Vibrotactile Targeting in Multimodal Systems: Accuracy and Interaction

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Abstract

Tactile displays that enhance appreciation of virtual and real environments are becoming increasingly common. Extending a series of prior studies, we explored spatial resolution for individual vibrating sites on very dense arrays worn on the observer's trunk, and their interaction with simultaneously-presented visual stimuli in an isomorphic display. Stimuli were composed of individual stationary vibrating sites in a tactile array worn on the chest or flashes of light projected on a screen. In all cases, the task for the observer was to identify the location of the target stimulus, whose modality was defined for that session. In the multimodal experiment, observers were also required to identify the quality of a stimulus presented in the other modality. Performance was affected by the location of the target tactor within the array and the presence and location of the distractor stimulus.

1. Background.

The research described here concerns the potential advantage of using a tactile display to provide targeting information coordinated with visual information displays. The advantage of tactile technology has been recognized in a number of military applications [21]. These include navigation and orientation in conditions of reduced visual and misleading vestibular sensory signals. Precise targeting and tracking of events in three-dimensional space is a skill that may be aided with a tactile augmentation system (e.g., [16], [20]). Tactile arrays have already been shown to assist in accurate positioning of prosthetic arms [1], to allow aircraft pilots to maintain attitudes without visual cues [15], as well as to hold rotary-wing hover above snow, sand, or water, which often requires attention to the position of the aircraft as well as to outside activities (e.g., [4], [19]). Similarly, navigation of high-speed rescue watercraft can be aided by tactile displays in conditions that require the pilot to attend to the craft's direction of movement while scanning for the location of the target [10].

Tactile technologies augment spatial awareness by enabling operators to appreciate information through non-visual sensory inputs, potentially decreasing the perceptual and cognitive load. Such displays do not have to be "looked at" - the information provided is always available regardless of gaze direction. However, the question of how such stimuli interact with those from other sensory modalities is still open to discussion. The aim of this research was to evaluate tactile targeting representative of environmental events under conditions requiring that the user integrate tactile data with information from vision, the other primary spatial sense. Our goal was to improve existing technologies by optimizing the tactile interface so as to ensure that the sharing of cognitive resources across sensory modalities does not interfere with the existing workload.

A large literature describes the interactions between visual and auditory stimuli, and the effects on workload and performance when cues from these modalities are concurrent or contradict one another (e.g., [29], [30]). One of these models of processing (**Fig. 1**) argues that sensory stimuli that do not share resources should neither reduce accuracy nor slow responses. When the task demands require resources that fall into the same cells of this "allocation" chart, from Wickens and Hollands [30], they are likely to result in a performance decrement. For example, the acts of dialing a cell phone while driving an auto involve competing manual and visual resources. The literature on workload interactions among touch and the "major" senses is less well developed.

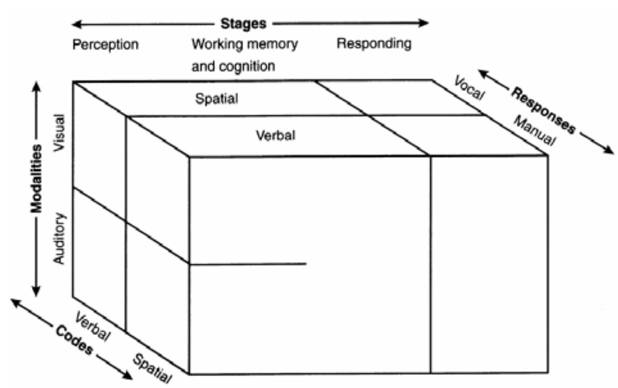

Fig 1. Wickens' model of information processing.

Past work on dimensional interactions often tested tactile stimuli at one site, varying vibratory frequency and intensity (e.g., [25]). Compared to 1-dimension performance, choice reaction times were faster when stimuli varied on a second correlated dimension, whereas neutral (orthogonal) variation slowed responses. These data indicated that perceived frequency and intensity were "integral" dimensions, as characterized by Garner [13]. Sherrick [23] showed a similar facilitatory effect with redundant covariation of vibratory rate (frequency) and intensity, measuring reaction time and static information transfer. In contrast, Sinclair [24] showed no intramodal redundancy gains for vibrotactile frequency and duration, suggesting these dimensions were "separable."

