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Path Following in Non-Visual Conditions

Alan Del Piccolo, Davide Rocchesso, and Stefano Papetti

Abstract—Path-following tasks have been investigated mostly under visual conditions, that is when subjects are able to see both the path and the tool, or limb, used for navigation. Moreover, only basic path shapes are usually adopted. In the present experiment, participants must rely exclusively on continuous, non-speech and ecological auditory and vibrotactile cues to follow a path on a flat surface. Two different, asymmetric path shapes were tested. Participants navigated by moving their index finger over a surface sensing position and force. Results show that the different non-visual feedback modes did not affect the task's accuracy, yet they affected its speed, with vibrotactile feedback causing the slowest gestures. Also, vibrotactile feedback caused participants to exert more force over the surface. Finally, the shape of the path was relevant to the accuracy, and participants tended to prefer audio over vibrotactile and audio-tactile feedback.

Index Terms—Human computer interaction, User interfaces, Audio user interfaces, Haptic interfaces.

1 Introduction

Path-following tasks, or steering tasks, consist of steering through a tunnel to reach a goal while avoiding to cross the tunnel's boundaries. It is a common activity in everyday interaction with digital devices. To navigate through a multi-level menu, or to type a text over a virtual keyboard such as 'Swype'[1] et similia (that is, to type a text by dragging a pointer from one letter to the next, thus forming a continuous track to form a word) are two examples of path-following tasks. Steering tasks are common in teleoperation as well, such as driving remote vehicles (e.g., military drones, undersea pods etc.) or operating remote devices (e.g., machine-operated surgical tools, maintenance factory tools etc.).

Performance in steering tasks was originally investigated in the context of vehicle driving by Rashevsky [1] and Drury [2]. However, the abstract task of navigating within boundaries can model finger or tool navigation as well, as summarized by Zhai et al. [3]. Those tasks differ from discrete interactions, such as object selection or pointing tasks, in that a continuous action-perception loop is established that guides the user's actions towards a goal. In this sense, steering tasks are far more complex than the pointing task described by Fitts' law [4]: A path can be split in sections, whose crossing represents a target per se. Therefore, a steering task can be seen as the integration of a series of pointing tasks. This intuition underlies the formulation of the steering law by Accot and Zhai [5], which relates the task completion time to the width of the tunnel to be navigated, as foreseen by Drury concerning vehicle control [2]. The impact of path shape, on the other hand, has been investigated in earlier studies by Lacquaniti et al. [6]. According to such studies, the curvature of the path is related to the gesture speed by means of a $^2/_3$ power law. Such law holds true for both constrained and free movements (e.g., scribbles with a pen).

The two studies mentioned above focused on the kinaesthetic aspects of steering tasks: They deduced the intrinsic limitations in performance due to human biomechanics and, similar to Fitts' law, to human information processing. As such, the perceptual aspects that drive the subject's movements were neglected, while paths and goals were meant to be perfectly visible to the participants.

Yet, real life situations often encompass visual impairment, partial occlusion of the interface, and multitasking; all factors that may prevent task completion when relying only on visual feedback. For this reason, the research described here aims at investigating steering tasks under non-visual conditions. Several scenarios can be envisioned that would gain from non-visual feedback in path-following tasks. For instance, navigating through the menus of a car stereo, which nowadays is often provided with a touchscreen interface, would be safer and more effective if it would not draw the driver's visual attention from the road [7]. Another relevant example concerns navigation aids for the visually impaired, who can only rely on audition and touch (see [8], [9] for some reviews on the topic).

This paper presents a path-following experiment in which participants had to steer the index finger of their dominant hand through a non-visual path over a flat surface. The experiment made use of an interface that could provide auditory and vibrotactile cues. Feedback was strictly affirmative, i.e. participants were exposed to continuous feedback (sound or vibration, or both) only when their finger was on-track. Two path shapes were tested, of different complexity. The purpose of the experiment was

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Manuscript received -; revised -.

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to ascertain if users can follow a path under non-visual conditions, and to test the effectiveness of auditory and vibrotactile feedback in facilitating such task. The study extends prior knowledge on the effectiveness of different kinds of sensory feedback in supporting path following [10], [11], with a specific focus on non-visual conditions and direct finger-based interaction.

The paper is organized as follows: Section 2 summarizes related works dealing with steering tasks and multisensory feedback, with special focus on the use of haptic cues. Section 3 describes the experimental design, including the tested hypotheses. Section 4 summarizes the quantitative results of the experiment and the participants' comments. Section 5 discusses such results, while Section 6 wraps up the conclusions drawn from the experiment and introduces future work.

2 Related work

2.1 Steering tasks

Most of the research on path-following tasks refers to the studies by Accot and Zhai [5] and by Lacquaniti et al. [6]. In particular, the former study introduced a *steering law*, which is now a popular tool in human-computer interaction for predicting performance in steering tasks under defined circumstances (e.g., the use of a particular input device). Such law states that the difficulty in executing a steering task depends on the path width $W(s)$, which is integrated along the path c. The resulting formula is as follows:

$$T_c = a + b \int_c \frac{ds}{W(s)} \quad (1)$$

where a and b are empirically determined constants encompassing the effect of the shape of the path, along with other context-dependent conditions. Indeed, the authors recommended to treat different path shapes separately. Lacquaniti et al. [6] introduced a $^2/_3$ *power law* describing the impact of path curvature on performance.

An integration of the two laws has been experimented by Lank and Saund [12], showing that the steering law overcomes the $^2/_3$ power law as the path becomes narrower, while the $^2/_3$ power law prevails when width constraints are looser.

Later studies identified limits to the scope of such formulas: The steering law seemingly applies only to a "middle range" scale of paths, due to the constraints of motor joints shift and human motor precision [13]. In the context of handwriting, the $^2/_3$ power law holds only when strokes follow elliptical or hyperbolic trajectories [14].

Kulikov et al. [15] extended the Accot-Zhai formulation – which makes use of only error-free responses – by introducing the measurement of out-of-path movement, namely the percentage of sample points outside the path boundaries. They also achieved a better prediction of the task execution time by analyzing the effective path width used by participants.

2.2 Multisensory feedback

Disturbing factors can disrupt performance for tasks relying on a single feedback modality such as vision. Moreover, presenting information solely via a single channel can lead to overload. Conversely, robust performance, improved efficiency and naturalness of interaction may be achieved by using additional sensory channels [16].

However, several factors should be taken into consideration that may affect the effectiveness of a multisensory percept, such as the synchronization of stimuli [17], their spatial coincidence [18], [19], and their similarity [20]. In experimental settings the matching of intensity may also be relevant, especially to avoid bias towards one sensory modality. Those factors can be relevant to steering tasks as well: In general, consistency among stimuli of different modalities should be sought with regard to their timing [21] and dynamics [22].

