Experimental Evaluation of Vibrotactile Training Mappings for Dual-Joystick Directional Guidance

Lorenzo Scalera[1(✉)], Stefano Seriani[2], Paolo Gallina[2], Massimiliano Di Luca[3], and Alessandro Gasparetto[1]

[1] Polytechnic Department of Engineering and Architecture, University of Udine, Udine, Italy
scalera.lorenzo@spes.uniud.it, alessandro.gasparetto@uniud.it
[2] Department of Engineering and Architecture, University of Trieste, Trieste, Italy
{sseriani,pgallina}@units.it
[3] School of Psychology, University of Birmingham, Birmingham, UK
m.diluca@bham.ac.uk

Abstract. Two joystick-based teleoperation is a common method for controlling a remote machine or a robot. Their use could be counter-intuitive and could require a heavy mental workload. The goal of this paper is to investigate whether vibrotactile prompts could be used to trigger dual-joystick responses quickly and intuitively, so to possibly employ them for training. In particular, we investigate the effects of: (1) stimuli delivered either on the palm or on the back of the hand, (2) with attractive and repulsive mappings, (3) with single and sequential stimuli. We find that 38 participants responded quicker and more accurately when stimuli were delivered on the back of the hand, preferred to move towards the vibration. Sequential stimuli led to intermediate responses in terms of speed and accuracy.

1 Introduction

Teleoperation is a renown method for remotely controlling robots in difficult or extreme conditions that could either endanger the operator or that could not be physically possible for the operator. Since the half of the 20th century, when the first master-slave manipulator was built by Goertz, teleoperation has proved to be invaluable in several different field of application. In particular, the capability of operating at a distance covers cases which could be dangerous or impossible for humans. These are, for example, radioactive environments [21], space missions [3], planetary explorations [20] and disaster areas [4,32]. Furthermore, teleoperation is applied when motion scaling, dexterity and enhanced visualization lead to better results compared to direct manual operation: above all in robot-assisted surgery [7].

The capability of manipulating objects remotely is always achieved thanks to a human-machine interface, which, in the majority of cases, relies on joysticks,

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especially in heavy and industrial applications. Joysticks are reliable, ergonomic, cost-affordable and, to certain extensions, intuitive to be controlled. In fact, in a large number of applications, each joystick degree of freedom (DoF) is mapped to each joint position or velocity of the slave manipulator. Therefore, a heavy mental workload is needed to calculate the inverse kinematics from the DoFs of the slave robot to the DoFs of the joystick [18,25,28,29]. Due to the counter-intuitive and mentally heavy mapping process, subjects operating remote systems by means of joysticks require long training in order to make the telemanipulation system transparent to them. In recent years, several training simulators, especially in the field of excavators and cranes [23,26], have been designed to shorten the learning period of unskilled operators. The training is usually performed with trial-and-errors sessions where an instructor verbally guides the user. At present, vibrotactile stimuli have not been used for training in dual-joystick directional guidance.

The aim of this paper is to investigate effective methods for training subjects in the guidance of two handled joysticks, using vibrotactile prompts. Starting from the results obtained in previously published works [28,29], our motivation to continue the investigation was given by the introduction of the sequential stimulation, already applied in the wrist rotational guidance [16,19]. In particular, we investigate the effects of: (1) stimuli delivered either on the palm or on the back of the hand, (2) with attractive and repulsive prompts, (3) with single and sequential stimuli.

The paper is organised as follows: in Sect. 2 a background is provided for a number of related works, in Sect. 3 a detailed exposition of materials and methods is reported and in Sect. 4 the experimental results are presented. Finally, Sect. 5 gives the conclusions of this work.