One of the few teams studying cross-modal spatial cueing involving the sense of touch is Driver and Spence. They have explored the ability of events presented within touch, audition, or vision to attract and direct attention in the other modalities (e.g., [11]), using a spatial cueing paradigm to direct attention to the location where stationary targets were to be presented when the eyes were initially on a fixation point. Thus "covert attention" was shifted towards the location of cue stimuli that may (or may not) anticipate the direction of the target. They found temporal and spatial interactions in this task. For example, target detection reaction times were optimal only if targets appeared within 50-300 ms of the cue. The proposed studies will also measure the ability of observers to divide or focus attention across sensory modalities when similar or different stimuli are presented.

2. Introduction.

Although rapid and accurate localization of target stimuli on the surface of the body might appear to be intuitive and precise, previous work from this laboratory has shown that identifying a small number of vibratory target sites arrayed around the waist was challenging.

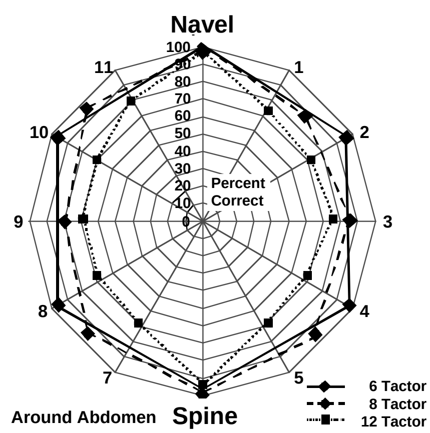

Fig. 2. Localization of abdominal tactile stimuli.

For example, fewer than 12 identical sites can be localized when placed at equal distances around the trunk of the body, apparently because of anatomical and perceptual factors. Near the navel or spine, however, localization was virtually perfect, in contrast to sites further away. For belts consisting of 12, 8, or 6 evenly-spaced tactors, the results, shown in **Fig. 2**, indicate that performance 1) is a function of the site on the body, and 2) depends on the proximity of alternative choices [6]. Using a somewhat different paradigm with an array across just the front of the body, van Erp and Werkhoven [27] have also shown that localization performance at the midline is more precise than that at sites to either side.

When used in a tactile display, such special sites as the joints, navel or spine, can improve the accuracy of localization. These site-related issues are of considerable importance to researchers who intend to use tactile localization to target events in the environment by mapping them to absolute locations on the body. In this set of studies, our intention was to push the limits of localization by presenting patterns on a tactile array that was extremely dense, relative to any known measure of spatial resolution for that body site [28]. Consequently, we expected the task to be very difficult. We also took advantage of the frequency-independence of localization, found in our studies on the abdomen (and forearm: [8], [9]). These findings were unexpected, considering that different tactile receptor systems optimally process different stimulus frequencies ([3], [7], [14]), but allow us to use tactile frequency here as a qualitative variable. In addition, since previous tasks were conducted without concurrent stimuli from other sensory modalities, it is of considerable importance to know if attention to tactile stimuli can be shared with that for vision, or, perhaps more importantly, whether localization of tactile stimuli might be distorted by the presence of visual distractors. It is well-know, for example, that visual stimuli often can "capture" auditory stimuli, as in ventriloquism, a common demonstration of sensory dominance.

2.1 Previous results: Localization of tactile stimuli on the abdomen.

In a previous study [5], localization of tactile targets was tested using 200-msec bursts of vibration at 80 or 250 Hz. In this case, the array was very dense, with tactors on 30 mm centers, and was placed on the left, right, or center of the abdomen. Repeated measures ANOVAs showed that there were significant main effects of array placement [$F(2,28)=38.715$, $p<.01$]. As would be expected by visual examination of the data shown in **Fig. 3**, tactor location within the array also played an important role, with better performance for those sites at the edges of the array compared to those in the center [$F(23,322)=17.164$, $p<.01$]. With the array placed across the body midline, performance was improved by some 15%, compared to the left or right, as shown graphically**.** T-tests showed overall performance for left or right placements was significantly poorer than that for the center, while there was no difference across loci between mirrored transpositions of these two. Interestingly, there were no significant differences between the two test frequencies, either. Static information analyses revealed that in this array of 24 potential sites, only about 2.5 bits of information (roughly 6 tokens) were transmitted [22].