Several steering task experiments investigated the effect of haptic feedback at the user's hand in addition to visual information, for instance vibration [21] or force feedback [23]: Regardless of the employed navigation tool, additional haptic feedback improved performance. Sun et al. [10] went further by adding auditory cues and comparing the performance in every combination of auditory (a repeatedly played system sound), visual (a color change in the path) and tactile (a vibration) feedback in the navigation of a circular path by means of a stylus. The main result was that participants performed most accurately with vibrotactile feedback, although they generally preferred the audio-visual modality. It is worth noticing that the path was always visible, and that the multisensory stimuli were related to error conditions, i.e. additional feedback was given when participants went off-track. Such negative strategy aimed to avoid possible fatigue due the continuous presence of audio or tactile cues, which could also lead to concentration decrease and sensory adaptation (see below). Conversely, [21] and [23] adopted an affirmative feedback strategy, i.e. stimuli were provided as long as participants stayed on the path.

Previous research proved that haptic sensitivity is highly variable among individuals. In particular, vibrotactile detection thresholds are affected by aging and, to some extent, by sex [24]. The aforementioned selective sensory adaptation is a phenomenon connected to vibrotaction: When the user's skin is exposed to vibration at a given frequency, it quickly becomes desensitized to stimulation at such frequency, while sensitivity remains unaltered for stimuli at other frequencies [25].

Experimental setups often implement tool-mediated interaction, for instance by adopting styluses enhanced with vibrotactile [11] or force [26] feedback, which may approximate real-life activities such as writing and drawing [27]. Bare-finger interaction, conversely, provides a richer somatosensory experience, e.g. by sensing skin stretch, and the orientation and vibration of an object at once [28], [29].

The experiment described here is inspired by the work by Sun et al. [10], and represents a follow-up to a former study by some of the present authors [11]. In that experiment, participants were asked to use a vibrotactile-enhanced stylus to run a curvilinear path displayed on a tablet in presence of affirmative feedback. The path was represented as a grating similar to railway ties: Consistently to such appearance, the participants perceived a stuttering sound and/or vibration when on the path. Similar to [10], all com-

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binations of visual, auditory and vibrotactile feedback were randomly submitted to the participants, yet the path was invisible when in non-visual conditions. Results showed that, when the path was visible, complementary auditory or vibratory stimulation had no impact on the performance, namely neither speed nor accuracy measurements were affected. When presented as alternatives, visual feedback greatly outperformed both auditory and vibratory feedback. Interestingly, non-visual feedback modes caused trajectories to be different than in visual mode.

2.3 Novelty and aim of the present work

Within the scope of previous studies on path following with multisensory feedback [3], [10], [11], the present research explores possible variations induced by bare-finger interaction and by multiple and irregular path shapes. Previous studies typically employed tools for the navigation (e.g., a stylus or mouse), which may limit the sensations brought to the user's skin. They also used basic path shapes (e.g., rectilinear or circular), which may cause learning effects. Also, non-visual conditions were rarely tested in the literature. The implementation of all of such variations in the present study intended to model the variables occurring in several real-life applications. Lastly, a first attempt to relate the performance (in terms of the measurements listed in Section 4) to the force exerted by the finger on the surface was made possible by the experimental setup.

Concerning the effectiveness of feedback, in the light of the factors described in Section 2.2, we expected that a combination of audio and tactile feedback generated by synchronized and coherent stimuli would have resulted in better performance.

3 Experimental design

A steering task was tested for different path shapes and non-visual feedback modes. The paths connected the two shorter sides of a rectangular interactive surface. Participants were asked to navigate with the index finger of their dominant hand through the path, left to right, as quickly and accurately as possible, based only on non-visual cues (i.e., the path was not visible). Strictly affirmative continuous feedback was used: When on track, sound and/or vibration were provided, while no feedback was produced when off track. Execution time, finger position over the x and y axes and normal force were recorded.

3.1 Apparatus

Fig. 1: The experimental setup. The Soundplane's surface is covered with a plastic foil, and the participant wears a glove to minimize friction. Black velcro stripes serve as tactile landmarks indicating the starting position.

The experiment made use of the Madrona Labs Soundplane [2], a computer music controller offering a 560×140 mm surface capable of sensing position and normal force of up to ten fingers. These data are sensed by a capacitive layer placed underneath the touch surface. A Clark Synthesis TST239 vibration transducer (shaker) was fixed to the bottom of the Soundplane. The participants' finger position and force were collected through the Soundplane software client, which was interfaced to the experiment's management system developed in Max[3]. Data were sampled every 10 ms.

Feedback was generated interactively, according to finger position, by means of the Sound Design Toolkit software[4] (SDT) – a set of sound synthesis tools simulating the acoustical outcome of basic physical interactions [30] – and the same signal was used for rendering both auditory and vibrotactile cues. Continuous audio signals were synthesized by using the 'rolling' module of the SDT, which simulates the rolling of a round object over a surface[5]. Parameters such as the mass of the object, the grain of the surface, the depth of penetration of the object can be adjusted. The module was devised to simulate an object rolling over an uneven terrain. Due to its ecological nature, the used sound may be categorized as of ambient type. Apart from the steering metaphor that such signal was intended to evoke, its wide frequency spectrum (similar to filtered noise) was meant to decrease the impact of selective adaptation under vibrotactile conditions.

The synthesized signal was sent to two output channels of an RME FireFace 800 audio interface, respectively leading to Beyerdynamic DT-770 Pro headphones and to a power amplifier connected to the shaker. The signal routed to the shaker was first band-pass filtered in the $80-250$ Hz range to maximize the transducer's efficiency while minimizing audible frequencies. Since sound spillage from the shaker was still perceptible, a masking noise signal (pink noise, with a small amount of white noise added for covering high frequencies) was sent to the headphones during the vibrotactile mode only.

The Soundplane surface was covered with a thin, opaque plastic foil (see Figure 1) to make its otherwise tiled surface uniform and reduce finger friction. It had been previously verified that such foil would affect neither the precision in position detection nor the detected force. Velcro stripes were glued at one side of the interface, thus allowing participants – who were blindfolded – to locate the starting position by means of touch. The Soundplane rested over a keyboard stand and rubber foam was interposed between the interface and the support, thus avoiding unwanted resonances due to spurious standing waves, at the same time minimizing vibration propagation through the floor.

3.2 Test conditions

A within-subjects design was used. Six conditions were available as the combinations of three feedback modes and

2. http://madronalabs.com/soundplane/
3. https://cycling74.com/
4. http://soundobject.org/SDT/
5. An audio recording of the signal and screen shots of the Max patches for the experiment can be found at https://doi.org/10.5281/zenodo.1257417

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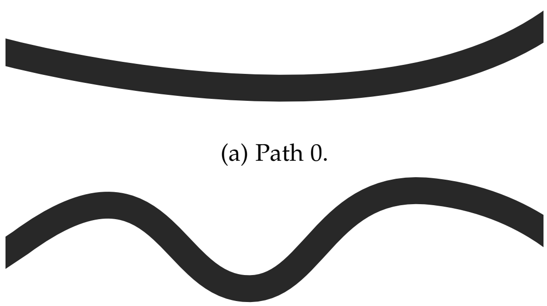
two path shapes. The feedback modes were: audio (A), vibrotactile (T), and audio + vibrotactile (A+T).

