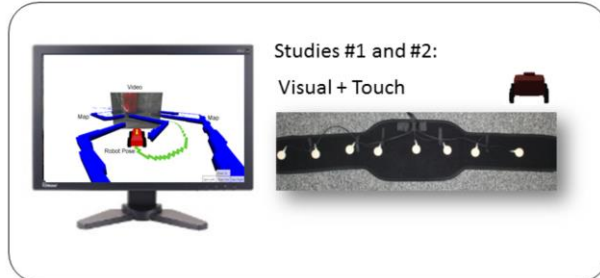
The goal of our research is to run a set of multi-sensory user interface studies and attempt to answer some of these questions.

Ultimately, the goal of the research work presented here is to improve human perception, cognition and performance during robot tasks in 3D real and virtual environments.

This is accomplished by making better use of non-visual human sensory channels, and also providing the research community with a valid set of instruments for assessing effectiveness of multi-sensory interfaces in HCI, VR and HRI.

Studies Summary

- Starting point
 - Visual interface by Nielsen & Goodrich (2006)
 - Fused interface
 - 3rd person view
- Evaluate adding multi-sensory feedback to a similar interface
- Scenario and robot
 - Simulated: 
 - Real: 



To recapitulate, we will start with a visually fused visual interface that approximates the interface that is currently used by other research groups, then we will gradually enhance it with multi-sensory feedback and measure the effects of such enhancements in a USAR task scenario using either a virtual (studies 1, 2 and 3) or real robot and scenario.

User Studies

Let us now move to describing the studies that were carried out and the interesting results that they have generated.

User Studies Data Analysis

- User Studies Data Analysis
 - Continuous data
 - Single-factor ANOVA ($\alpha = 0.5$)
 - Tukey test (HSD, 95% confidence level)
 - Ordinal and ratings data
 - Friedman and Wilcoxon tests
 - SSD: statistically-significant difference

First, let us give an overview of the methodology shared by all studies. For the data analysis in all studies, we have applied ANOVA and Tukey tests when dealing with continuous data, while we have used Friedman and Wilcoxon tests for ordinal or ratings-related data.

One term that I would like the audience to take notice is the acronym SSD which stands for “statistically significant data”, which means the results for conditions being compared in the study differed with statistical significance.

Input Method

- Sony PlayStation® 2 controller
 - Control differential-drive robot
 - Pan and tilt robot camera
 - Take pictures with robot camera



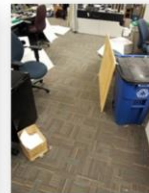
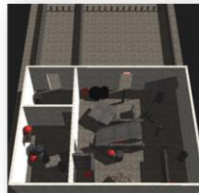
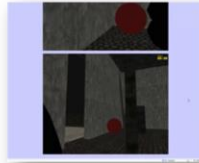
The input mechanism for all studies was the same: A Playstation 2 controller.

It is going to be used for three basic tasks:

1. Controlling the robot movement, which uses differential-drive for turning in place like a tank.
2. Controlling the robot pan-tilt camera and enable the user to look around;
3. Taking pictures with the robot camera. The pictures can be used by the subject after the task as an aid during the map sketching task, which is explained in the next slide.

Primary Study Task

- Task
 - Search for red spheres (circles): 9 - 12
 - Avoid collisions as much as possible
 - Do it as fast as possible
 - At the end, sketch a detailed map with the location of spheres (circles) found
- Environment and tools
 - Closed debris-filled location
 - Virtual or real robot and scenario
- Secondary Stroop Task
 - Do color and text match? **Red**



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All studies shared the same task which was to search for a number of red spheres (or circles when using the real robot) in a debris filled environment. Subjects had to do that as fast as possible, while avoiding collisions as much as possible.

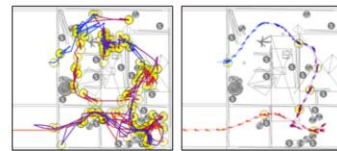
At the end of the task, they were asked to report the number of spheres found and sketch a map with details of the environment traversed, but more importantly, reporting the location of the spheres found.

In later studies, they were also asked to perform a secondary task, called a Stroop task, the idea was to indicate whether the name of a color that would periodically show up on screen would match the color in which it was written. This second task was used to detect variations in cognitive load, which has been previously claimed to have an effect on user's level of situation awareness (SA).

Dependent Variables

- Incrementally improved over studies
- Workload too high -> lower SA [Endsley, 2000]
 - Stroop task
 - Objective measure cognitive load
 - NASA-TLX
 - Subjective measure of workload
- Normalization varied depending on study design
- Example: Subject S normalization results for variable X
 - Raw: (Interface 1, Interface 2, Interface 3) = (10, 20, 30)
 - Normalized: $(\text{Interface 1, Interface 2, Interface 3}) = \frac{(10/60, 20/60, 30/60)}{\approx (0.17, 0.33, 0.5)}$

Measure	Study number			
	1	2	3	4
Number of collisions	+	+	+	+
Number of spheres (circles) found	+	+	+	+
Task completion time	+	+	+	+
Quality of sketchmaps	+	+	+	+
Spatial Aptitude Test		+	+	+
Questionnaire (SUS, SSQ)		+	+	+
Stroop task measures			+	+
NASA-TLX			+	++
Normalization per minute	+	+	+	+
Normalization per path length		+	+	
Normalization per subject		+	+	



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The dependent variables were incrementally improved along the studies. High workload has been previously associated with a decrease in subjects situation awareness. On account of that, we have included new measures on later studies to attempt to detect variations in workload and mental effort (or cognitive load). The measures introduced were the Stroop task and the NASA–TLX test.

During data analysis we have performed different types of normalization. The normalization performed varied depending on whether the study had a within subjects-design or a between-subjects design. On a within-subjects design, a subject is exposed to all conditions in the study. In a between-subjects design, the subject is only exposed to one of them.

Below, you can see an example of a per-subject normalization. Here a subject S obtained three results for each condition of a variable X. Per-subject normalization consists of dividing the results by their sum, thus generating a percentage. This is specially useful when subject experimental performance has a lot of variation due to different levels of experience with advanced interfaces.

This was the case of our studies as can be seen by the pictures in the bottom right corner of the screen. They represent two subjects for the same task and scenario. The line represents the robot path while each yellow circle represents a robot collision. You can see that the performance for different subjects varied significantly.