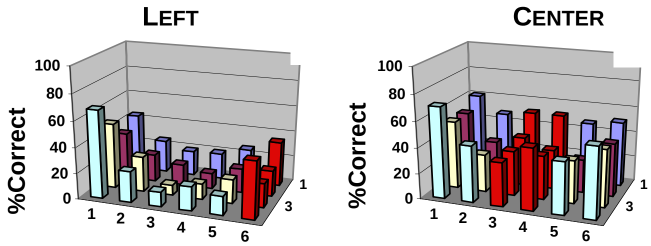

Fig. 3. Localization for dense tactile arrays on the left or center of the body midline. The 6 x 4 arrays are shown with the midline shown in red.

3. Methods.

We measured localization accuracy and response times in unimodal and bimodal conditions. In the first case, targeting accuracy was measured for tactile or visual stimuli, presented in separate sessions. In the bimodal condition, stimuli presented in one modality occurred in the presence of a stimulus in the other sensory channel. The task required participants to localize visual or tactile targets (in separate sessions), while identifying the quality (vibratory stimulus frequency or visual hue) of the stimulus in the other modality. Modality, site, and quality (color of the light, or vibratory frequency) were varied for both targets and distractors. Requiring subjects to identify the quality of the secondary stimulus forced them to attend to the location of the distractor, making different attentional demands on their perceptual resources. The subject was required to make a speeded detection response so we could evaluate the task difficulty and the intersensory contribution on a trial by trial basis, so response times for all trials were measured.

3.1. Apparatus.

A computer-controlled system was designed to generate tactile patterns on a dense wearable vibrotactile matrix as well as visual stimuli on a projection display. The computer controlled the trial conditions, logged response data, and provided information to the subject (on the visual display) regarding the progress of the test session. The tactile display consisted of an 8 inch neoprene belt that subjects wore around their waist, on which the 6 wide x 4 high tactor array was attached. Because of the superiority of sites on or near the body midline, the array was centered horizontally just above the navel so that the middle two columns fell on either side of the saggital plane. The array was composed of Engineering Acoustics, Inc C2 tactors, on 50-mm centers (**Fig. 4, A**). These are 30 mm in diameter, 8 mm thick, weigh c. 17 gm, and were driven at stimulus frequencies of 80 or 250 Hz. The 200-msec duration stimulus was generated by a 7-mm driver moving in a direction perpendicular to the skin's surface, centered in a 9-mm hole in the top stationary surface of the tactor. The stationary surround minimized the mechanical spread of the vibrotactile signal beyond the central source [12].

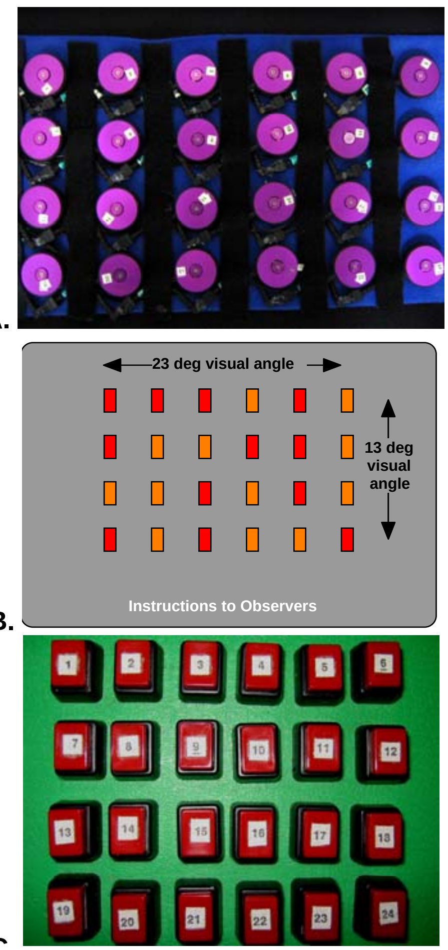

Fig. 4. Array of electromechanical tactors (A), visual display (B), and isomorphic keyboard (C).