2 Background

In the recent years, vibrotactile stimuli have been applied for directional guidance to improve motor learning and to reduce mental workload [2,30]. Applications of vibrotactile displays can be found in sports: soccer, skating and cycling [34], dancing [8], boat rowing [27], snowboarding [31] and karate [5]. A vibrotactile feedback system has been adopted also in the field of music to teach violin bowing [33]. Moreover, vibrotactile guidance has been studied and applied in the field of rehabilitation, especially for stroke [9] and Parkinson's disease patients [17] as well in gait retraining [1]. Vibrotactile displays have also been implemented to enhance navigation and orientation in both real [35] and virtual environments [15,22].

In order to provide an instructional prompt, different stimulation mappings have been studied: attractive/repulsive (pull/push), in which a single vibration is meant either to pull the body toward the signal or to push it away, and "follow me" [19], which consists in a sequence of stimuli that directs the user toward a direction. Attractive and repulsive instructional cues have been compared in the study of torso balance performance [12], in anterior-posterior trunk movements [13] and in wrist guidance [10,16]. On the other hand, a "follow me" mapping has been applied to give a feeling of rotational signal and to guide the user wrist and forearm in 2D space [6,14,16,19].

To the best of Authors' knowledge, no studies on the effects of single and sequential stimuli for dual-joystick directional guidance have been performed until now. Results of this work could, in the future, lead to the development of a practical training protocol for operators involved in joystick-based telemanipulation.

3 Materials and Methods

3.1 Participants

Data were collected from a total of 38 healthy participants (aged 20–45, ten females). They were recruited at the University of Trieste and their academic level was mixed, from undergraduate to associate professor. Before starting the tests, all participants have been subjected to the Handedness Questionnaire [24], which permits the calculation of the Laterality Index (LI); thirty-six of them result to be mainly right-handed, the other two left-handed. All participants were volunteers and signed an informed consent form before the experiment, which was approved by the University of Trieste Ethics Committee.

3.2 Experimental Set-Up

The experiments have been performed using two 2-DoFs joysticks and two gloves, reported in Fig. 1. Each joystick is equipped with 4 vibrating motors along the cardinal directions, whereas each glove with 5 actuators of the same type located in a cross configuration when the user grasps the joystick. These electric actuators, by Precision Microdrives, operate at 3 V and have a diameter equal to 10 mm and a thickness of 3 mm. They have a typical rise time of 92 ms, a stop time of 116 ms and operate at a frequency of 200 Hz, drawing less than 90 mA and providing a vibe force with an amplitude of almost 1 g. The joysticks, by Speedlink, have been modified by substituting the original handle

(a) (b)

Fig. 1. Experimental set-up: joysticks (a) and gloves (b).

with one in teflon, which presents a rubber ring thanks to which the vibrations are not transmitted to the whole stick during the tests. Inside each joystick, two potentiometers detect the motion of the stick in the four directions.

During the tests, the activation of vibrating motors is controlled by a myRio-1900, a portable data acquisition device by National Instruments that is also used to log the data recorded by the potentiometers at a sampling rate of 1 kHz. For this purpose, an ad-hoc real-time software has been developed in LabView™.

Fig. 2. A subject performing the experimental test using the two 2 DoFs joysticks.

3.3 Vibrotactile Training Mappings

With respect to the results obtained in previous works [28,29], where only single stimuli have been applied to test dual-joystick directional responses, the main overall aim of this case study is to investigate whether a sequential stimulation could lead to more accurate responses with respect to a single prompt. For this purpose, six different vibrotactile training mappings have been completed by the 38 subjects involved in the experiments:

- two tests stimulating the palm of the hand from the actuators placed on joysticks, with attractive (move the joystick toward the vibration) and repulsive (move the joystick in the opposite direction with respect to the vibration felt) single 200 ms vibrotactile stimuli (respectively called *Attractive* and *Repulsive Joystick*);
- two tests stimulating the back of the hand from the vibrating motors placed on gloves, with attractive and repulsive single 200 ms vibrotactile stimuli (*Attractive* and *Repulsive Glove*);
- two tests stimulating the back of the hand with a sequence of three vibrotactile prompts that induce the motion along the direction indicated by the saltatory pattern. One condition is composed of three stimuli of 200 ms each separated by 20 ms (*Slow Follow me*), the other one is comprised of three stimuli of 150 ms one right after the other (*Fast Follow me*).