Vibro-tactile vs. Visual Feedback in Virtual Robot USAR

Study #1

Enhancing Robot Teleoperator Situation Awareness and Performance using Vibro-tactile and Graphical Feedback

De Barros, P.G.; Lindeman, R.W.; Ward, M.O.

Proc. of IEEE 2011 Symp. on 3D User Interfaces (3DUI). Singapore, March 19th to 20th, pp. 47 - 54.

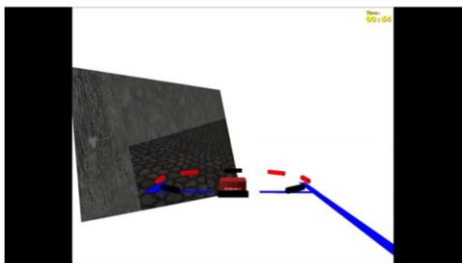
Print ISBN: 978-1-4577-0063-7.

DOI: 10.1109/3DUI.2011.5759216.

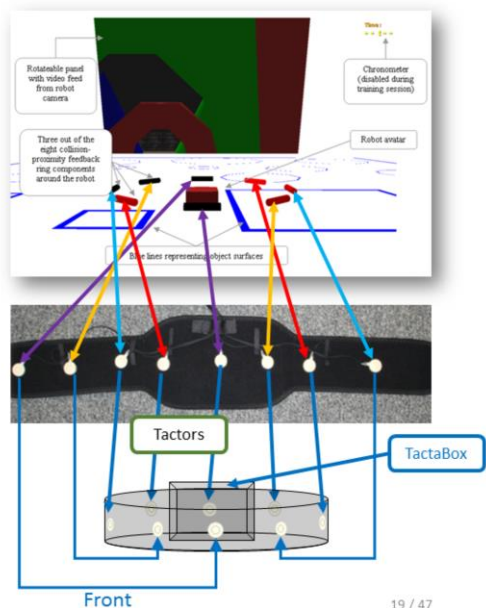
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Let us now describe our first user study, whose results was published in the 3DUI conference in 2011.

Study #1 Overview



- **Between-subjects design** (27 subjects)
- **Independent variable (conditions):** Type of Collision Proximity Feedback (CPF) display
 1. No feedback (none)
 2. Visual feedback (ring)
 3. Vibro-tactile feedback (belt)
 4. Visual and vibro-tactile feedback (both belt and ring)



This study had a within subjects design with a total of 27 subjects and approximately 7 per condition.

This study compared visual and vibro-tactile displays for providing collision proximity feedback. The displays were used separately or together and were compared to a control case where neither display was used.

The behavior of the displays were the same: the closer the robot would approach an object in a certain direction, an alert would be presented to the user in that direction. This alert would be displayed as an increase in intensity of the color red of a cylinder around the robot avatar on screen or as an increase in vibration intensity of a tactor around the users torso. The closer to an object, the more intense the color or vibration. Notice there are a total of eight cylinders and vibration units. Their orientation match forward, backward, left and right as well as their intermediate directions.

Notice also the appearance of blue lines representing surfaces of objects near the robot as it moves around the environment. These emulate robot sensing data using area-triggers.

Hypotheses

- Previous studies claimed that vibro-tactile feedback with(out) redundant visuals
 - Improve reaction and completion time
 - Well-suited for providing spatial and directional cues
- **H1:** Receiving either ring or belt feedback should improve
 - User performance;
 - User situation awareness (SA);
- **H2:** Receiving both types of feedback should cause further improvements

As explained in the related work, previous studies have shown that vibro-tactile feedback can improve performance in many ways. Based on these, we claim similar hypotheses for this study, that is:

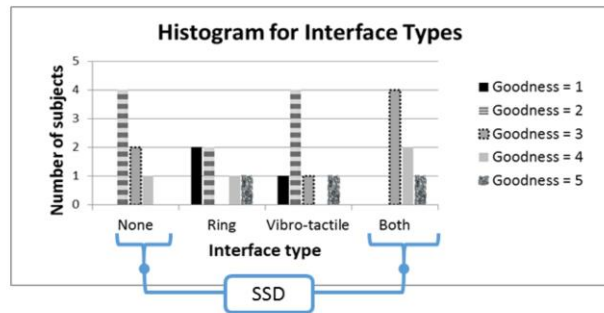
H1) that receiving either the visual or vibro-tactile feedback should improve subjects performance and SA;

H2) that redundantly receiving the same type of feedback through both types of displays should cause even further improvements.

So, what results have we obtained?

Results

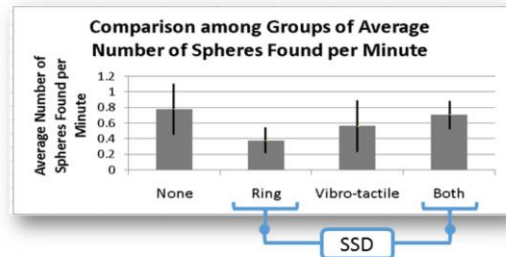
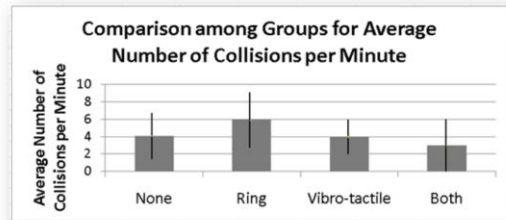
- Map Quality
 - “Both” improved map quality compared to “None”
 - Not affected by time spent in the environment
 - Lower cognitive load → higher AS
- Support H2



An improvement in map quality was detected for the condition where both types of feedback were used. This might be an indication that the use of the multi-sensory interface has improved subjects' situation awareness.

Results

- Number of collisions
 - Increase for group “Ring”
 - No increase for “Vibro-tactile”
 - Decrease for group “Both”
- Number of Spheres Found
 - Decrease for the Ring SSD between groups “Ring” and “Both”
- **Do not support H1**
visual + (ring ^ vibro-tactile) > visual only
- **Could support H2**
visual + ring + vibro = visual only



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Additionally, we have seen an increase in the number of collision and decrease in the number of spheres found for the ring interface. It seems to be that the ring interface degraded user performance.

The vibro-tactile feedback seems to have somewhat supplemented the Ring deficiencies, leading to improvements in the number of collisions and counterbalancing the degradation in the number of spheres found when both displays were used together.