The two paths had a constant width of $28\,\mathrm{mm}$, namely twice the average fingertip's contact area proposed in the literature [31]. After a pilot test, such width was chosen to accommodate possible changes due to the varying exerted force and inclination of the wrist, and to limit the overall difficulty of the task.

The paths were labeled 0 and 1: Path 0 (see Figure 2a) featured a curvilinear trajectory that mostly retains the same, mild curvature, while path 1 (see Figure 2b) featured several changes in direction with a pronounced slope. While the paths shared the same left and right boundaries, path 1 was 13.1% longer than path 0 (respectively $672\,\mathrm{mm}$ and $594\,\mathrm{mm}$).

To avoid learning and sensory adaptation effects, the conditions were presented in a guided random order, i.e., in the case of two subsequent occurrences of the same condition, they were manually distanced. Each condition was repeated ten times, for a total of 60 trials, resulting in an average session duration under 60 minutes.



(a) Path 0.

(b) Path 1.

Fig. 2: The two path shapes to be followed.

3.3 Design rationale

After pilot-testing several path shapes with a few subjects, the duration of experimental sessions was limited by reducing the number of paths to two, and by excluding more complex shapes which resulted in excessive execution time and possible arising of frustration. For instance, two of the discarded shapes presented five turning points instead of the one and three points respectively found in path 0 and 1. In an attempt to reduce the possibility of memorization of the paths, shapes that were too similar (e.g., they started with the same orientation, either upwards or downwards) were eliminated as well.

The number of trial repetitions per condition was set to ten to achieve statistical significance in the results, and to enable the identification of possible execution trends.

In agreement with previous studies [11], [21], [23], the task relied on presenting affirmative feedback. Indeed, when exploring a space it feels more natural to look for a path (i.e., for clues signaling its location) rather than the opposite.

In the present experiment, fixed intensity was used for both auditory and vibrotactile cues. The intensity levels were set according to a pilot test phase involving six participants, with the goal of achieving a clear yet comfortable intensity of both feedback modes. Arbitrary reference intensity levels were provided to the pilot testers, who could ask to raise/lower them to achieve a clear perception, thus leading to a progressive refinement of the levels. Moreover, the vibration intensity was measured by means of an accelerometer across the interface's surface. The results ($\mathrm{mean} = 114.851\,\mathrm{dB}$, $\mathrm{SD} = 3.065\,\mathrm{dB}$, $\mathrm{re}\,10^{-6}\,\mathrm{m/s^2}$) show that the vibration was well above the level that is necessary for a clear vibrotactile sensation in the case of active touch [32], [33].

3.4 Procedure

The experiment took place in a quiet room at the Zurich University of the Arts, involving thirty participants: 16 females and 14 males, mean age 28.7 years (female = 27.4, male = 30.1, SD = 9.0). All participants but one were right-handed. Twelve participants declared to possess a trained manual ability, e.g., as musicians, painters or sculptors. Before the experiment, each participant signed a customary consensus form following the rules of the local Ethics committee. Participants were rewarded a voucher valid at the local canteen and cafeterias.

During the briefing phase, the experimenter demonstrated the execution of one trial. Then participants had to wear headphones and a light cotton glove that minimized friction with the plastic foil covering the surface. They were blindfolded, so as to avoid the visual guidance of the Soundplane frame borders, as well as to prevent them to mentally project a path over the surface. Participants were allowed to gain familiarity with the task by freely exploring the surface with one of the paths randomly loaded, while all feedback modes were provided in sequence. They were instructed to consider both speed and accuracy as important to the task, while feeling free to choose their navigation style. The experiment could be performed either sitting on an adjustable piano stool or standing. The level of fatigue and stress was constantly monitored, and mandatory breaks were given every ten minutes.

During the debriefing phase at the end of the experiment, participants had to report about physical and mental fatigue. Then, they were asked to express their preference over the three feedback modes. Lastly, they could express their opinion about the task and the overall experience.

3.5 Hypotheses

The following hypotheses were tested:

1) The average task completion time with non-visual feedback does not follow the Accot-Zhai prediction for steering tasks in visual mode [5];
2) The shape of a path affects task speed and accuracy. Specifically, path 1 yields worse performances than path 0 due to the number and steepness of changes in direction;
3) Since auditory and vibrotactile feedback are synchronous and originate from the same signal, the combined auditory and vibrotactile mode produces a better performance than a single sensory mode [20];

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4) Manual skills, demographic factors, fatigue, and preference over the feedback modality affect the task execution;
5) The exerted force generally shows a coherent behavior, e.g., it is higher for a particular path shape or feedback mode.

4 RESULTS

The three main quantities that were considered during the experiment were task completion time, run distance, and average exerted force (main variables). For the sake of the analysis, times and distances were used to obtain metrics of performance in terms of speed and accuracy (derived variables). In summary, the means of the following variables were considered:

- Task completion time;
- Gesture speed;
- Task completion speed;
- Time-related accuracy;
- Space-related accuracy;
- Exerted force;
- Trend analysis: Task completion speed and space-related accuracy within each trial repetition and along the ten trial repetitions for each condition (considered separately), plus the exerted force along the ten trial repetitions per condition .

The meaning of such variables and the motivation of their choice are explained in the respective sections.

A considerable variability among participants was registered: The coefficient of variation was 0.31 for completion time, 0.23 for distance and 0.46 for exerted force.

By visualizing means, medians and standard deviations for all the main and derived variables, no obvious grouping within the participants could be isolated. A further attempt at grouping was done according to subjective factors such as gender (age could not be used due to little variability), presence of trained manual abilities (e.g., as musicians), and physical or mental fatigue self-reported at the end of the session. Anyhow, non-parametric Mann-Whitney U-tests detected no significant differences in performance among such groups (see the Appendix).

ANOVA tests were performed with path and feedback mode as factors. The hypotheses of normal distribution and sphericity of data were often not fulfilled, thus justifying the application of ϵ-corrections and the adoption of non-parametric tests whenever necessary. Friedman with post-hoc (Conover's F at $\alpha = .05$ for a two-tailed test), and Wilcoxon signed-rank were used as non-parametric tests depending on the number of conditions. For the significant results, η-squared estimates of effect size were computed, together with their confidence intervals (CI).

4.1 Task completion time

The mean time for completing a single task repetition was $41.839\,\text{s}$ ($\text{SD} = 13.092\,\text{s}$). Such time largely exceeds what would have been necessary to complete the task under visual conditions, namely less than five seconds, as informally tested.

The average execution time for path 1 was 39.6% longer than for path 0, and this difference was significant ($F_{1,29} = 94.435,\ p < .005,\ \eta^2 = .197,\ \text{CI} = [.014\ .479]$). Since there was only a 13.1% difference in length, this suggests the presence of other factors affecting performance.