Visual stimuli consisted of 200-msec-duration rectangles of light presented without a fixation point at one of 24 locations (**Fig 4**, **B**). These were projected onto a screen 200 cm in front of the observer in the dimmed room. The field subtended visual angles of 23 deg wide by 13 deg high. Depending on the test condition, each of the 24 sites could be colored white, red, orange, or green. The size of the display fit comfortably within the normal visual fields for color, as shown in **Fig. 5**, for the left eye ([2], pg. 108). No fixation point was provided, to better mimic a natural display.

In every condition, subjects identified the location of the target on a rectangular keyboard (**Fig. 4**, **C**) designed to be isomorphic to the displays (i.e., upper left key=upper left tactor or flash of light in the array). When quality was to be identified, a second 2-button keyboard was attached to this one. Localization accuracy and static rates of information transmission were calculated as a function of target location [22]. Although Miller [17] argues that few of our 24 tokens should be well-identified, Rabinowitz [18] suggest that with appropriate designs, higher rates are possible.

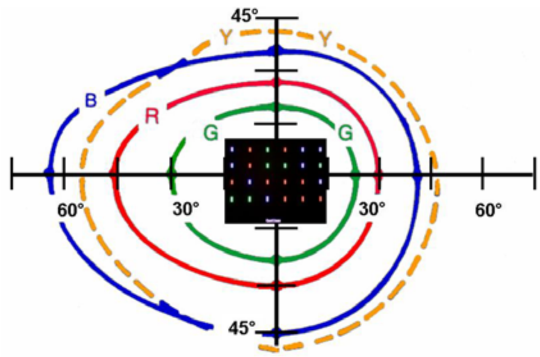

Fig. 5. Normal color visual fields (left eye).

3.2. Subjects.

For each experiment, eighteen subjects were recruited from the Aviation Schools Command at the Naval Air Station, Pensacola. They were instructed to report to the test site wearing a standard issue military T-shirt so that we could control the tactor-skin interface. Participants were briefed regarding the aims and procedures of the studies, and read and signed informed consents. They completed a brief medical survey to screen for conditions or medications that might interfere with visual or tactile sensitivity, were administered the Mental Rotations Test of spatial abilities [26], and their abdominal girth was measured. They were comfortably seated, facing the visual display, 200 cm away, and the tactor array was fitted around their waist. Subjects wore 31 dB (NRR) Leighting sound-attenuating headphones with white noise at a level of c. 68 dB SPL. This combination was sufficient to mask extraneous sound that might be produced by the tactors or ambient distractors. The response keyboard could be held in the hands or rested securely on the arm of the subjects' chairs. They were also debriefed at the end of the study, provided an opportunity to ask any questions, and were given Laboratory patches as an expression of appreciation. As members of the military, they were not allowed to receive reimbursement of any significant value. The research protocol was reviewed and approved by the Institutional Review Board for the Protection of Human Subjects of the Naval Aerospace Medical Research Laboratory.

3.3. Preliminaries.

Prior to testing, familiarization presentations were provided using vibratory and visual stimuli identical to those in the trial series proper. These were intended 1) to acquaint the subject with the qualities of the stimuli, 2) to ensure that all tactors were making adequate contact with the skin, producing comparable levels of perceived intensity, and 3) to introduce the subject to the apparent locations of both tactile and visual stimuli. Subjects were also introduced to the custom-designed keyboard to be used to indicate the perceived target locations. The vibration test intensity was set to c. 20 dB SL, approximating that felt by a user of a vibrating cell phone.