These results don't support hypothesis #1 that either display would improve interface by itself, but it seems to support hypothesis #2 that there is improvement when the displays were used together.

Conclusions

- Did not support H1 : visual + (ring ^ vibro-tactile) > visual only
 - Vibro-tactile caused no improvements
 - Improve ring interface design
 - Does not support other research group results
- Supported H2 : visual + ring + vibro-tactile > visual only
 - Redundant visual and vibro-tactile feedback
 - Improved search results
 - Improved user awareness (SSD)
 - Supports other research group results
- One type feedback seems to supplement the deficiencies of the other

In summary, for this study, we could not conclude that either feedback helped performance and SA by itself as stated in hypothesis 1. This is interesting because it goes against what other researchers have previously reported. This difference could be caused by a small population sample size.

However, we did find evidence that, when used together, the displays improved SA and reduced the number of collisions. This result, on the other hand does seem to support the result from other researchers.



Comparing Different Types of Vibro-tactile Feedback in Virtual Robot USAR

Study #2

Comparing Vibro-tactile Feedback Modes for Collision Proximity Feedback in USAR Virtual Robot Teleoperation

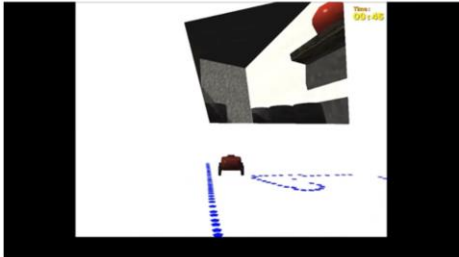
De Barros, P.G.; Lindeman, R.W.

Poster, Proceedings IEEE 3DUI – 2012, Orange County, CA, USA, March 4th to 8th.

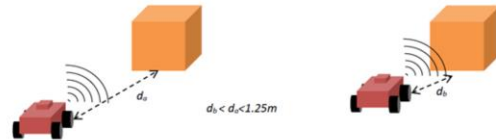
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Let us now move on to our second study, the results of which were presented as a poster in the IEEE 3DUI conference in 2012.

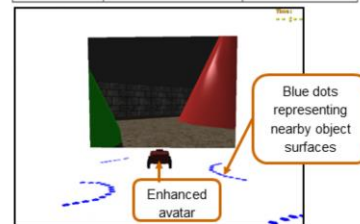
Study #2 Overview



- **Within-subjects** design (36 subjects)
- Independent variable (conditions): Type of Collision Proximity Feedback (CPF) display
 1. No feedback (none)
 2. Intensity vibro-tactile feedback mode (Intensity)
 3. Frequency vibro-tactile feedback mode (Frequency)



Type of Belt Feedback	Belt Vibration Signal	
	d_o	d_o
Intensity (I)		
Frequency (F)		



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Intrigued by the fact that, in our first study, adding the vibro-tactile feedback interface did not lead to improvements, as in other researchers' studies, we have decided to run another experiment related to adding vibro-tactile feedback, but now experimenting with different modalities to investigate how the manner with which data was displayed could affect users performance and SA.

This time, the study had a within-subjects design and a larger sample size. A total of 36 subjects have participated this time (36 per condition).

We compared two vibro-tactile feedback modes to a control case without any vibro-tactile feedback. The first mode was the same as in the first study, where the intensity of the vibration increased as the robot got closer to an object. The second mode had pulsing behavior. As the robot got closer to an object, the pulses became smaller and more frequent.

There were a couple of differences between the visual interface used in this study and the one used in the first study.

- 1) Since we are evaluating vibro-tactile feedback only, the visual ring was removed from the interface.
- 2) Additionally, the surfaces of nearby objects are now being simulated using ray casting, which gives more accuracy and realism to the map blueprint presented.
- 3) Last, the robot avatar has also been enhanced to look more like a real USAR robot.

Hypotheses

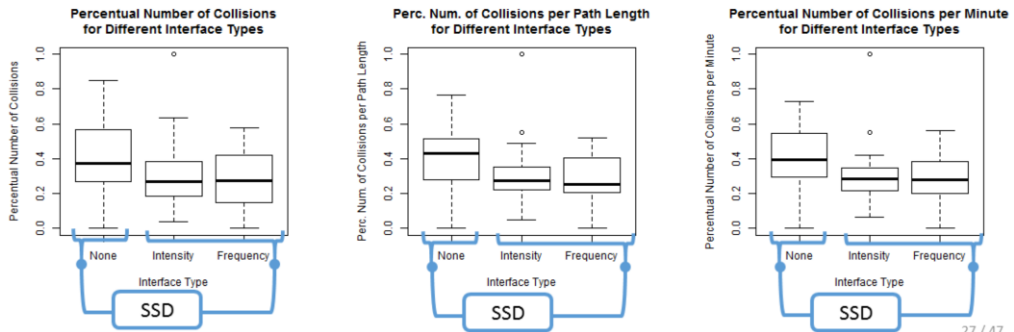
- Based on other researchers results
 - Improve reaction and completion time
 - Well-suited for providing spatial and directional cues
- Pilot study indicated users' preference for Intensity mode
- **H1:** Receiving either vibro-tactile feedback mode should improve
 - User search and navigation performance;
- **H2:** Improvement by Intensity mode > Improvements by Frequency mode

For this study, and again based on previous results obtained by other research groups, we expect that the use of vibro-tactile feedback should lead to benefits in performance and SA, regardless of the vibro-tactile feedback mode used.

Before starting this study, a pilot study was run with 8 subjects. The results and subjective feedback led us to believe that the Intensity interface was the preferred choice for subjects. It also appeared that subjects performed better when using it. Based on this initial analysis, in this study we also claim that the Intensity mode should lead to greater improvements than the Frequency mode and be the preferred choice by subjects.

Results

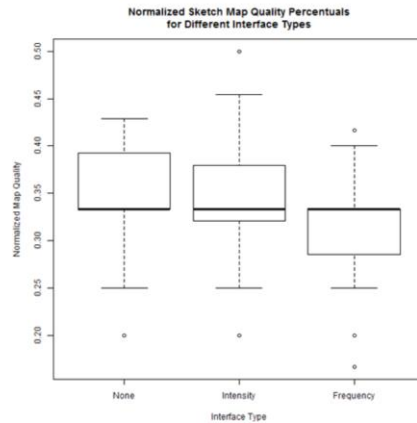
- Number of collisions
 - Both interfaces reduced the number of collisions
 - Support H1: Improvement by using vibro-tactile displays



And indeed, we have now detected improvements in navigation performance with regard to the number of collisions. Both interfaces led to significant improvements in the number of collisions, thus, supporting our first hypothesis.