In Fig. 2 a subject performing the experimental test using the two 2 DoFs joystick is shown, whereas in Fig. 3 examples of vibrotactile training mapping are

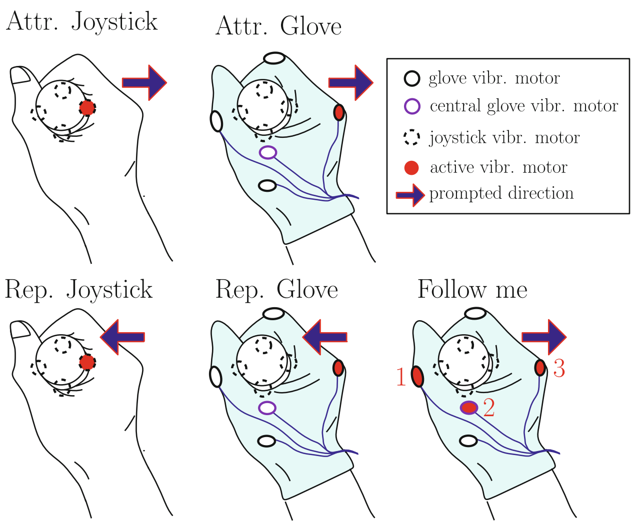


Fig. 3. Examples of vibrotactile training mappings: the red dots indicate the vibrations whereas the arrows the prompted directions. (Color figure online)

reported for the different tests; the Follow me mapping is the same in both Fast and Slow modalities. Each test consists of 16 stimuli delivered in random order, two for each joystick DoF (Forward, Backward, Rightward and Leftward). In particular, the attractive prompts are intended to induce the motion of the joystick in the direction of the vibration prompt, whereas the repulsive mode induces the motion in the opposite direction to the one from which the vibration is delivered. Moreover, a sequential stimulus induces the motion in the direction provided by the saltatory pattern. The 16 prompts are delivered one at a time for each hand every 3000 ms, lasting a total of 48 s for each test. The different tests are completed by participants in random order, so as to avoid the effects of a possible progressive learning.

The experimental protocol was the following: each subject was instructed to handle the joysticks with both hands and to listen which test will be provided. Then, each participant was asked to move the joystick related to the prompted hand in the direction indicated by the stimuli as soon as it was felt. After the motion, the joystick had to be brought back in its central position. No training sessions have been performed before the experiments and the vibrotactile stimuli were the only feedback that the subject received. This experiment could be seen as a particular case of the One-Interval, Two-Alternatives, Forced-Choice decision model (1I-2AFC) [11], in which eight stimulus alternatives are presented on each trial instead of two (1I-8AFC). Indeed, each subject expects one of eight possible stimulations (four for each hand) and has to choose only one response direction within the time interval.

3.4 Performance Metrics

Data logged during the experiments were elaborated and analysed in Matlab™ in order to extract the information about accuracy and reaction times performed by participants during the experiment. Accuracy is computed as the percentage of correct responses for each of the six tests. Reaction times are calculated as the time elapsed between the beginning of the stimulation and the time at which one of the two joysticks potentiometers reached the 75% of its range. This particular threshold was determined with pilot tests as it could trigger the response before the end of the joystick workspace, but it also prevented the system to record small unintentional motions. In Attractive mappings, the response is considered right if the potentiometer that reached the threshold is in the direction of the vibration, whereas in Repulsive conditions in the opposite way. Finally, in Follow me test, the potentiometer that is taken into account is the one related to the direction of the third stimulus out of three. To better visualize how reaction times are computed, an Attractive, a Repulsive, a Fast and a Slow Follow me prompt are depicted in Fig. 4. The joystick position is ranged between 1 and −1.

