Reaction times to constraint violation in haptics: comparing vibration, visual and audio stimuli

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ABSTRACT

In teleoperation and in particular in surgical robotics, it is important to avoid getting closer to certain forbidden areas typically limited by virtual constraints. In this paper we compare different sensory modalities, vibratory, auditory and visual, to convey information about constraint violation to the operator. We focus on which of these modalities can elicit the fastest reaction time on the user. An experiment was devised in which subjects were asked to slowly insert a virtual tool by means of a haptic interface, and retract it as soon as they hit an obstacle; such event triggered an alert signal. We evaluated different signals: auditory, vibrotactile, and visual, with two amplitude levels for audio and vibration. Lower reaction times were observed on the strong vibrotactile modality, followed by the weak vibrations and the loud auditory tone, although the latter was described as uncomfortable by the subjects. The vibrotactile feedback was described as pleasant by most subjects and appears promising for future developments.

Index Terms: H.5.2 [Information interfaces and presentation]: User Interfaces—Haptic I/O;

Figure 1: The experimental setup: the user moves his hand along a line, the haptic device is constrained on, and retacts as he perceives an alert which can be a vibratory, visual or auditory cue.

1 INTRODUCTION

When dealing with moving systems that are interacting with their physical environment, be it real or virtual, contact forces are almost inevitably produced. These forces can be unimportant, like those produced by the wind blowing on a slowly moving tractor, but can also be extremely important, as would be the case for a tightrope walker trying to keep his balance.

We are interested in the case where an operator should be aware of such forces (in contrast to systems where the system or robot reacts autonomously to them). Many options are available to present such information. Visually, screens can display text, images, changing colors, force bars, flashing indicators, and many others, but can also be placed on a console or as indicators on instruments. Aurally, warning alarms, frequency and amplitude varying signals, spoken messages, can be given to an operator. The third option, which is through the operator's haptic system, has been under very active research in the last few years, and includes cutaneous as well as kinesthetic alternatives.

While designing an interface for the user, many factors come into play, and it turns out to be very application specific. However, each modality presents its own advantages and disadvantages. In our work on teleoperation, we asked ourselves which of these would a human operator be faster to react to, while using a master haptic manipulator. That is, if the operator is focusing his attention on a teleoperation task, what kind of stimulus (choosing among visual, auditory, and haptic) will trigger a faster reaction at the tool? To the best of our knowledge, in literature this specific problem has not been investigated. This work tries to provide an answer to this question.

In the medical context, the time it takes a surgeon to react might very well be crucial to the result of his intervention. While moving the surgical tool at a given speed, the reaction time directly translates into the undesired movement beyond the point at which a warning stimulus was produced. The desire to be as fast as possible to react while teleoperating on very delicate environments motivated this work.

While using a haptic interface for telemanipulation, it was natural to choose the haptic vibratory cue as one of the stimuli to convey information about constraint violation. The other stimuli were audio and visual cues. The three modalities were compared in terms of reaction time.

In Section 2, we present the related work and the background for our research. In Section 3, we present our experimental setup, the task at hand, and explain the experiment. The obtained results are described and discussed in Section 4, and finally, we present our conclusions and ongoing work in Section 5.

2 BACKGROUND / RELATED WORK

Robotic assisted minimally invasive surgery with force feedback is the context in which this paper is situated. Many authors have shown the advantages of teleoperation with force feedback over teleoperation without it. In [6], it is shown that force feedback decreases overshoot in puncturing tissues by 52 percent. In [20],

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authors describe a sensorized system with force feedback on the master side for endoscopy.

However, providing force reflection directly at a master interface can cause stability issues. In case of time delays or data loss, instabilities and undesired movements can appear both at the master and slave side of the teleoperation system [9]. In medical applications, this is a crucial problem and is the reason why many of the commercially available systems today do not have such force reflection.

As a solution to get around this problem, many people have taken the road of sensory substitution, where instead of applying forces directly back at the surgeon's hands, the feedback is given through another modality, such as visually or aurally. For example in [11] authors show that by using auditory and visual cues to give feedback about applied forces, knot tying with the DaVinci system was performed more efficiently. Also, Massimino and Sherridan describe a system in which an audio signal gives feedback about the forces arising between a remote effector and it's environment [14].

A more recent approach to sensory substitution involves the use of vibrations as the feedback modality. Vibrations can be applied to different parts of the body [7, 3, 12] or directly at the point of contact. This last case has the advantage of being perceived as more realistic since the feedback is perceived where it is expected to be [16]. In [15], authors used vibrations on a wearable glove that allowed users to control grip forces more effectively in teleoperation, and [2] describes a commercial robotic catheter system measuring applied forces on the catheter tip and modulating vibrations at the master handle.