TABLE 1: Average task completion times (in s).

	path 0	**path 1**	*mean*
A	33.072	44.278	38.675
T	40.448	53.920	47.184
A+T	31.240	48.077	39.658
mean	34.920	48.758	41.839

On both paths, feedback mode T required considerably longer times than A and A+T (see Table 1 and Figure 5). Conversely, the differences between feedback modes A and A+T were smaller, albeit statistically significant ($F_{2,58} = 23.363,\ p < .005,\ \eta^2 = .059,\ \text{CI} = [0\ .221]$). The interaction between the two factors was marginally significant ($F_{2,58} = 3.624,\ p = .033$). However, ϵ-corrections on the separate paths (Huynh-Feldt = 0.859 for path 0, Greenhouse-Geisser = 0.659 for path 1, $F_{1,24} = 9.049,\ p < .005$ and $F_{1,19} = 1.789,\ p = .189$ respectively) showed that the feedback mode was significant on path 0 but not on path 1.

4.2 Speed

Two measures of speed were considered: gesture speed and task completion speed. Gesture speed was computed by dividing the total distance run in a single trial by its completion time, or movement time, which is a common measure of performance [15]. Task completion speed was computed by dividing the original path length by the completion time. While gesture speed accurately depicts the space-time performance, the task completion speed considers only the time performance.

4.2.1 *Gesture speed*

Gesture speed was 4% slower on path 1 than on path 0, and such difference was significant ($F_{1,29} = 4.499,\ p = 0.043,\ \eta^2 = .006,\ \text{CI} = [0\ .166]$). T was the slowest feedback mode (8.5% slower than A, and 9.7% slower than A+T), while A and A+T were almost equivalent. Indeed, while the difference between the feedback conditions was significant ($F_{2,58} = 25.788,\ p < .005,\ \eta^2 = .030,\ \text{CI} = [0\ .141]$), post-hoc comparisons after Friedman test showed that A and A+T did not differ significantly, but they were significantly different from T on both path 0 ($\chi^2 = 20.067, p < .005$) and path 1 ($\chi^2 = 12.600, p < .005$).

4.2.2 *Task completion speed*

Analysis of task completion speed confirmed the results related to gesture speed, with even larger differences. Task completion speed on path 1 was 19.9% slower than on path 0, and such difference was significant ($F_{1,29} = 30.977,\ p < .005,\ \eta^2 = .081,\ \text{CI} = [0\ .336]$). Concerning feedback modes, T was 18.5% slower than A and 22.4% slower than A+T on path 0; On path 1, T was 13.0% slower than A and 8.0% slower than A+T. Differences among feedback modes were significant ($F_{2,58} = 41.827,\ p < .005,\ \eta^2 = .044,\ \text{CI} = [0\ .179]$). Post-hoc comparisons after Friedman test showed that differences

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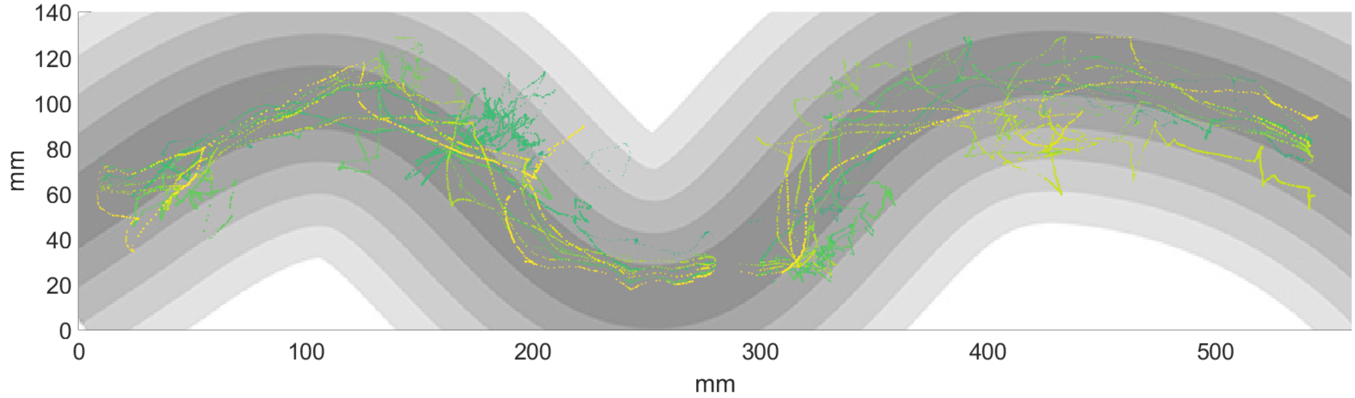

Fig. 3: Tracks performed by a participant on path 1 in audio-tactile mode. Different colors correspond to different repetitions: The color is darker for later repetitions. The shown $14\,\mathrm{mm}$-wide gray stripes enable a quick evaluation of distances. After the second turning point, a 'zig-zag' strategy is apparent.

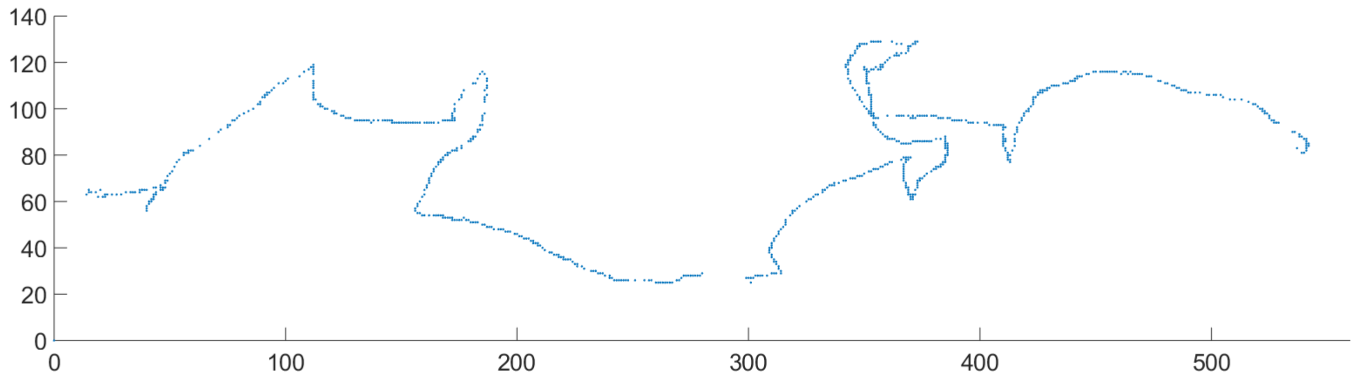

Fig. 4: The recorded position points for a single repetition by a participant.