3.4. Procedures.

In each of the following conditions, after the preliminary tasks were completed, subjects were tested with the following general procedures: On each trial a keystroke initiated a preparatory delay of 700 msec that was followed by the target stimulus. Each target stimulus event was either a burst of vibration (or a flash of light) having duration of 200 msec, of a quality and on a site quasi-randomly chosen for that trial. The random orders were constrained so as to present equal numbers of each stimulus condition within every session in order to control for factors such as fatigue and daily variations in attention. Subject responded by pressing the button on the keyboard corresponding to the perceived location of the sensation, and the computer recorded the response and response latency. The system paused, waiting for the subject to initiate the next stimulus with another designated keystroke. Feedback was provided on each trial by indicating, on the bottom of the screen, the correct location of the target, as well as an indication of whether the response was correct or not. This trial sequence repeated for each trial: with 24 locations and 2 repetitions, 48 trials were presented in a block, while 5 blocks were conducted in each session. Between each block of trials, a brief rest period was always available. Subjects served in 2 sessions to ensure each person judged all combinations of the stimulus variables in each condition. Responses and reaction times were recorded and analyzed for correct performance as well as static information transfer. Note that chance performance for these tasks was c. 4%.

Following preliminary preparations, separate groups of 18 subjects were tested in the following 4 experiments:

1) Compare tactile vs. visual localization with 250-Hz vibrations or white lights;
2) Compare tactile vs. visual localization with 80-/ 250-Hz vibrations or red/green lights;
3) Compare tactile vs. visual localization while identifying stimulus quality with 80/ 250 Hz vibrations or red/orange lights;
4) Compare tactile vs. visual localization identifying 80/ 250 Hz vibrations or red/orange lights, respectively;

4. Results and discussion.

4.1. Baseline unimodal fixed quality condition.

In order to establish baseline performance without qualitative variations in the targets, subjects in this first study were required to identify the locations of 250-Hz tactile stimuli or flashes of white lights on their respective arrays. To minimize cues related to local variations in tactile sensitivity, vibratory intensity was varied at each site over a 6-dB range from presentation to presentation Each subject was tested with a tactile target series and a visual target series in each of their two sessions. The orders of modality were randomized over subjects.

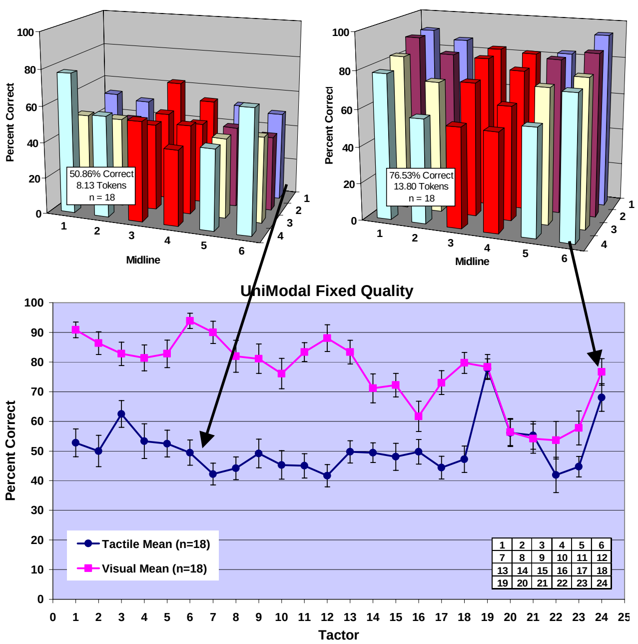

Fig. 6. Localization of tactile and visual targets in 24-site arrays as a function of location and modality plotted in two ways.

Each participant provided a total of 20 observations per location per modality (2 observations/ block, 5 blocks/ session, 2 sessions/ modality). As in **Fig. 3**, the 4 rows and 6 columns of the array are represented graphically in the upper two graphs of **Fig. 6** with location of each tactor on the abscissas of each plot, while the ordinate shows performance, in Percent Correct. Columns 3 and 4 in the center of the graphs are colored red to indicate the position of the body midline under the array. Visual examination suggests a difference in performance between the two modalities, as well as some variation in performance over the surface of the array. In particular, it appears as though localization over the tactile array is relatively uniform, while, in contrast, that for visual targets appears to be a function of height on the array. Specifically, visual targets at the top of the display are better localized than those towards the bottom. Somewhat surprisingly, performance for targets in the lowest row for each modality appears remarkably similar. This similarity is best seen when these data are replotted in the lower graph in **Fig. 6**, with performance as a function of site, so as to illustrate differences across the field at each locus. Tactor locations may be identified in the small matrix in the lower right of the figure. Localization showed a strong and significant effect of stimulus modality [$F(1, 17)= 59.072$, $p<.01$]. As would be expected with a visual examination of these data, location of the tactor in the array also played an important role, with the scalloping indicating better performance for those sites at the edges of the array compared against those in the center [$F(23,391)= 8.5913$, $p<.01$]. The convergent patterns of results over the target field is supported by a statistically significant interaction [$F(23,391)= 11.441$, $p<.01$].