As far as the reaction time from different stimuli is concerned, the literature is mature but does not consider the specific case this paper is dealing with. The mean reaction times to different modalities is measured with *simple* (or choice) experiments with only one stimulus and one response [13]. Many experiments have shown humans to be faster to react to sound, at about 150 ms, followed by touch at 155 ms, and being the slowest to visual reaction, at around 190 ms [22, 17, 21], although these values value across different studies, mainly depending on the setup (for example, compare [1] and [8]). However, all these experiments supposed getting a simple stimulus through one channel, and reacting through another (like pressing a button). Our approach differs in the fact that we plan to exploit the same channel for both input and output in one of the modalities, namely, the vibrotactile one, but not in the visual and auditory cases.

Another important factor that can affect reactions and plays a role in the design of our experiments is the intensity of the stimuli. In [13], Luce shows that weaker intensity stimuli elicit slower reaction times, and that gradually increasing the intensity decreases response times until a constant response is reached.

3 Experimental setup

In our experiment, we simulated a simple task in which a surgeon is inserting a tool, like a needle, along one degree of freedom, when he suddenly encounters and unexpected, potentially dangerous, situation. He is then presented with one of several stimuli to which he must react as fast as possible, by retracting the tool. We measure this simple reaction time for each of the modalities.

To track the position of the tool, we use a haptic device from Force Dimension: the Omega 6. Having a very high spacial and temporal resolution, it allows to get accurate measurements. Moreover, it serves the additional purpose of providing the precise vibratory feedback, that will subsequently be described. It is fitted with a pen-like tool that is comfortable to grasp and convenient for the given task.

We try to keep the experiment as simple as possible, in order to limit undesirable effects of external variables on the values that we measure. On this light, we constrain the path of the tool to only one degree of freedom, following a straight line. This is done by continuously tracking the position of the tool, and applying forces to keep it on the desired path. A simple spring and damper model is used to apply forces on the directions orthogonal to the path. This keeps the end effector point on the desired trajectory, while applying zero forces on the axis of movement.

The different modalities we use to alert the subject that he must retract the tool are auditory, haptic, and visual. Given that the reaction times are expected to change according to the intensity of the stimuli [13], we use two intensities for the auditory and haptic modalities.

In the auditory cases, a beep is played through a headset worn by the user, until a reaction is detected. We chose two levels of intensity: one which was comfortable, without being considered significantly loud nor quiet, and one that was loud at the limit of discomfort. This choice was made in order to observe the reaction times that we could obtain in a feasible scenario, but also looking into possible improvements.

For the visual modality, the screen in front of the users goes from black to white and stays this way until the user retracts the tool. The brightness was set to its maximum value to obtain the fastest possible reaction time.

With the haptic feedback, the tool starts vibrating at a frequency of $250Hz$. Such frequency was chosen as it has been shown to be the most effective to stimulate the Pacinian corpuscle receptors in our skin [5]. The haptic device is controlled in force, and is alternatively applying forces in two opposite directions. Since we are interested in measuring the time of retraction of the tool, these directions were chosen orthogonal to the tool insertion axis, so as not to move the end effector in the direction of interest. As it has been shown in [4], humans are unable to discriminate direction in high frequency vibration, so this implementation choice does not affect perception. Two magnitudes were employed: $2N$ for the weak vibration, and $4N$ for the strong one. Since the vibrating device produced a perceivable buzz and we wanted to measure the reaction to a purely tactile stimulus, pink noise was played through headphones throughout all of the part of the experiment that involved vibrations. Given the frequency and amplitude of the signal, it was not possible to perceive the stimulus visually while the tool was held by the operator.

Every trial started with the tool moving autonomously to a fixed point on the path, and locking in position until the beginning of the task. The point at which the stimulus is triggered is randomly placed at a distance of between $30mm$ and $75mm$ to the start position, along the free degree of freedom, to prevent learning effects. We will refer to it as the alert-point in the remainder of this document.

The subject was instructed to push (insert) the tool along the path, and informed that he would be warned when he reached a certain point that he shouldn't cross. He was also told that this point would be randomly placed, varying in each trial. The instruction was to retract the tool as soon as possible when the warning was triggered. In the instructions, the emphasis was on the time of reaction, giving no special attention to the insertion nor extraction speed of the tool. It was however expected that insertion would be slow, to avoid going beyond the alert-point, and extraction fast, given the urgency of the response.