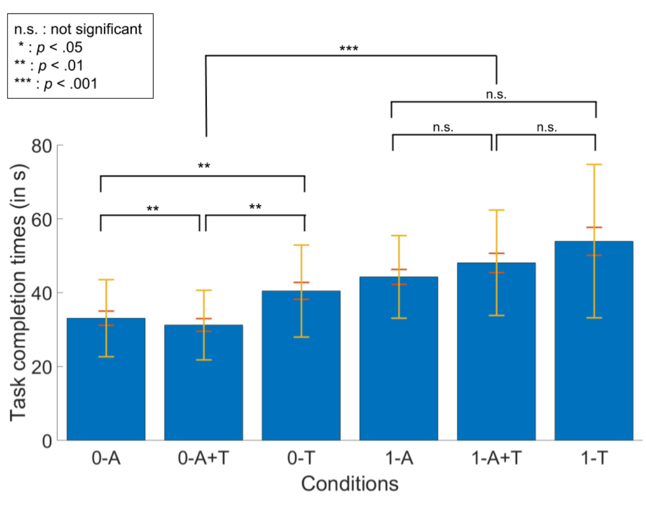

Fig. 5: Average task completion times by test condition with SEM (short whiskers) and SD (long whiskers).

were significant among all feedback modes on path 0 ($\chi^2 = 30.067, p < .005$), while on path 1 the differences were significant only between T and the other two modes ($\chi^2 = 17.267, p < .005$).

4.3 Accuracy

Two measures of accuracy were considered: time-related and space-related accuracy. Time-related accuracy was computed by dividing the total time spent on-track during a trial by the total trial completion time. Such measure was inspired by the Out of Path Movement metric as found in [10], [15], which consists in the percentage of sample points outside the constraint lines. Space-related accuracy is a measure of trajectory error, and was computed as the mean of the Euclidean distances of each sampled position point from the nearest edge of the correct track. The sampling resolution was $1\,\mathrm{mm}$ over the x-axis.

4.3.1 Time-related accuracy

The trials performed on path 0 were 16.6% more accurate than those performed on path 1, and such difference was significant ($F_{1,29} = 47.446,\ p < .005,\ \eta^2 = .233$, CI $=$ $[.023\ .502]$). Conversely, the differences caused by the feedback mode were not significant ($F_{2,58} = .456,\ p = .636$).

By running the Friedman test on the two paths separately, post-hoc comparisons showed that the differences among feedback modes were not significant on path 0 ($\chi^2 = .867, p = .648$), while they were significant when comparing T to A and A+T on path 1 ($\chi^2 = 7.800, p < .05$).

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Overall, time-related accuracy shows an interesting result: Participants spent on average 67.1% of their trial time on-track. Considering a space of $14\,\mathrm{mm}$ around the track – which is comparable to the average diameter of a fingertip [31] – the above value rises from 67.1% to 93.0%. Such result indicates that participants spent most of the time on the correct track or in its immediate vicinity, meaning that the participants responded promptly to the variations in feedback and produced small trajectory errors.

4.3.2 *Space-related accuracy*

The feedback mode had no significant effect on trajectory accuracy $(F_{2,58} = .690,\ p = .506)$. Such result suggests that the participants adopted the same cautious navigation style with all feedback modes. Moreover, this determined a generally small average trajectory error $(3.050\,\mathrm{mm})$.

Path 1 resulted in an error 74.7% larger than path 0, and this result was significant $(F_{1,29} = 19.103,\ p < .005,\ \eta^2 = .138,\ \mathrm{CI} = [0\ .403])$.

4.4 Exerted force

There was a high variability in the forces exerted by the participants $(\mathrm{mean} = 2.218\,\mathrm{N},\ \mathrm{SD} = 1.024\,\mathrm{N})$, but most participants were active in a relatively small sub-range $(\mathrm{SEM} = 0.187\,\mathrm{N})$. Figure 6 displays the distributions of exerted forces per participant, and shows that 25 out of 30 participants were roughly comprised within the range $1{-}3\,\mathrm{N}$, with only a few high-force participants and one light-force participant.

Looking at per-participant distributions, there is no evident relation between the mean of the exerted force and its variability.

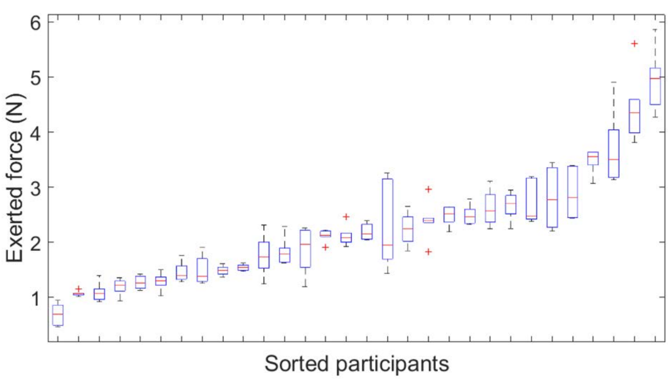

Fig. 6: Box plot of the exerted forces for each participant, ordered by mean value. The central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers indicate the most extreme data points not considered outliers. Outliers are indicated by the '+' symbol.

The path factor was not significant $(F_{1,29} = 0.121,\ p = .730)$. Conversely, the feedback mode significantly affected the exerted force $(F_{2,58} = 22.312,\ p < .005,\ \eta^2 = .032,\ \mathrm{CI} = [0\ .145])$: On average, participants exerted a stronger force when executing the task with vibrotactile feedback than with the other two modalities (see Table 2 and Figure 7).

TABLE 2: Average exerted force (in N).

	path 0	**path 1**	*mean*
A	2.056	2.037	2.046
T	2.459	2.480	2.469
A+T	2.119	2.156	2.137
mean	2.211	2.224	2.218

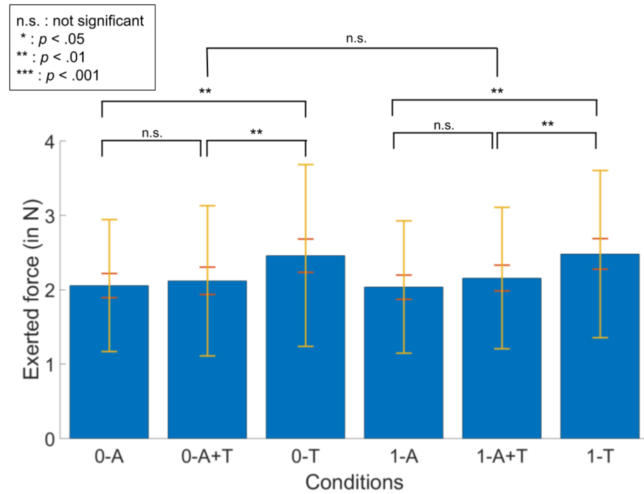

Fig. 7: Average exerted force by test condition with SEM (shorter whiskers) and SD (longer whiskers).