Having established that neither task would suffer from either a ceiling or floor effect when additional dimensions were added to the display, in the next experiment we added variation in target quality to the localization task.

4.2. Baseline unimodal variable quality condition: localization response.

In this second experiment, another 18 participants were required only to respond to the location of the stimulus, although two different qualities of each target were presented (in equal numbers): either red or green lights, or high (250 Hz) or low (80 Hz) stimulus frequencies. These were designated as "high" or "low" priority, respectively. The intensities of the vibrotactile stimuli were adjusted to provide equivalent sensation magnitudes, although they were presented at several intensities to minimize cues related to local differences in tactile sensitivity, as in the first experiment. These subjects also provided a total of 20 observations for each location per modality (2 observations/ block, 5 blocks/ session, 2 sessions/ modality), although they were equally

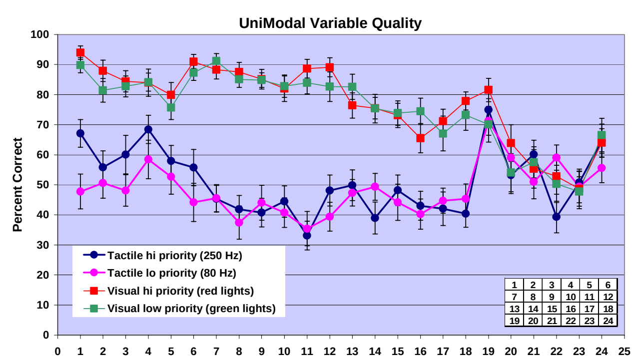

Fig. 7. Localization of tactile and visual targets as a function of location, modality, and quality.

divided between the high and low priority qualities. These data are plotted by quality in **Fig. 7**, although we want to repeat that subjects only were required to report location. Location of each target is shown on the abscissa of the plot, while the ordinate shows performance, in Percent Correct. Although there was, again, a significant overall main effect of stimulus modality [*F*(1, 17)= 75.557, *p*<.01] and target site [*F*(23,391)= 10.344, *p*<.01], as well as a significant interaction between the two [*F*(23,391)= 15.684, *p*<.01], no significant differences were found between qualities, indicating that they were equally discriminable. This finding was particularly reassuring(and interesting) for the vibrotactile stimuli. As we described earlier, some models of vibrotactile sensitivity would argue that high-frequency stimuli would be less well localized than low-frequency stimuli. This was clearly not the case here. Finally, when these data were collapsed over quality by modality and compared against the first experiment, we did not find a significant effect of adding the qualitative variation **(Fig. 8)**. Consequently, subjects' localization performance was not affected by the presence of targets that varied in quality.

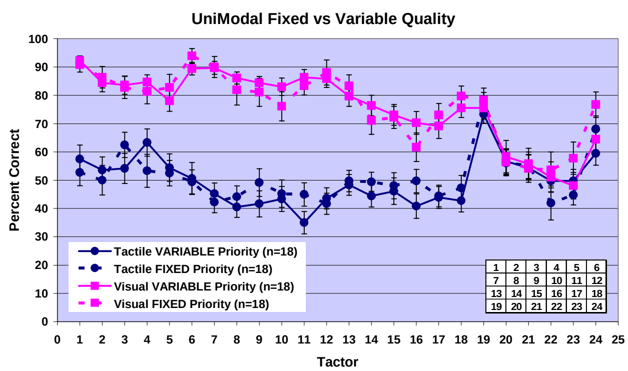

Fig. 8. Localization of tactile and visual targets as a function of location, modality, and quality.

In the next unimodal experiment, subjects were presented with either visual or tactile stimuli, but did have to attend to the quality (or "priority").