Results

- Map Quality
 - Frequency interface caused degradation (trend)
- Questionnaires
 - Both vibro-tactile interfaces
 - Improved user's sense of presence
 - Were more distracting and uncomfortable
 - Frequency mode received multiple ratings lower than Intensity mode
- Comments:
 - In Intensity mode, adjacent factors were perceived as single vibration region
 - Frequency deemed more accurate by few, but difficult to learn
- Support H2:
Intensity mode improvements > Frequency mode improvements



In terms of map quality, there was no improvement. In fact, the Frequency interface led to a slight reduction in the quality of the maps, which might be an indication that it is more cognitively demanding.

For the questionnaires, both interfaces have improved subject's sense of presence, but they were also claimed to be distracting and uncomfortable. Overall, the Frequency mode has received lower ratings than the Intensity mode*.

Two interesting comments made by subjects were that:

- 1) The Intensity mode made it easier to understand cluster of adjacent factors vibrating as a single vibrating unit. With more factors, this might be an indication that this mode is more suitable for presenting larger continuous surfaces.
- 2) On the other hand, the accuracy of the Frequency interface was deemed higher. This makes sense, because of the fact that the sensibility for detecting differences in vibration levels on the skin when using the Intensity mode may decrease as the factors vibrate continuously over prolonged periods of time.

These results seem to point that the Intensity interface was more beneficial to the task than the frequency interface, despite its lower accuracy, thus, supporting our second hypothesis.

- * - Compared to Intensity mode, Frequency mode was rated as
 - More nauseating
 - More difficult
 - More distracting
 - More uncomfortable
 - Made simulation feel less real

Summary Results

- Confirmed for USAR other researchers results on improvements caused by the addition of vibro-tactile feedback
- H1 supported:
 - Both interfaces improved performance
- H2 supported:
 - Intensity interface was preferred by subjects
 - Intensity interface led to less map quality degradation
- Interface design balance between
 - (Display accuracy) vs. (ease-of-use and learning time)

In this study we have been able to confirm both our hypothesis that:

- 1) Similar to the results of other research studies, this study has shown the benefits of adding vibro-tactile feedback to a visual-only interface, by showing the improvements this type of feedback has caused in robot navigation.
- 2) We have also shown that the Intensity mode caused greater improvements and received higher ratings by subjects, an indication that it seems to be the best choice of interface for vibro-tactile feedback for collision-proximity among the two evaluated.

A last interesting result from this study was to be able to detect the perceptual difference in accuracy versus ease-of-use from the subjects point-of-view. This seems to match similar situations that can take place in visual-only interfaces. Such similarities in results with visual interface evaluations might be an indication that perhaps researchers can easily adapt and reuse visual interface evaluation techniques to interfaces for other senses.

We have seen so far that we can improve a visual-only interface by adding one extra sense to it. The question now is: can we keep on adding more senses and still continue to obtain further improvements in performance and SA?

Exploring Multi-Sensory Feedback Interfaces and Redundant Feedback in Virtual Robot USAR

Study #3

Performance Effects of Multi-sensory Displays in Virtual Teleoperation Environments

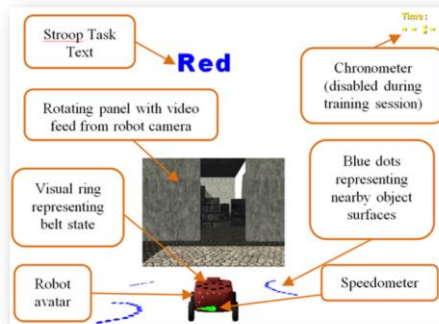
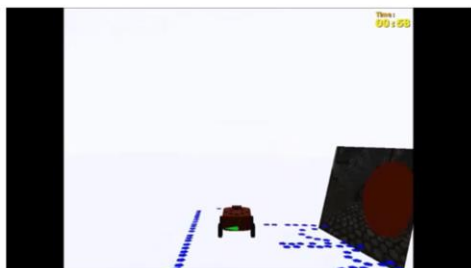
De Barros, P.G.; Lindeman, R.W.

Proceedings ACM SUI - 2013, Los Angeles, CA, USA, July 20th to 21st.

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Let me explain to you the third study that we have carried out, the results of which were published last year in the proceedings of the SUI conference in L.A.

Study #3 Overview



- **Within-subjects** design (18 subjects)
- Independent variable (conditions):
Type of feedback for collision proximity, collision and speed feedback:
 - Intensity mode (Interface 1)
 - Interface 1 + audio (Interface 2)
 - Interface 2 + redundant visuals (Interface 3)

Condition Number	Type of Feedback			
	Visual	Vibro-tactile	Audio	Redundant Visual
1	✓	✓		
2	✓	✓	✓	
3	✓	✓	✓	✓

This third study consisted of a within-subjects design. A total of 18 subjects participated in the study (18 subjects per condition). The type of interface was again what determined the study conditions:

- 1) In this study we are no longer using a visual-only interface as our control case. Instead, we have used the best multi-sensory interface we have discovered so far, which was the visual interface with the Intensity vibro-tactile feedback mode. And the idea behind doing this is that, if we any improvements are detected due to the addition of feedback by the two other conditions with enhanced interfaces, they will add to the improvements already obtained by our bi-sensory vibro-visual interface.
- 2) The second interface adds audio feedback for robot collision and speed using the cartoonified and metonymic approach we have explained earlier.
- 3) The third and last interface adds redundant visual feedback to the non-visual types of feedback. The visual ring is back from study one with an enhanced design, and sitting on top of the robot, presents data for collision (the dots will become red) and collision proximity (portrayed in tones of yellow) while a speedometer on the back of the robot shows the robot current speed.

Hypotheses

- The research review has shown that audio with(out) visual feedback can:
 - Improve search and collision avoidance
 - Improve realism and SA
- H1: Adding redundant (collision) and complementary (speed) sound feedback should improve
 - User navigation and search performance;
- H2: Adding redundant visual feedback should cause further improvements

Once again, previous research has shown several benefits of using audio feedback together with the standard visual interface.