Post-hoc comparisons after Friedman test, run on the two paths separately, showed that the difference was significant only if comparing T with A and A+T on both path 0 $(\chi^2 = 18.067, p < .005)$ and path 1 $(\chi^2 = 17.267, p < .005)$, while there was no significant difference between A and A+T on both paths.

On average, the force exerted by participants when off-track was slightly $(+4.5\%)$ higher than when on-track, and such difference was significant $(F_1 = 28.409,\ p < .005)$. This result is confirmed by a Wilcoxon Signed-Rank test $(z = -4.494,\ p < .001)$.

Lastly, correlations among all variables were computed to highlight possible redundancies in the analysis. No unpredicted correlations were found. In particular, force resulted correlated neither with speed $(r(28) = -.011,\ p = .954$ with gesture speed, $r(28) = -.037,\ p = .846$ with task completion speed) nor trajectory errors $(r(28) = -.016,\ p = .933)$.

4.5 Trend analysis

The participants' performance was investigated to detect possible trends. Trajectory error and task completion speed were considered as measures of performance. Additionally, the exerted force was evaluated.

Trend analysis was computed 1) at repetition level, that is monitoring the evolution along a single trial, and 2) at trial level, that is considering the trend along the 10 repetitions for each test condition.

4.5.1 *Trend at repetition level*

This analysis examines two factors that might affect performance: path length and shape. It was hypothesized that if, after covering the same distance over the two paths,

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performance was comparable, then the path shape would not be relevant. If, otherwise, performance on path 1 was worse than on path 0, then the path shape would be proven a difficulty factor.

Task completion speed and trajectory error were computed on the portions of the repetitions that corresponded to the first $600\,\mathrm{mm}$ of space run by each participant, sliced in twelve $50\,\mathrm{mm}$-long sections. Such distance slightly exceeds the length of path 0, and was run by all of the participants on all trials. Speed was averaged over each section, while errors were cumulated to account for backwards movements: Once a section was crossed completely, the successive trajectory errors were considered in the next section. Average values were computed over all participants and all trials on the six available conditions.

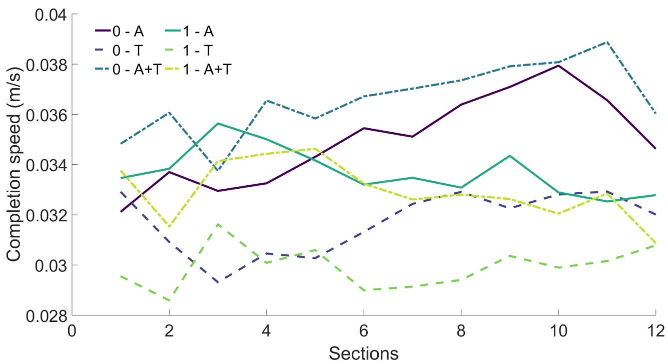

Fig. 8: Completion speed along the first $600\,\mathrm{mm}$ of the paths, according to conditions (A: solid lines, T: dashed lines, A+T: dash-dotted lines).

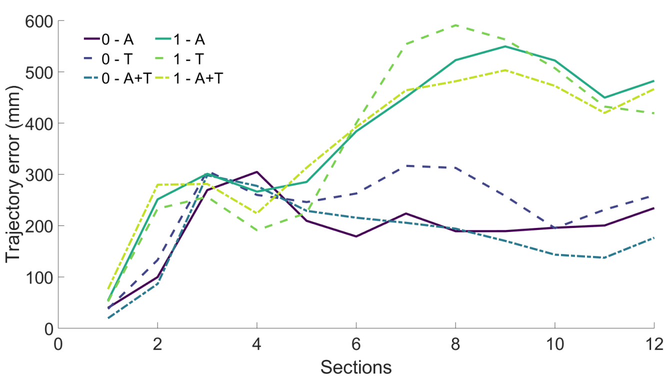

Fig. 9: Cumulative trajectory error along the first $600\,\mathrm{mm}$ of the paths, according to conditions (A: solid lines, T: dashed lines, A+T: dash-dotted lines).

The resulting speeds are displayed in Figure 8 and do not show any particular trend, except for the lower speed of trials using feedback mode T (dashed lines) compared to those using A or A+T on the same path, whose speeds are instead similar, as noticed in Section 4.2. Conversely, Figure 9 shows that trajectory errors are comparable in the first sections, but soon diverge depending on the path: The repetitions on path 0 caused lower trajectory errors compared to those on path 1, as noticed in Section 4.3.

Such visualizations suggest what follows:

1) Trajectory errors are affected by the path shape, which consequently is a difficulty factor for the task;
2) Due to the lack of clear trends in speed, the presence of a linear speed/accuracy trade-off cannot be evaluated.

To further investigate the relationship between path shape and trajectory errors, the magnitude of the estimated curvature of path 1 was superimposed to the average trajectory errors (see Figure 10). The curvature of path 1 seems to modulate the trajectory errors ($r(559) = .597,\ p < .005$).

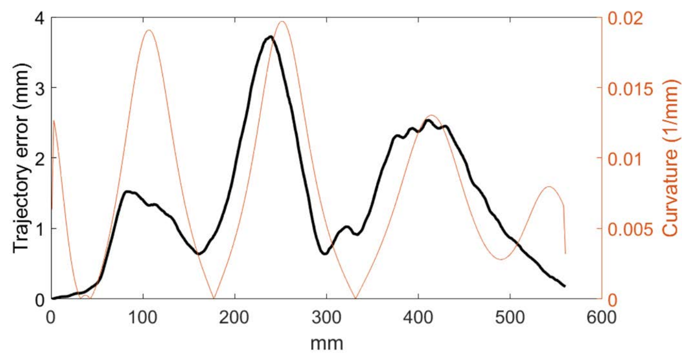

Fig. 10: Average trajectory error (darker line) and absolute value of curvature of path 1 (lighter line).

4.5.2 Trend at trial level

The values of trajectory errors, task completion speeds and exerted forces were averaged across the participants for each of the 6 conditions, thus forming piecewise linear curves formed by 10 points (one per repetition), which are depicted in Figures 11, 12, and 13.

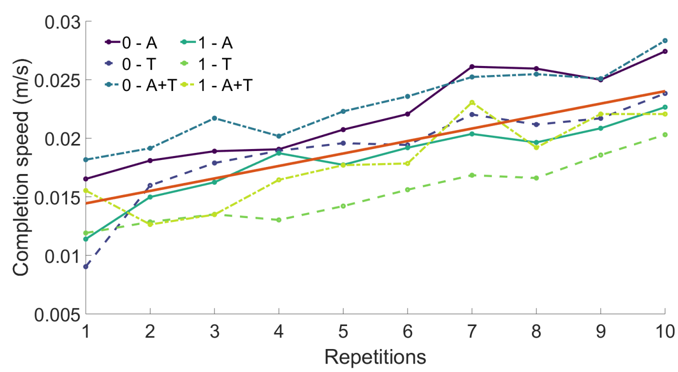

Fig. 11: Completion speed over the 10 repetitions (A: solid lines, T: dashed lines, A+T: dash-dotted lines). Linear regression for the mean values is shown.