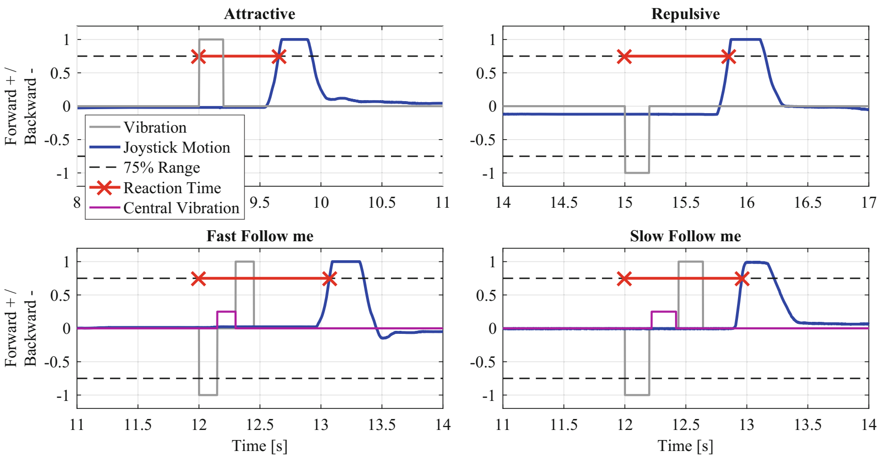


Fig. 4. Computation of reaction times in the different tests. The y-axis for the vibrations is only qualitative: we have assigned a value equal to 1 for the attractive prompt, to −1 for the repulsive one and to 0.25 for the central vibration.

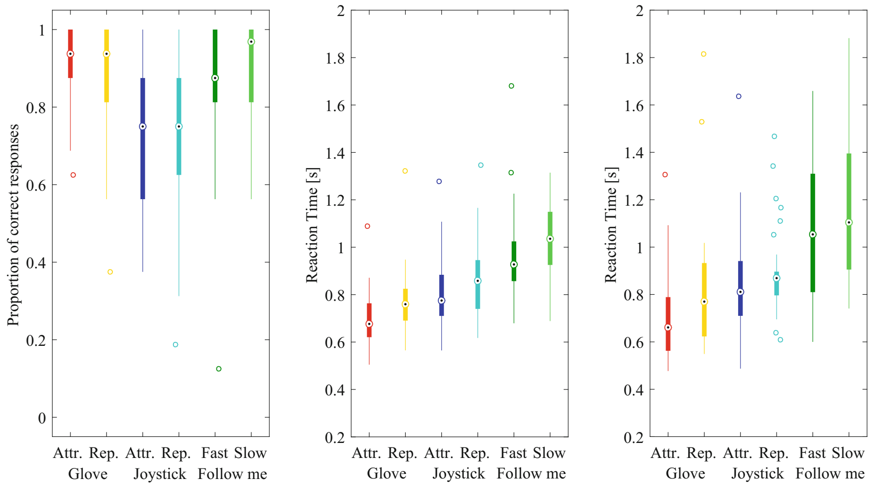
4 Experimental Results

4.1 Accuracy

Figure 5(a) reports the box-plot representation of the proportional number of correct responses, whereas in Table 1 the percentage values are reported as median and interquartile range. Results for a Kolmogorov-Smirnov test for normality indicated that correct responses are not normally distributed ($p < 0.001$ for all the six conditions). A non-parametric Friedman test was conducted to test differences between each condition leading to a Chi-square of $\chi^2(5, 185) = 59.3$, which was statistically significant $p < 0.001$. Furthermore, in order to test differences between every couple of conditions a Bonferroni corrected Wilcoxon matched-pairs signed-ranks test has been applied. Results are reported in Table 2, where significant differences ($p < 0.05$) have been highlighted. Participants responded more frequently in the correct direction with both Glove and Follow me conditions with respect to the Joystick ones. No coherent differences in the number of correct responses have been obtained due to the attractive/repulsive task demand as well as due to the fast/slow mapping.