Based on these results, we expect , as in the previous studies that:

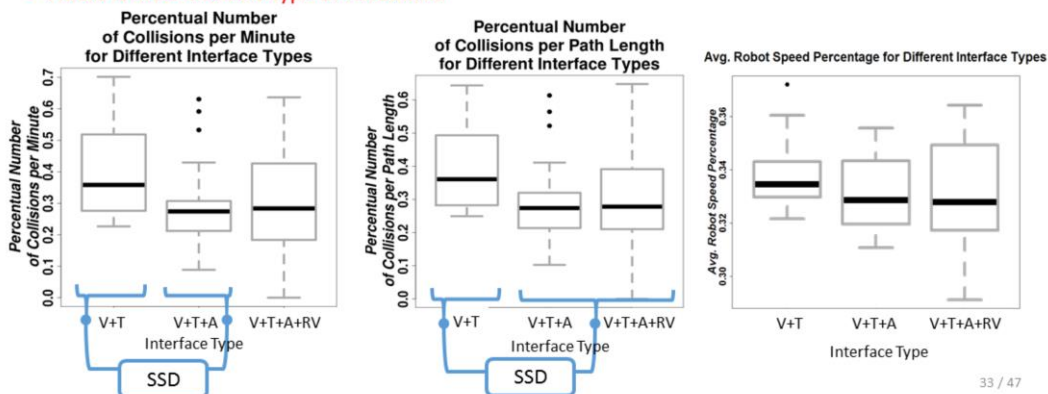
- 1) Adding audio feedback, be it redundantly or complementary, should improve subjects navigation and search performance.
- 2) Additionally, we expect, in accordance with what was detected in our first study and reported by other researchers, that the addition of redundant visual feedback should cause further improvements in performance and SA.

Results

- Number of collisions
 - Support H1: audio improved navigation performance
 - **Audio is after-the-fact type of feedback!**

Legend:

- Interface 1: visual (V) + touch (T)
- Interface 2: visual (V) + touch (T) + audio(A)
- Interface 3: visual (V) + touch (T) + audio(A) + redundant visual feedback (RV)



Now, here is an amazing result:

The addition of audio by interface 2 has indeed caused a further decrease in the number of collision by subjects. This supports our first hypothesis that stated exactly that such enhancement would occur.

What is even more amazing about this result is that, differently from the collision proximity feedback received by the vibro-tactile belt, the feedback for collision only happened after-the-fact, that is, once a collision has already occurred. Still, this type of feedback seems to have helped user better navigate the environment. Perhaps, the initial collisions helped the subjects have an estimate of how far visually they should keep the robot away from objects in order to avoid collisions.

The speed sound might also have played a role in allowing subjects to better estimate and control their speed. In the third plot in this slide, it is visible that the addition of audio led to a reduction in robot speed. Although such difference was not statistically significant, this variation might have been just enough to allow subjects to better navigate the robot.

On the other hand, it is visible that interface 3 caused no improvements in the number of collisions. In fact its data is even more dispersed than the data of interface 2. This increase in variation goes against our second hypothesis that stated that there would be improvements in performance caused by the redundant visual feedback added by interface 3.

Results

- NASA-TLX Stoop Task
 - More improvements and less degradation due to Interface 2
- Comments
 - Appraisal to audio feedback (bump sound)
 - Complaints about redundant visual feedback
 - Not very useful
 - Distracting
- Audio enhancement improvements confirmed (H1)
- Benefits of redundant visual enhancements not confirmed (H2)

Legend:

- Interface 1: visual (V) + touch (T)
- Interface 2: visual (V) + touch (T) + audio(A)
- Interface 3: visual (V) + touch (T) + audio(A) + redundant visual feedback (RV)

Measure	V+T+A	V+T+A+RV
Being There*	✓	●
Performance workload*	●	✗
Felt like driving*	●	✗
Difficulty*	✗	●
Positive impact on performance*	✓	●
More Straightforward*	✓	✓
Made user feel rushed*	✓	●
Stoop response time	✓	✓

In terms of questionnaires, it was noticed that second interface, the one that added audio, led to better overall results than the third one that added redundant visual feedback. Subjects comments also pointed in that direction.

- 1) They have praised the audio feedback, especially the bump collision sound.
- 2) And they have also complained about the redundant visual feedback, saying that it was not very useful and even annoying at times.

As in the previous slide, the results presented here seem to point to the fact that the audio feedback has brought significant benefits to subjects (in support of H1) but that the same was not the case for the redundant visual feedback (thus not supporting H2).

MADE USERS FEEL RUSHED

For the NASA-TLX questionnaire, a trend indicated that Interface 2 had a higher temporal workload score than Interface 1 ($w = 37.0, z = -1.87, p = 0.06, r = -0.31$).

This measure indicates how hurried or rushed subjects felt during the task. Subjects felt more in a rush when exposed to Interface 2. Because no difference in task time

was detected among interface groups, the only other factor that could have affected subjects' rush levels would have to be related to the visual timer on screen and subjects' behavior towards it. A plausible explanation would be that subjects were able to check the timer more often to see how efficiently they were doing. This behavioral change would only be possible if the rest of the interface was less cognitively demanding. Hence, an increase in timer look-ups could have been due to a decrease in cognitive demand from the rest of the interface. If this claim is true, such a decrease would support H1

Summary Results

- H1 confirmed:
 - Audio feedback to bi-sensory interface further enhanced
 - Navigation performance
 - Interface use
- H2 rejected:
 - Redundant feedback did not add to the SA and performance of the user

“Redundant data over multiple senses brings no benefit to the user of a multi-sensory display that already maximizes the user’s omni-directional perception and cognition of such data.”

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In summary, we have seen that adding a third type of feedback, audio feedback, has brought even further improvements to performance compared to our initial vibro-visual bi-sensory interface.

We have also seen that more is not always better. The redundant feedback did not improved users overall data perception and awareness of the multi-sensory and omni-directional data sensed by the robot and displayed by our interface. It only cluttered the visual interface and ended up distracting and annoying subjects.

So what is the next step? Can we actually add more multi-sensory feedback to our robot interface and further enhance users performance and SA?

More importantly, are the results obtained in a simulated robot and scenario actually reproducible in a real USAR situation?