The reaction time was taken to be the elapsed time between the onset of the stimulus, and the moment in which the speed of the tool became negative in the insertion axis, where the positive direction is that of the insertion. A little threshold was necessary to avoid false detections (in case the insertion is very slow), and was taken at $10mm/s$. Although this adds about 5 miliseconds to every measurement, it is consistent across every trial and does not affect our subsequent analysis. Moreover, since different kinds of signals were produced on the computer, we measured if any of the modalities had an unfair disadvantage (like a system call to start audio being slower than a signal to flash the screen). By artificially generating a signal that indicated a reversal in probe direction, we were able to determine that the minimal timing of the computerized sensing system was of about 18 milliseconds. This is much faster than the fastest possible human reaction time, so we considered the trials to be fair across modalities.

As in other implementations involving reaction times [19], we set out to discard measures lower than 100 ms as outliers, but decided *not* to perform any kind of outlier exclusion on the slower side. Abnormally high response times can be observed in case of user distraction or confusion, but we consider this to be a phenomenon that will also be present in real scenarios.

The trials were divided in five blocks: one for each modality and intensity. However, the order in which each block was presented was randomized for each participant, so as to minimize the presence of training effect in our results. We chose this block grouping instead of randomizing all the trials, since in a real life implementation, only one choice of modality would be made, and the operator would know what kind of feedback to expect. Furthermore, having sequential trials should result in lower reaction times than totally randomized ones [18]. Each block consisted of 25 identical trials, and started with a message on the screen informing the subject of the modality being used.

Eight people took part in the experiment (two female), half of which had previous experience with haptic devices. All of them were right handed, and the age average of the participants was of 28 years. All subjects were healthy and didn't report any particular medical condition.

At the end of the experiments, the subjects were asked to fill a small questionnaire in order to express their qualitative evaluation about the different modalities they were subjected to. They were left a blank space for remarks and comments both about the experiment and the modalities. For each modality, the subject was presented the following statements: "Modality *X* was useful to produce low reaction times", and "I liked receiving feedback through modality *X*". They had to answer on a five point Likert scale with "Strongly disagree", "disagree", "neither agree nor disagree", "agree" and "strongly agree", that were associated respectively to numbers from -2 to +2.

4 Results and Discussion

4.1 Reaction times

Analysis of the data showed that none of the subjects produced anticipatory responses while performing the tests (fastest reaction time was 141 milliseconds). The slowest measured reaction was at 813 milliseconds, and can be considered in the normal range (and not arising from abnormal causes). In Table 1, we report the mean reaction times for each modality and for every subject. In bold blue, we highlight the fastest modality of each subject, and the slowest in underlined red. For convenience, we've grouped first the users with previous experience with haptic interfaces (A-D), and then users without such experience. We can observe that the obtained mean reaction times are slower than those typically reported in literature. However, having a slightly more complex task than pressing a button, and the previously discussed delay in reversing the direction of the tool seem to account for this.

As can be seen, in average, the fastest reaction times were obtained under the strong vibrotactile modality for all users except one. The longest reactions times were mostly under the visual and low-volume auditory modalities, with only one case user being slowest on the high-volume modality.

	VibrHigh	VibrLow	AudiHigh	AudiLow	Visual
A	**176**	198	238	312	259
B	**158**	183	213	225	224
C	**192**	215	222	289	267
D	**234**	245	306	308	325
E	**247**	273	317	314	302
F	**191**	204	209	212	209
G	232	263	**231**	260	274
H	**213**	255	222	271	283
$\bar{x}$	**205**	230	245	274	268

Table 1: Mean reaction times in milliseconds by subject for each modality. Best and worst are shown in bold blue and underlined red respectively for each subject. Users A to D had previous experience with haptic interfaces.

In Figure 2, we show the results of all 125 trials for a particular subject (subject B in Table 1). It shows the median, the 25th and 75th percentile of the samples, and the rest of the data-points below or above these percentiles. It shows a clear difference across some of the modalities (vibroHigh, VibroLow), while some show less evident dissimilarity (AudioHigh, AudioLow, Visual).

Out of the eight subjects performing the experiment, the four having previous experience on haptic interfaces had the most distinct results across the different modalities, while the inexperienced ones showed less difference.