4.2 Reaction Times

The statistical distribution of reaction times does not deviate significantly from a normal distribution (K.-S. test for the six conditions: Attr. Glove $p = 0.822$, Rep. Glove $p = 0.664$, Attr. Joystick $p = 0.534$, Rep. Joystick $p = 0.847$, Fast Follow me $p = 0.313$, Slow Follow me $p = 0.666$). Figures 5(b) and (c) report the box-plot representation of reaction times for right and wrong responses respectively in the six conditions, whereas in Table 1 mean and standard deviation values are reported in milliseconds. The repeated measures one-way ANOVA between reaction times of the different conditions resulted statistically



(a) Proportional number of correct responses. (b) Reaction time of right responses. (c) Reaction time of wrong responses.

Fig. 5. Experimental results: box-plot representation. The central mark indicates the median, the bottom and top of each box represent the first and third quartiles, the whiskers extend to the most extreme data points not considered outliers (the empty circles).

Table 1. Accuracy [%] and reaction times [ms] of right and wrong responses.

Test		Accuracy		Right responses		Wrong responses	
		Median	Int. Range	Mean	St. Dev.	Mean	St. Dev.
Glove	Attractive	93.8	12.5	692	111	707	201
	Repulsive	93.8	18.8	773	136	822	295
Joystick	Attractive	75.0	31.3	803	148	848	217
	Repulsive	75.0	25.0	862	153	895	183
Follow me	Fast	87.5	18.8	959	184	1099	357
	Slow	96.9	18.8	1028	162	1181	351

Table 2. Comparison between accuracy results for each couple of conditions: Bonferroni corrected p-values of Wilcoxon matched-pairs signed rank-test (significance at $p < 0.05$).

		Glove		Joystick		Follow me	
		Attr.	Rep.	Attr.	Rep.	Fast	Slow
Glove	Attr.		> 0.99	< 0.001	< 0.001	> 0.99	> 0.99
	Rep.			0.0020	< 0.001	> 0.99	> 0.99
Joystick	Attr.				> 0.99	0.0061	< 0.001
	Rep.					0.0051	< 0.001
Follow me	Fast						> 0.99
	Slow						

significant $F(5, 227) = 59.9$, $p < 0.001$, $\eta_p = 61.8$. A series of Bonferroni corrected paired-sample t-tests has been applied on the right responses reaction times for each couple of conditions (Table 3). From the table it can be seen that participants responded faster in the glove condition rather then in the joystick one. Furthermore, in the Glove condition, faster responses were given with attractive modality rather than with repulsive one. In the Follow me condition, reaction times are higher than in both Glove and Joystick mappings but no significant differences have been found between Fast and Slow conditions.

4.3 Relation Between Accuracy and Reaction Times

In order to analyse the relationship between accuracy and reaction times, a linear mixed-effects analysis has been performed for the different conditions. We have adopted the following model: $y \sim x_1 + x_2 + (z_{11}|g_1)$, where the dependent variable y is the proportion of correct responses, the fixed effects x_1 and x_2 are the conditions and the reaction times, whereas z_{11} and g_1 represents the random effects covariance parameters and the grouping variables, respectively. We have obtained a value of the Log-Likelihood test equal to 95.625.

Table 3. Comparison between reaction times for each couple of conditions: Bonferroni corrected paired-sample t-test (significance at $p < 0.05$).