Further Exploring Multi-sensory Feedback Interface in Virtual USAR and Validating Previous Results with a Real Robot

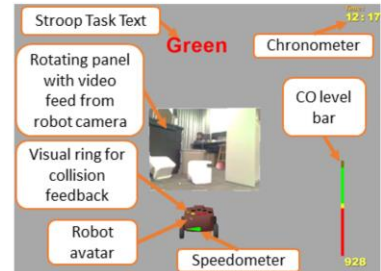
Study #4

To be published

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Answering these two questions is to be the main objective of our fourth study, whose results are yet to be published.

Study #4 Overview



- **Between**-subjects design (48 subjects)
- Independent variable (conditions): Type of feedback for collision proximity, collision, CO and speed feedback:
 - All Visual (Interface 1)
 - Visual + audio (Interface 2)
 - Visual + audio + touch (Interface 3)
 - Visual + audio + touch + smell (Interface 4)

Condition Number	Type of Information Displayed			
	Speed	Collision	Collision Proximity	CO Levels
1	V	V	V	V
2	V, A	V, A	V	V
3	V, A	V, A	V, T	V
4	V, A	V, A	V, T	V, O

V = Visual, A = Aural, T = Tactual, O = Olfactorial

This study has a between subjects design. A total of 48 subjects have participated in it (12 per condition).

The condition was again the type of interface used. The four conditions were the following:

- 1) The control case a visual interface that displayed all the possible information that can be obtained from the robot sensors.
- 2) The second interface added redundant audio feedback to it in the same way as in the previous study (for speed and collision feedback)
- 3) The third interface added the Intensity mode vibro-tactile feedback redundantly to the already present visual ring;
- 4) Last, the fourth interface added smell feedback as redundant source of CO level feedback for the user. The smell used by this display was the smell of Rosemary, which is claimed to improve human alertness and memory.

You can see from the video and picture that there are some differences on the visual interface:

- 1) The map blueprint is no longer present;
- 2) There is a bar in the bottom right corner of the screen that displays CO levels.

Whenever the robot would get close one of the circles being searched, the CO levels would increase and this would help the user's find circles even if he does not yet see them. For the smell interface, the smell of Rosemary would be dispersed in different intensities that attempted to match the level variation in the visual bar.

Hypotheses

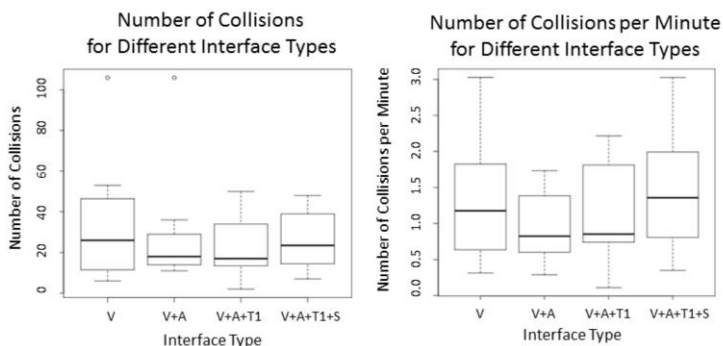
- H1: Expect that audio and vibro-tactile feedback cause same obtained performance enhancements regardless of order
- Smell feedback should enhance
 - H2: search performance
 - H3: map quality (SA)
- H4: Results similar to previous studies are now expected with real robot

Based on other research studies and our own previous results, four hypotheses were formulated for this study:

- 1) First, the addition of redundant vibro-tactile and audio feedback to a visual-only interface should enhance the robot operator navigation performance, regardless of the order with which these are added;
- 2) Second, the addition of redundant smell feedback to the multi-sensory interface with visual-only CO sensor feedback should enhance operators search performance, leading to an increase in the number of circles found;
- 3) Third, The addition of redundant smell feedback should also lead to improvement in the operator's memorization of the environment layout, leading to an increase in the quality of the maps sketched.
- 4) Fourth, the performance results obtained with the simulated robot in previous studies should be all reproducible with a real robot.

Results

- Number of collisions
 - Decrease for interfaces 2 and 3 but not between them
 - Sniffing behavior for interface 4 led to increase in collisions
 - Added improvement on number of collisions per minute across studies 2 and 3

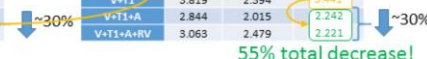


Types of feedback: A=audio, RV= redundant visual, S = smell, T1 = Intensity vibro-tactile, T2 = Frequency vibro-tactile, V = visual

Interface #	Mean	Std. Dev.	Median
V	4.982	2.893	4.814
V+T1	3.854	3.286	3.074
V+T2	4.032	2.981	3.343

Interface #	Mean	Std. Dev.	Median
V	3.815	2.994	3.441
V+T1+A	2.844	2.015	2.242
V+T1+A+RV	3.063	2.479	2.221

Interface #	Mean	Std. Dev.	Median
V	1.286	0.816	1.177
V+A	0.957	0.487	0.824
V+A+T1	1.196	0.685	0.853
V+A+T1+S	1.472	0.848	1.358



AUDIO:

Once again, we have seen for this study a decrease in the number of collision with the addition of audio feedback in interface 2 even though no SSD was detected. This is probably due to the smaller population that was used per condition. However, if we look closer at the medians for the number of collisions per minute for this and the second and third studies, where audio and vibro-tactile feedbacks were added, we can see that there is indeed a similar decrease of 30% in their value due to the use of the audio feedback. This indicates that with a larger population sample, we could have potentially obtain statistical significance for the improvements due to audio feedback.

VIBRO-TACTILE:

For the vibro-tactile feedback introduced in interface 3, the further decrease was not obtained as in previous studies. We believe this was due to mis-adjustment of the interface to the real robot scenario that introduced delay and robot wheel friction with the ground. These factors altered the behavior of the user, and the vibro-tactile feedback was not as well suited for such behavior as in previous studies.

These results seem to support at least in part:

- 1) Hypotheses 1 about which stated that improvements caused by the multi-sensory feedback should happen regardless of the order these types of feedback are added to the interface
- 2) And hypothesis 4, where it was stated that the results obtained with a simulated robot should also be obtainable with a real robot.

SMELL:

Another interesting point to notice is that the addition of smell feedback actually caused an increase in the number of collisions. We believe this was caused by the dog-like “sniffing” behavior subjects assumed when they detected the change in the CO levels due to smell feedback. When that happened, they would turn around the area the robot was in and look closely into nooks and crannies, thus increasing their chances of collision with objects, but also increasing their chances of finding circles as it is reported later on.