4.3. Baseline unimodal variable quality condition: localization and priority response.

The third experiment tested another 18 participants who were required to respond both to the location of the stimulus as well as to the qualities of each target. Because of the high performance levels seen in the case of the visual stimuli, we changed the second visual quality from green to orange lights, while the frequencies of the vibrotactile stimuli remained the same: 80 and 250 Hz. A second smaller 2-button keypad was added to the side of the 24-button keyboard for the quality response. These keys were identical to those shown in **Fig. 4**, **C**, were marked with red and orange labels, and designated as "high" or "low" priority, respectively. As before, baseline intensities of the vibrotactile stimuli were adjusted to provide equivalent sensation magnitudes, although they were presented at several levels to minimize cues related to local differences in tactile sensitivity, as before. These subjects also provided a total of 20 observations per location per modality (2 observations/ block, 5 blocks/ session, 2 sessions/ modality), 10 per level of quality.

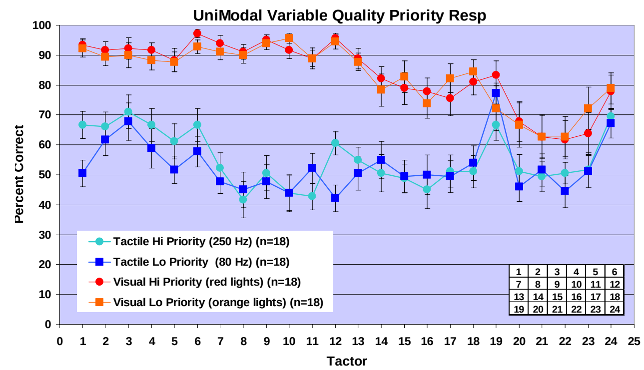

Fig. 9. Localization of tactile and visual targets as a function of location, modality, and quality.

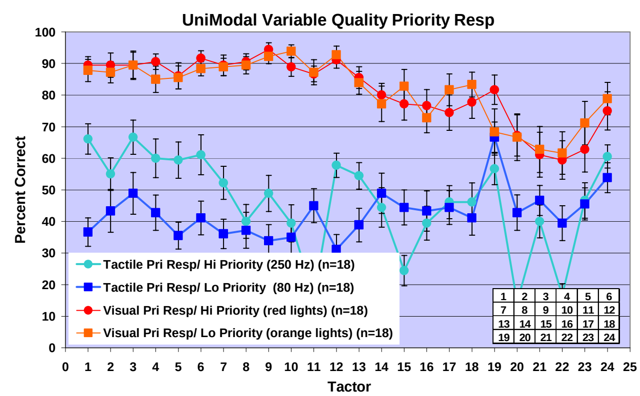

Fig. 10. Localization of tactile and visual targets as a function of location, modality, and quality.

As shown in **Fig. 9**, there was virtually no difference in localization performance between the two qualities for either modality, borne out by repeated-measures ANOVA. Again, the main effects of modality [*F*(1, 17)= 303.348, *p*<.01] and target site [*F*(23,391)= 8.755, *p*<.01], as well as the interaction between the two [*F*(23,391)= 2.620, *p*<.01] were highly significant. Unexpectedly, performance was slightly improved for both conditions over that from previous experiments. We expected the task to become more difficult by making the lights more similar in hue, comparable to the difference in perceived frequency for the vibrotactile stimuli, we felt. Perhaps the added attention to the targets required by the additional task led to the improvement in localization. When the priority responses themselves are examined, the data can be plotted as shown in **Fig 10**. Note that in this case, chance performance is 50%, so, whereas identification of visual quality is generally very good, tactile quality is, for all practical purposed, at random levels.

4.4. Bimodal variable quality condition.

In this experiment we tested another cadre of participants who were required to respond both to the location of the target. However, in this case they were to report the quality (not location) of a simultaneous distractor in the other modality, as well. Although, as before, the target could occur at any of the 24 locations, the distractor would only occur at one of the four corners of its array (as indicated **Figs 11 and 12**). In a session of 5 blocks of 48 trials, target modality (as well as that of the distractor) was fixed. Only target stimuli were presented in the first block, so as to establish baseline performance. In the remaining trials in the session, simultaneous presentations of stimuli in both modalities occurred. We expected differences between the modalities in that one had to attend to a visual distractor's location to identify its hue, while a vibrotactile distractor's location could be irrelevant to identification of its perceived frequency.