			Glove		Joystick		Follow me	
			Attr.	Rep.	Attr.	Rep.	Fast	Slow
Glove	Attr.	t		-6.4239	-5.8862	-10.1079	-9.5810	-15.5401
		p		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Rep.	t			-1.5598	-5.9210	-6.4843	-12.4896
		p			> 0.99	< 0.001	< 0.001	< 0.001
Joystick	Attr.	t				-2.4924	-5.8414	-8.3457
		p				0.2594	< 0.001	< 0.001
	Rep.	t					-3.4845	-8.2684
		p					0.0193	< 0.001
Follow me	Fast	t						-2.7501
		p						0.1374
	Slow	t						
		p						

In Fig. 6 the interpolating lines of the predicted responses together with the 95% confidence intervals for the predictions are reported. From the figure it can be seen that, across participants, reaction times increase as the proportion of correct responses decreases. This trend could be due to a higher sensibility of skilled subjects, who respond with fewer errors. By analysing the interpolating lines, differences between Glove and Joystick conditions can be clearly seen. Moreover, the lines associated to the Fast and Slow Follow me condition are higher than both the Joystick and Glove, suggesting that a sequential stimulation led to better performances in terms of proportion of correct responses with respect to a single stimulation, on equal reaction times.

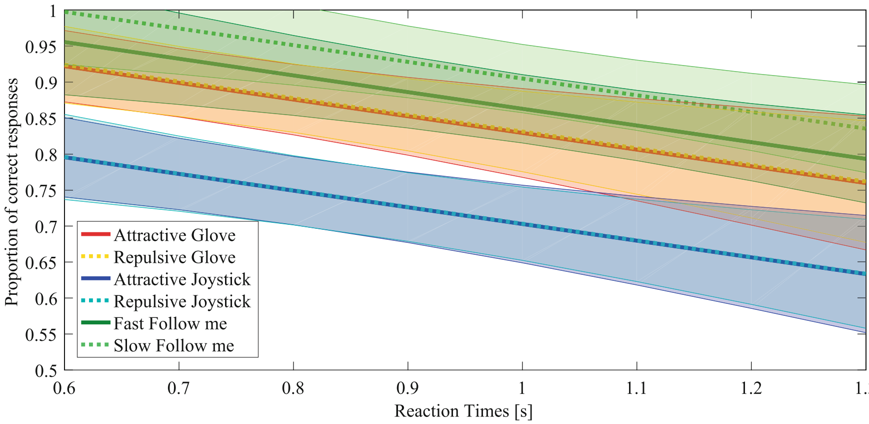


Fig. 6. Linear mixed-effects analysis between accuracy and reaction times for the six different conditions: interpolating lines and 95% confidence intervals.

5 Conclusion

In this work we investigated effective methods for the training of subjects in the guidance of two handled joysticks, using vibrotactile prompts. In particular, we studied the effects of: stimuli delivered either on the palm or on the back of the hand, with attractive and repulsive mappings, and with single and sequential stimuli. Experimental tests, consisting in six different tests each composed by 16 random stimuli, have been performed on 38 healthy subjects and the results have been analysed in terms of accuracy and reaction times. With respect to previously published works [28,29], the experiments here presented confirmed that a stimulation on the back of the hand could lead to better results with respect to a stimulation on the palm and that an attractive mapping gives better performance with respect to a repulsive one. Furthermore, the main overall result of this novel study is given by the differences between single and sequential stimuli (Follow me condition): it has been revealed that a slow saltatory pattern could give better results in terms of proportion of correct responses compared to the other tested conditions. Reaction times could be slower in the Follow me condition due to the longer pattern of stimulation. Furthermore, the sequential presentation of the stimuli could require higher level processing to interpret the vibration pattern as a whole and the subjects could have spread attention on a large area of the hand over the course of stimulation. Finally, a linear mixed-effects analysis suggests that the Follow me condition could lead to better results in terms of proportion of correct responses with respect to both Glove and Joystick ones on equal reaction time.

In the future, we plan to further investigate vibrotactile training mappings for dual-joystick directional guidance. In particular, we will start from the results of this study to better analyse the progressive co-adaptation of subjects responses to vibrotactile prompts in a dual-joystick guidance. Furthermore, because of the relative low-cost of the experimental hardware and of the overall easy practical implementation of the tests, this research holds promise for the development of new practical training protocols for operators involved in telemanipulation tasks in several different fields.

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