Figure 11 shows that the task completion speeds increased almost linearly for all conditions: A significant regression equation was found ($F_{1,9} = 207, p < .005$), with an R^2 of $.963$. In absence of a generalized improvement in performance affecting both speed and accuracy, the presence of learning effects along with repetitions may be excluded. Instead, the increasing trend of speed may be related to a progressive familiarity of the participants with the task.

Figure 12 clearly shows the offset in average trajectory errors between the two paths. A slight increase for path 1

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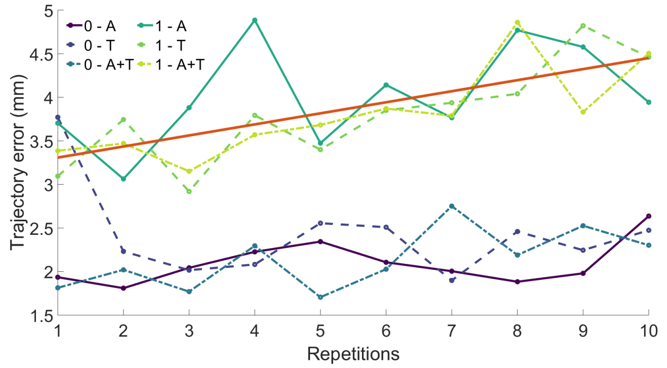

Fig. 12: Average trajectory error over the 10 repetitions (A: solid lines, T: dashed lines, A+T: dash-dotted lines). Linear regression for the mean values on path 1 is shown.

can be seen: A significant regression equation was found ($F_{1,9} = 20.2, p < .05$), with $R^2 = .716$. Conversely, no significant increase was found for path 0 ($F_{1,9} = .627, p = .451$), with $R^2 = .073$. It may be hypothesized that the growing fatigue along with repetitions affected performance in the more difficult path.

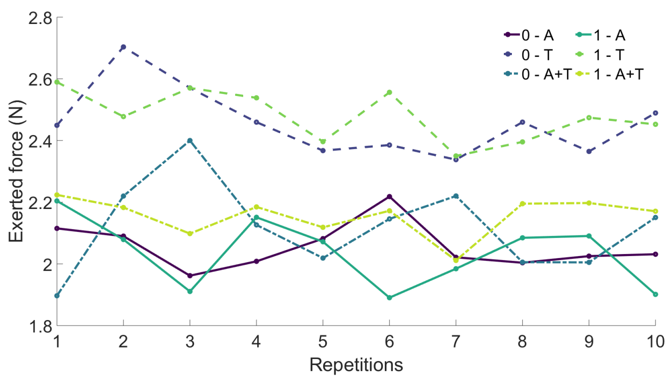

Fig. 13: Exerted force over the 10 repetitions (A: solid lines, T: dashed lines, A+T: dash-dotted lines).

No trend could be identified for force data over the ten repetitions (see Figure 13). However, it is evident how participants used more force in the vibrotactile feedback condition.

4.6 Participants' behavior and debriefing data

Due to the invisibility of the paths, participants generally adopted a cautious navigation style. This was in agreement with a previous study by some of the present authors [11], and regardless of the feedback mode. Even though, in case of lost track, participants were instructed to explore the surface vertically to intercept the correct track again, they rarely adopted this behavior. Instead, they tended to backtrack to the last known correct finger position, and to resume the navigation from that spot. A few participants even went back to the starting position as soon as they could not find the path. Some participants opted for an extremely slow, supposedly error-proof, pace, while others at times adopted a zig-zagging navigation strategy (see Figure 3), which in their intention would have allowed them to find the path more promptly. Actually, the latter strategy did not improve their accuracy significantly, while it did cause considerably longer task completion times.

The participants were kept unaware of the number of different paths. Probably due to the random presentation of the conditions, such number was generally considered to be between four and six, while two participants believed that the path had changed at each trial.

Sixteen participants reported physical strain, namely a slight stiffness in the wrist and/or shoulder or, more frequently, the finger.

When asked about their preference for feedback modes, 22 participants said to have preferred A, 3 preferred T, 3 A+T, and 2 had no preference.

Six participants reported a progressive desensitization towards the end of each trial with vibrotactile feedback, while ten participants reported difficulties in perceiving vibratory cues.

To determine if the difficulties in sensing the vibration actually impacted performance, the twenty participants who did not report any of such difficulties were compared with the ten who did. The resulting differences are not statistically significant ($p > .05$ on Student's t-test on all of the conditions), and are reported in Table 3. It can be noted that completion times were essentially equivalent in the two groups, however the participants who reported difficulties in perceiving vibrotactile feedback exerted more force than the others in all conditions ($+15.9\%$). Interestingly, on path 1 they performed the task with considerably smaller trajectory errors (-16.8%).

TABLE 3: Participants with and without reported vibrotactile perception issues.

	With (N = 10)	Without (N = 20)	*% diff.*
Completion time (s)			
mean	41.587	41.965	-0.9%
A	39.078	38.473	+1.6%
T	47.842	46.855	+2.1%
A+T	37.841	40.566	-6.7%
path 0	35.855	34.452	+4.1%
path 1	47.319	49.476	-4.4%
Trajectory error (mm)			
mean	2.817	3.166	-11.0%
A	2.923	3.126	-6.5%
T	2.872	3.237	-11.3%
A+T	2.657	3.135	-15.3%
path 0	2.214	2.224	-0.4%
path 1	3.420	4.109	-16.8%
Exerted force (N)			
mean	2.441	2.106	+15.9%
A	2.234	1.952	+14.5%
T	2.730	2.339	+16.7%
A+T	2.359	2.027	+16.4%
path 0	2.444	2.095	+16.7%
path 1	2.438	2.117	+15.1%

5 Discussion

Overall, compared to the feedback conditions including auditory cues, relying on vibratory cues only resulted in slower task execution, while accuracy was not significantly affected. This suggests that perceptual issues such as inter-individual variability and sensory adaptation should be

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taken more into consideration when using vibrotactile cues for guidance. The path shape factor was relevant to the accuracy, specifically the amount of turning points and radius of curvature.

No significant correlation was found between exerted force and performance or experimental conditions. Nevertheless, participants exerted more force under vibrotactile feedback conditions, suggesting that they were instinctively aiming at maximizing tactile sensation – a phenomenon that was verified in [32]. Consistently with this interpretation, a slight increase in force was also recorded when participants were off-track and searching for the correct path.

Two issues affecting the collected experimental data had to be taken into account during the analysis, namely the noisiness of trajectories and the generally high variability of data among the participants. Noisiness was likely due mainly to the use of non-visual feedback, which resulted in participants adopting an exploratory behavior. Overall, noise and discontinuities in trajectories invalidated the estimate of navigation progress, and rendered instant velocity data meaningless. As a consequence, comparisons with predictions of the steering law [5] or the $^2/_3$ power law [6] were not viable.