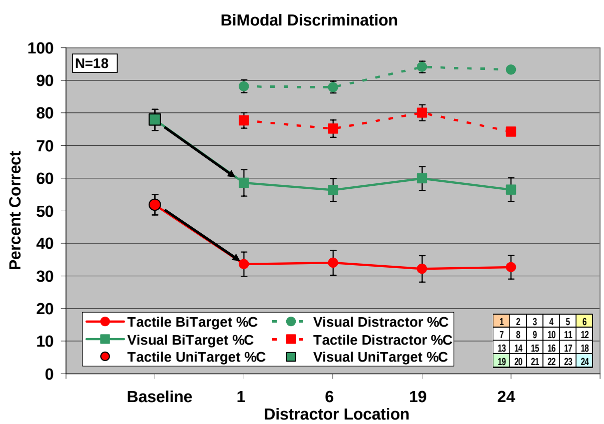

Fig. 11. Localization of targets and distractors as a function of modality and distractor location.

Localization results with the baseline performance levels are shown in **Fig 11** as a function of distractor location for each modality. In addition, the accuracy with which subjects identified the quality of the distractor is also shown. Because one of our primary interests was the effect of the distractor on processing times as well as any potential spatial mislocalizations that might result, it was important that subjects attend (even covertly) to distractor location. Response times, shown in **Fig. 12**, indicate the increase in processing time required to encode and report the additional quality, and can be contrasted to those in **Table 1** from the earlier experiments described in **4.1.-4.3**. The patterns (and directions) of spatial localizations for the target-distractor combinations are in the process of being analyzed.

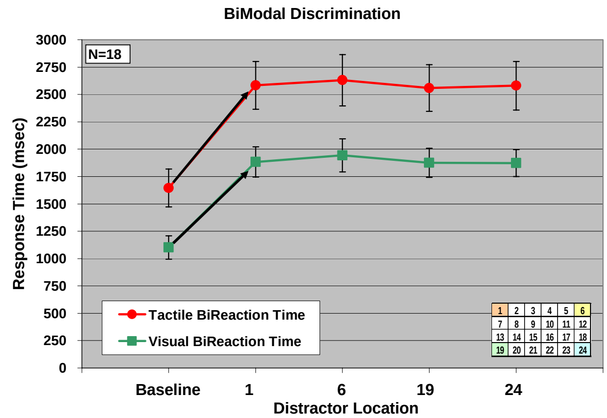

Fig. 12. Response times for tactile and visual targets as a function of distractor location.

5. Summary and conclusions.

We have shown that similar patterns of processing occur for qualitatively different briefly-presented visual and tactile targets. When presented simultaneously in a divided attention task, substantial decrements in performance occurred. (as measured by accuracy and response times). Further analyses will explore whether spatial distortions might have also taken place when tactile and visual spatial stimuli have to be attended.

Table 1. Summary statistics

			PC	RTime	InfoXfer	Tokens
			%	sec	bits	items
4.1)	Tactile	mean	50.86	0.850	2.78	7.01
		se	1.71	0.109	0.07	0.34
	Visual	mean	76.53	0.609	3.69	13.27
		se	2.00	0.074	0.10	0.77
4.2)	Tactile	mean	49.70	1.069	2.77	6.98
		se	1.84	0.091	0.08	0.44
	Visual	mean	76.06	0.629	3.65	12.92
		se	1.32	0.074	0.08	0.79
4.3)	Tactile	mean	54.25	1.717	2.98	7.89
		se	2.13	0.121	0.11	0.52
	Visual	mean	83.58	1.104	3.89	15.52
		se	1.89	0.131	0.09	1.26

6. Acknowledgements.

This research was supported by a grant from the U. S. Navy Bureau of Medicine and Surgery “Core Capabilities” Research Program to the Naval Aerospace Medical Research Laboratory. We wish to thank CAPT Angus R. Rupert, MC, USN, for his support of this program of research. We also wish to express our appreciation to the many participants for their careful attention as they served in these studies.

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