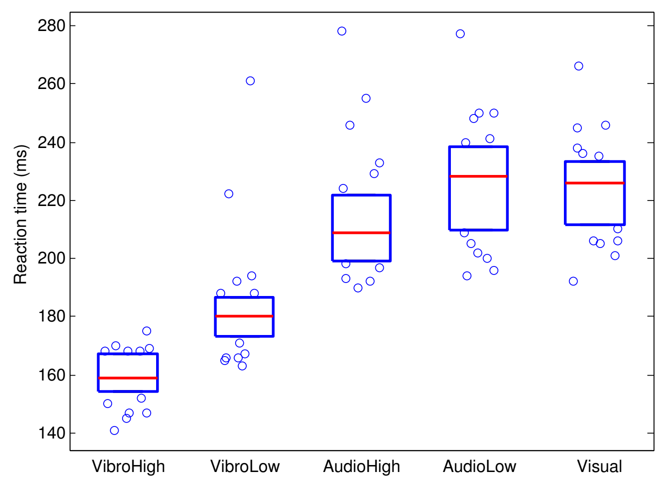

Figure 2: Plot of subject B's trials (in ms), showing the median, 25th and 75th percentile, and data-points below and above such percentiles.

We performed a repeated measures ANOVA on the mean reaction times reported on Table 1 to investigate if there was any statistically significant difference across modalities. First, we tested the data with Mauchly's test of sphericity and saw that the sphericity assumption was not violated. Results showed that there was indeed a statistically significant difference in the mean reaction times across modalities ($F(4, 15.071) = 15.243, p < 0.0005$). Post-hoc pairwise tests using Bonferroni correction were run; in the following we present statistically significant ($p < 0.05$) results. The strong vibrotactile modality was faster than the weak one by 24ms ($p = 0.002$), than the low volume beep by 68ms ($p = 0.011$), and than the visual modality by 62ms ($p = 0.001$). The weak vibrotactile category was itself faster than the visual one by 38ms

($p = 0.036$). No other statistically significant differences were found. On Figure 3 we show the reaction times of all subjects grouped together on each modality.

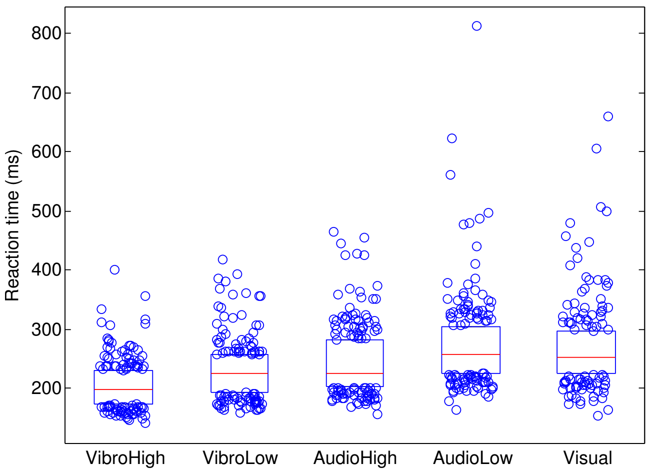

Figure 3: Plot of all users' trials (in ms), showing the median, 25th and 75th percentile, and data-points below and above such percentiles.

4.2 Standard deviation

As can be observed at a glance in Figures 2 and 3, the data distribution seems to change across modalities. Having performed tests on the mean reaction times, we were also interested in studying how much the data varied across trials in each modality. In Table 2, we report the sample standard deviation observed for each of the subjects for each modality.

We can observe that again, the smallest data variations can be observed for most subjects on the strong vibrotactile modality, while the data is more spread across the visual trials. The means suggest that the modalities play a role in the distribution of the samples, with strong vibrotactile modality being the less disperse, followed by the weak vibrations, the loud audio, the low volume audio, and finally the visual stimuli. However, given the small number of subjects in the test, no statistically significant conclusions ($p < 0.05$) could be drawn from the available data.

	VibrHigh	VibrLow	AudiHigh	AudiLow	Visual
A	**16.79**	19.88	54.27	150	63.46
B	**8.65**	20.32	21.20	19.69	16.64
C	**15.73**	24.93	22.85	46.52	63.06
D	**21.20**	26.04	40.29	59.80	77.38
E	**37.09**	54.94	46.66	48.87	60.41
F	26.61	49.42	31.49	**22.04**	36.12
G	48.70	**44.36**	56.13	58.46	55.68
H	**41.70**	53.54	63.23	52.88	109.42
$\bar{x}$	**27.06**	36.68	42.02	57.35	60.27

Table 2: Sample standard deviation (normalized by N-1) by subject for each modality, in milliseconds. Best and worst are shown in bold blue and underlined red respectively for each subject. Users A to D had previous experience with haptic interfaces. The mean of these values by modality is shown for reference, note that it is *not* the standard deviation of the combined data-points.