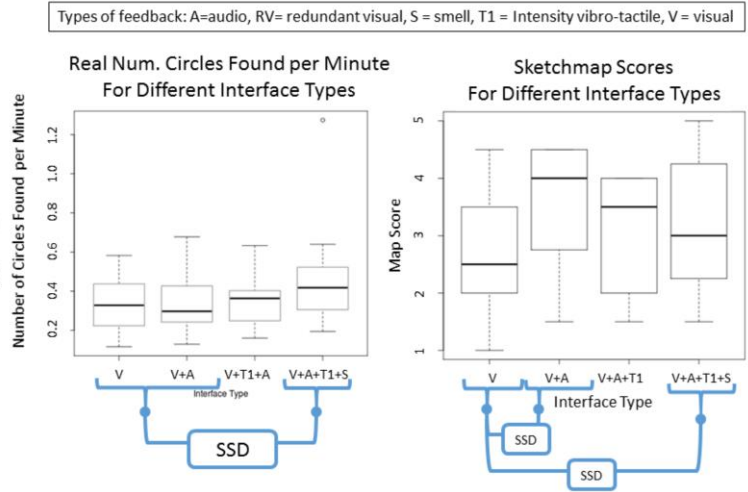
INCREMENTAL IMPROVEMENTS:

Last, I would like to use the tables presented here to highlight the incremental benefits that the use of multi-sensory feedback has caused on the number of collisions.

- 1) You can see on the table for study #2 that the number of collisions has been reduced from 4.8 to about 3.2 due to the addition of vibro-tactile feedback.
- 2) In study #3, you can see that the median for the control case, which was also a vibro-visual interface had a similar median value. This shows that the results between studies are consistent. Then, when we have added audio feedback, the number of collisions has then further decreased to about 2.2, showing that indeed, the incremental addition of multi-sensory feedback has caused gradual improvements in the number of collisions across studies, leading to a total decrease of 55% in the number of collisions, which is quite amazing.

Results

- Number of Circles Found
 - Interface 4 led to increase
- Map Quality
 - Interface 4 improved map quality (trends)
 - Improvement caused not just by the Rosemary smell effects on memory
 - Interfaces 2 also improved map quality!



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Another very interesting result was the increase in the number of circles found due to the use of smell feedback. This means that the redundant smell feedback indeed helped the user better perceive the CO levels.

Additionally, the smell feedback interface has also caused an improvement in the quality of the maps sketched by subjects.

These two results support our hypothesis H2 and H3 about smell feedback. Well, one could argue, especially one who is an aroma therapist, that both of these results could be simply justified as the mere consequence of the dispersion of the smell of Rosemary in the air, which could have improved user alertness. And, in fact, I would also say that this argument is plausible.

However, we have also obtained significant improvements in the quality of sketchmaps when interface 2 was used, where the visual interface was enhanced only with audio. What this means is that it is not just the psychological effects of Rosemary that are causing such improvements. The multi-sensory interfaces are indeed impacting user cognition and ultimately its task performance.

Summary Results

- H1: integration order of vibro and audio feedback does not matter
Plausible
 - Audio feedback led to improvements
 - Not so much for vibro-tactile feedback
- H2: smell feedback enhances performance
Confirmed
 - Smell feedback did enhance search performance
- H3: Smell feedback enhances SA
Confirmed
 - Smell feedback did improve map quality
 - **Audio feedback also caused the same effect**
- H4: Simulated results obtainable with real robot
Partially confirmed
 - Audio OK
 - Vibro-tactile needed adaptation for real robot scenario

In summary, we have been able to show that:

- 1) At least in part, that a well-designed multi-sensory feedback display components will improve user performance regardless of the order with which they are added to the interface. This has been shown by adding audio feedback in different orders and still obtaining the same type of performance improvement.
- 2) We have also shown that smell feedback has improved user performance for the search task, leading him to find a larger number of circles
- 3) Additionally, we have shown that smell also led to improvements in the quality of sketchmaps. What it was more surprising was that the audio enhancements also led to such improvements, indicating the positive effects of different types of multi-sensory feedback on user SA.
- 4) Last, we have also been able to show in part that the results obtained with the simulated robot could also be obtained with a real robot in real environment. This was shown by the reproduction of the improvements obtained by adding audio feedback. For the vibro-tactile feedback, we believe we could have reproduced the results obtained in simulation had we used a more robust robotic platform and better adjusted the belt behavior to subjects behavioral changes.

Our Answer to the Questions Asked

- Can multi-sensory displays also help improve USAR robot interfaces?
 - Yes, definitely.
- What are the downsides of multi-sensory interfaces?
 - If poorly designed, can be distracting and hinder performance and SA.
- How diverse can multi-sensory feedback become before cognitively overwhelming the user?
 - As diverse the number of human senses!
- Does redundantly providing the same type of feedback through different senses help the user?
 - Tough question to answer.
 - It depends on the interface design and task.
 - Positive: Redundancy may supplement each other;
 - Negative: Useless redundancy may also become distracting and hinder performance.

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Let us now get back to the questions stated at the beginning of this presentation and try to answer them based on the results of this research work presented here.

1) Can multi-sensory displays also help improve USAR robot interfaces?

Yes, definitely. As our studies have shown, using them may improve performance, SA and reduce cognitive load.

2) What are the downsides of multi-sensory interfaces?

We have seen that, if poorly designed, can be distracting and hinder performance and SA.

3) How diverse can multi-sensory feedback become before cognitively overwhelming the user?

Perhaps as diverse the number of human senses! The interfaces we have used here had even four types feedback and caused little degradation on workload.

- 4) Does redundantly providing the same type of feedback through different senses help the user?

Tough question to answer.

The first obvious answer is? "It depends". It depends on the interface design and task for example.

Positive side: Redundancy may supplement each other;

Negative side: Useless redundancy may also become distracting and hinder performance.

Our Answer to the Questions Asked

- Is the usefulness of multi-sensory interfaces limited to certain types of task?
 - Probably not.
- Are there effects in user cognition when displays from different senses are put together?
 - It is not about putting displays from different senses.
 - It is about distributing data perception;
 - It is about increasing the human perceptual bandwidth;
 - With good design and the right perceptual data load balancing, then the answer is probably **yes**.
- What methodologies can be used to evaluate multi-sensory displays?
 - The ones used here might be a good start.

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1) Is the usefulness of multi-sensory interfaces limited to certain types of task?