In contrast with the findings of [10], accuracy was only partially affected by the considered feedback modalities. As a point of contact, in both studies subjective evaluation highlighted a general preference for auditory feedback over vibrotactile feedback.

Using audio and vibrotactile feedback simultaneously did not improve performance: the results were comparable to those of audio feedback alone. Indeed, 5 participants declared that, in the combined audio-tactile condition, they had focused on the audio feedback alone. Moreover, while 8 participants found the combined condition helpful, 5 found it confusing. This disagrees with the general improvements reported in [16] when using multimodal feedback, and suggests that information redundancy over multiple sensory channels – in this case concurrent auditory and tactile cues generated by the same signal – is not necessarily integrated constructively [34]. However, the type of task might affect the effectiveness of multimodal feedback in reducing mental workload [35].

In the mentioned related experiment by some of the present authors [11] it was concluded that the presence of visual cues practically nullifies any contributions of multimodal feedback: When visual cues were available, performances were very similar regardless of the presence of additional feedback modes.

Based on the overall superior performance reported in [11] for visual feedback as compared to non-visual conditions, and on the generally faster performance measured in our study when auditory cues were present, a hierarchy may be hypothesized for steering task scenarios, in which visual information prevails over audio, which in turn overcomes tactile cues. This may recommend the inclusion of auditory feedback in an interaction loop whenever possible. Moreover, the results of the mentioned experiments highlighted the effectiveness of ecological sounds in contrast to the simplified tones (e.g., beeps, sine waves) usually employed in experimental settings. The general preference of audio for sensory feedback in non-visual path-following tasks indicates that special care should be put in designing sounds that are informative, responsive, and compatible with the contextual soundscape. Sounds are often shared with others and contribute to the quality of the environment, and an ecological attitude is recommended when designing sonic interfaces. On the other hand, touch is an intimate kind of feedback, and this quality may ultimately make it preferable in many applications.

Although vibration feedback was designed to prevent selective adaptation, desensitization took place to some extent, possibly due to the relatively high intensity and continuous character of the vibratory cues. Despite the fact that vibration intensity had been globally calibrated and validated as explained in Section 3.3, since several participants reported either desensitization or difficulties in sensing vibration, it is possible that preliminary individual level adjustments would result in better acceptance of vibratory feedback, and even improved performance.

Confirming what previously reported in [11], the present experiment showed that the use of strictly affirmative vibrotactile cues as an effective guiding means in steering tasks is not trivial, even when targeting young participants, that is excluding the natural progressive deterioration in sensitivity and neural elaboration of stimuli that is associated with aging [24]. However, to motivate the need for further research on the use of haptic guidance in steering tasks, the following may be considered:

- In practical scenarios visual and auditory impairments are common, due to occlusion, noisy environments or concurrent tasks;
- The paths proposed in this experiment were much longer and more complex than what is typically required by human-machine interfaces (e.g., menu navigation usually implies movements that are short, discrete, and rectilinear);
- In the present experiment, task accuracy was similar in all the considered (non-visual) feedback conditions.

Finally, it is worth considering a few practical issues found in the experimental setup and data collection, namely:

- The intensity of vibration was upper-bound by the unavoidable drawback of related acoustic spillage originating from the shaker. Even though masking noise was used to counteract this, its loudness (i.e., its efficacy) was limited by comfort requirements;
- The finger is a rather inaccurate pointing tool for touch interfaces: its softness causes touch position to be sensed anywhere within the fingertip's contact area. This is an aspect of the so-called "fat finger problem" [36]. Indeed, such effect may have been amplified by the scale of the movements required in the experiment, which involved the finger and various joints (wrist, elbow and shoulder);
- Force measurement showed varying accuracy across the surface: A characterization of force sensing was performed by means of test weights placed across the surface, showing a mean coefficient of variation of 0.183. The measured data were fitted resulting in

a calibration curve, which was then used in the analysis phase to compensate for varying force sensing accuracy across the surface.

6 Conclusions

The main result of the present experiment is that the use of different non-visual feedback modalities in a steering task do not affect accuracy differently, yet they differently affect speed. In particular, vibrotactile feedback causes slower gestures than auditory feedback. Moreover, when in presence of auditory cues, vibrotactile feedback becomes irrelevant to the performance. Combining these results with subjective reports – which highlighted a marked preference for audio feedback – it can be argued that vibrotactile cues suffer from selective sensory adaptation [25], which in turn induces desensitization.

The shape of the path is relevant to the task accuracy: Pronounced curvatures seemingly increase trajectory errors. Although noise and discontinuities in trajectories prevented comparisons with the predictions of the steering law [5] and the $^2/_3$ power law [6], such models seem not to hold for steering tasks under non-visual conditions. The cause resides in the exploratory nature of the gestures when a path is invisible. Conversely, when the path is visually available, exploration and anticipation are done by eye.

The force exerted by the participants with their finger over the explored surface seems not to be related to performance. However, force was considerably higher under vibrotactile conditions, and slightly higher when participants were off the track, indicating their effort to maximize tactile information [32].

Further research in this direction may gain from testing alternative cutaneous feedback cues (e.g., friction modulation [37], [38]), aiming at decreasing the impact of the encountered perceptual issues. Also, the experiment may be repeated using a negative feedback strategy or adopting feedback differentiation, that is stimuli at several intensity levels or with various frequency content (e.g., sine waves), which may highlight how signal-related features may impact on performance.

Appendix

Statistical analysis

Mann-Whitney U-tests for subjective factors

Legend:

- "Gender": gender of the participant;
- "Touch": presence of trained touch-related abilities (e.g. as painter, sculptor etc.);
- "Physical'/'Mental": reported physical or mental strain at the end of the task.

TABLE 4: Mann-Whitney: Task completion speed

Factor	z value	*p value*
Gender	-0.956	0.339
Touch	-1.312	0.189
Physical	-1.039	0.298
Mental	-0.748	0.454

TABLE 5: Mann-Whitney: Trajectory error

Factor	z value	*p value*
Gender	-0.665	0.506
Touch	-1.312	0,189
Physical	-1.455	0.146
Mental	-0.836	0.403

TABLE 6: Mann-Whitney: Exerted force

Factor	z value	*p value*
Gender	-1.580	0.114
Touch	-0.042	0.966
Physical	-1.039	0.299
Mental	-0.792	0.428

Acknowledgments

The work described in this paper is part of project SkAT-VG, which received financial support from the Future and Emerging Technologies (FET) programme within the Seventh Framework Programme for Research of the European Commission under FET-Open grant number 618067. The authors wish to thank Germán Toro-Pérez (Institute for Computer Music and Sound Technology, Zurich University of the Arts) for providing additional funding, as well as Hanna Järveläinen, Sébastien Schiesser and Martin Fröhlich for technical support.

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