4.3 Qualitative analysis

We now analyze the answers recollected in the questionnaire. The statements to which the participants had to give their agreement or disagreement were: "Modality X was useful to produce low reaction times", and "I liked receiving feedback through modality X". The results are summarized in Figure 4.

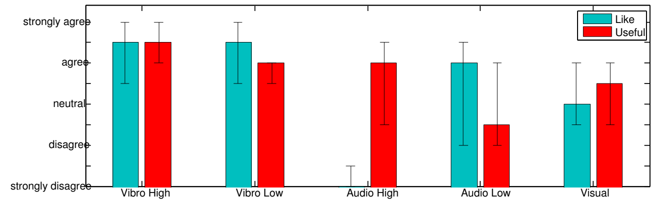

Figure 4: Summary of answers to qualitative survey. Evaluation of perceived usefulness and likeliness are shown with the median, and the 25th and 75th percentiles on the whiskers.

On the overall, the vibratory modalities were the most liked by the subjects, and were also perceived as the most useful for a fast reaction time. The loud auditory feedback was a very particular one, being highly disliked by all participants, but still found to be efficient for the task. An explanation to this is found in the comments of the participants, detailed further ahead. The low intensity auditive feedback suffered the contrary effect, in which it was found rather comfortable, but not so useful. Finally, the visual modality stood rather neutral both in terms of likeability and usefulness.

On the blank space left for comments and remarks, several observations were found to be specific to each modality. One of the most recurrent remarks expressed by the subjects was that the high volume feedback mode was felt as highly inappropriate. The volume being quite loud, it surprised the participants, and some described being scared the first few times. They also expressed being annoyed by the loudness of the beep. Even though people thought that it did elicit fast reaction times, they felt their movements were almost involuntary, that they had no control over their reaction. In a surgical scenario, such kind of feedback would therefore be totally unacceptable. The low volume beep was perceived as more comfortable, but inefficient. It was easy to be distracted, and no sense of urgency was conveyed by it. It became difficult to stay alert with it.

Both vibration strengths were judged similarly. Subjects globally enjoyed it, and described it as feeling quite natural. One subject said he felt he had entered some sort of area when the tool vibrated, and one (subject F) said it felt unnatural. The most recurrent remark was that it was more difficult to get distracted with vibrations, and retracting the tool required less concentration, and felt instinctive. One subject reported he didn't feel much difference between the two vibration intensities.

Most participants commented that the visual modality required more concentration from their part, and that it was easy to get distracted with it. Instead of being driven to react spontaneously, one had to take the decision of retracting the tool. Subject F reported that it felt more natural than the other modalities. This is discussed below.

Interestingly enough, one person was convinced that she would be faster to react to the visual stimuli, both before, and after the experiment. This person also expressed that the vibratory modality felt inefficient. This person was subject F from Table 1 and 2, whom had the fastest reaction times with the strong vibratory modality, and the second slowest with the visual feedback, much contradictory to her belief.

During the experiment, we realized that by offering no feedback to the subjects about their performance, they quickly got tired of the 25 trials, and their effort seemed to diminish, both as trials went on, and as blocks succeeded each other.

5 Conclusions and future work

In this paper, we devised an experiment to measure the reaction times to a haptic task using auditory, visual, and vibrotactile modalities. Eight subjects participated in the study. Our results show that, contrary to existing literature, the haptic channel can elicit faster reaction times than the auditory one, with statistical significance for the strong modality (except when confronted with the loud beep that we deemed unsuitable). Moreover, the standard deviation was lower on the vibrating modalities. Answers to a post-experiment survey showed a general acceptance to using vibrations to indicate contact interaction, being the most natural solution compared to the other ones presented. In accordance with previous results, a stronger intensity of stimuli proved to lower reaction times.

We've seen the advantages of using the same channel both for manipulation and feedback. A likely explanation to the observed results is that with vibrotactile feedback, the stimulus had the same anatomical properties as those of the moving hand. The sensory stimulation and motor action paths spatially coinciding could be the cause of the observed faster reactions [10].

As was suggested by our results, but could not be confirmed due to the low number of participants, people with experience with haptic devices seem to perform better with the vibrotactile modality. Since we hope to exploit these results in medical teleoperation scenarios, we plan to exploit our partnership with medical partners to have surgeons take part in our experiments. More realistic and complete experiments will be designed for medical use.

Another extension to this work is to use combined stimuli, that is, using a combination of several modalities. This is likely to further diminish reaction times, as shown in [8]. More people will be recruited for the study to increase the significance of results. Furthermore, we plan on having one or more break times between blocks. Adding feedback to the subjects about their performance, will also have a significant effect to keep them motivated and trying to outdo themselves.

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