Probably not. In our studies, we have tested different USAR multi-sensory feedback interfaces that proved to be useful for both the navigation (audio, vibro-tactile) and search (smell) tasks. Logically, there are limitations on how each type of feedback is intuitive and useful for each specific type of application.

2) Are there effects in user cognition when displays from different senses are put together?

It is not about putting displays together, but instead about distributing data display across senses.
This also means increasing the human perceptual bandwidth that the interface can use.
With good design and the right perceptual data load balancing, then the answer is probably yes.

3) What methodologies can be used to evaluate multi-sensory displays?

We have proposed a set of metrics, many of which pointed out interesting results;
These could be reused not only for multi-sensory USAR interface evaluation, but also for evaluation of other multi-sensory feedback systems

Future Work

- Further validation with real robots
 - Improved robot
 - Belt functionality improved (collision vs collision proximity?)
 - Improved smell display system
- Metrics improvements
 - Use of biometric measures
 - More contextualized version of presence questionnaire for HRI

As future work is to further validate the results obtained here with a more robust and reliable robotic platform and better adjusted vibro-tactile feedback display. We also need to perform enhancement on the smell device in terms of its smell diffusion process and intrusiveness.

We also envision further improvements in the metrics proposed here that could lead to more accurate estimation of workload and cognitive load levels. Examples of that would be:

- 1) Adding biometric measures, such as sweat, heart-beat and pupil dilation measures;
- 2) And a better HRI-contextualized presence questionnaire.

Future

- Tools for multi-sensory interface exploration
 - Toolkit for adaptable interaction
 - Interface can be changed according to situation, task and user;
 - Customized interface profiles loaded in real-time.
 - Collaborative multi-sensory interaction
 - Split multi-sensory load among robot crew according to each persons roles
 - Sharing multi-sensory feedback when necessary
 - Feedback logging and review
 - Asynchronous display exploration

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Another interesting and very important work for the future is the development of a toolkit that allows the adaptable integration of multi-sensory interfaces. In other words, this toolkit would allow the multi-sensory feedback to change according to the situation, task and user for example. Additionally, each user could have its library of customized displays, each to be loaded and used according his needs.

Last, the multi-sensory interface could also be adjusted for collaborative work.

- 1) For example, a crew of two people controlling a robot could divide the search and rescue task into robot navigation and search. Each person would then leverage from different subsets of robot senses and multi-sensory displays to accomplish their tasks.
- 2) The displays could also be temporarily shared to allow for better team communication and collaboration.
- 3) Additionally, the robot-sensed data should also be logged so that the search could be further analyzed even after exploration is done;
- 4) This would also allow the team members to work on their own tasks (search, navigation) asynchronously and only synchronize their ideas, findings or tasks when necessary.

Contributions

- Verified the benefits of multi-sensory interfaces for USAR robotics
- Provided a first exploration on how far the benefits of multisensory interfaces can go
- Evaluation the impact of multi-sensory redundant feedback on interfaces
- Designed a reusable methodology for testing HRI interfaces
- Introduced the concept of user omni-directional perception

“Redundant data displays, be it through one or multiple-senses, are only beneficial to the user of an interactive system if they help further enhance the user’s omni-directional perception and understanding of the data that is relevant to the task at hand.”

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From my view, this work has contributed in many positive ways to HRI research.

- 1) It has verified that the benefits that multi-sensory interfaces can bring also apply to the area of USAR robotics;
- 2) It has performed a first exploration on how diverse multisensory interfaces can become and still benefit the end user. In our case, it was shown that it can be pretty diverse!
- 3) We have also evaluated how redundant multi-sensory feedback can impact user and the task at hand.
- 4) We have designed a methodology to allow researchers to evaluate their own multi-sensory interfaces.
- 5) Last, we have introduced the concept of omni-directional user perception and have shown how beneficial it can be to leverage from its potential through the use of multi-sensory interfaces.

Thank you

- Questions
- Comments



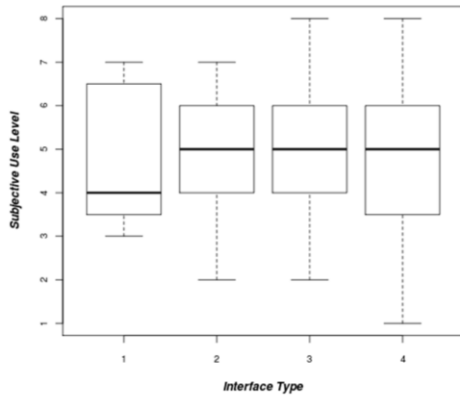
WPI Human Interaction in Virtual Environments Lab
<http://web.cs.wpi.edu/~hive/>

With being sad, I would like to thank you all for listening. Now, I would be more than happy to accept comments and attempt to answer any questions you might have.

Slide Appendix

Results

Use Levels for Different Interface Types
Based on Separate Feedback Type Ratings











Measure	V+A	V+A+T1	V+T1+A+S
Stroop num. incorrect answers*	●	●	✓ V, V+A
Stroop response time*	●	●	✗ V+A+T
Mental Workload*	●	✗ V+A	✗
Feedback*	✓	●	●
Ease of Use*	✓ V+A+T1	●	●
Fatigue*	●	✗ V+A	●
Discomfort*	●	●	✗ All

- Number of Positive comments
 - 1st Audio
 - 2nd Vibro-tactile
 - 3rd Visual
 - 4th Smell

Evaluating Interface Multi-sensoriality

- Four user studies evaluate different aspects of UI multi-sensoriality:

- Study #1: virtual robot 
 - Feedback to 1 vs. 2 senses
 - Redundant feedback
- Study #2: virtual robot 
 - How to display data through vibration
- Study #3: virtual robot 
 - Feedback to 2 vs. 3 senses
 - Redundant visual feedback
- Study #4: real robot 
 - Feedback to 1, vs. 2 vs. 3 vs. 4 senses
 - Redundant feedback

Study Number	Type of Feedback			
	Visual	Audio	Vibro-tactile	Smell
1 	✓	✓		
2 	✓	✓		
3 	✓	✓	✓	
4 	✓	✓	✓	✓

Note on Study 4: Vibro-tactile Results

- Study4
 - Change in subject navigational behavior
 - Friction
 - Delay
 - Decreasing battery power
 - Effect
 - Affected belt usefulness
 - Ring might have ended up providing better navigational help to subjects

