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Recommended Paper

Effects of Multimodal Error Feedback on Human Performance in Steering Tasks

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This paper investigates the relationship between "error feedback" (when tracking or trajectory errors are made) and user performance in steering tasks. We conducted experiments to examine feedback presented as visual, auditory and tactile modalities, both individually and in combinations. The results indicate that feedback significantly affects the accuracy of steering tasks but not the movement time. The results also show that users perform most accurately with tactile feedback. This paper contributes to the basic understanding of "error feedback" and how it impacts steering tasks, and offers insights and implications for the future design of multimodal feedback mechanisms for steering tasks.

1. Introduction

Graphical user interfaces (GUI) have long been used to communicate between humans and computers through the visual channel, i.e., "what you see is what you get". As interaction tasks become more complex and intense, visual feedback as the sole channel is showing its limitations. It is necessary to study user performance under different modalities both individually and in combinations. Several classes of fundamental tasks exist, such as pointing, crossing [1)], and steering. Burke, et al. [2)] mentioned that the effect of sensory channel feedback was likely to vary across different tasks. Many researchers [3)–6)] have compared the effects of different modalities of feedback on user performance in pointing tasks and crossing tasks. However, little work has been done on steering tasks. The term "steering task" stands for a set of human actions in HCI, for example, navigation in hierarchical menus, drawing, writing, etc. With pen-based interaction becoming increasingly popular, the steering task has also become a common task in daily human-computer interaction, and is thus worthy of further investigation.

Another reason we chose the steering task is we are interested in feedback that continuously alerts users to errors and prompts them to make corrections on the fly; discrete tasks such as pointing and crossing are not as suitable. Trajectory-based tasks (also known as steering tasks) [7)], such as navigating through a tunnel or tracing a picture, require continuous adjustment along the trajectory and are thereby appropriate for our purpose. In standard steering tasks such as those performed with a stylus, the user traces a path through a visual tunnel, and is required to keep the stylus within the tunnel at all times. Therefore, we conducted a controlled experiment to study the effects of multimodal feedback on human performance in steering tasks.

Although two papers [8),9)] present studies on steering tasks, they only used "affirmative" feedback for guidance and affirmation. Affirmative feedback means feedback is given only when the cursor is moved inside the tunnel or area in which the user expects it to move. Affirmative feedback only reminds the user that the cursor (pen-tip) is in the correct area or direction. It has been shown to be beneficial especially for the older and/or visually impaired population as it confirms that they are on the right track. For example, when a pedestrian light turns green, a sound starts and changes over time. The blind can be guided to cross the road with the help of voice prompts. They can also understand how long it will be before the light changes color, according to the rhythm or tempo of the sound. Affirmative feedback is also used for guiding the user through the ideal motion in steering tasks in GUI environments. As examples, there are computer-aided design, surgical training, computer gaming and other simulated environments.

However, continuous affirmative multimodal feedbacks may have considerable drawbacks for people with normal sensory capabilities. Firstly, most people do not like to be disturbed when they are performing normally. Imagine how disturbing or annoying it would be if you are driving on a flat road and nonstop vibrations or constant extraneous sounds, above the normal traffic noise is used

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to, inform you that you are in the right lane. Secondly, when presented over a long period, continuous tactile or auditory feedback may result in fatigue or even low responsiveness from the user. As a result, the user may not be able to promptly detect feedback that indicates that an abnormal situation requires attention. Thirdly, for motor tasks, the presence of tactile feedback may interfere with the normal motion of the hand and pen and compromise performance. For example, continuous vibrations may affect the stability of a stylus causing lower trajectory accuracy.

Due to several drawbacks with affirmative feedback, we study the effects of feedback only when the cursor is moved out of a tunnel or a specified (required) area in a steering task. In this paper, we define this kind of feedback as "error" feedback. In GUI environments, "error" means the cursor is moved outside of the tunnel or the area which the system expects. "Error" feedback can alert the user promptly when she/he makes an "error" in order to make a correction promptly, i.e., it may decrease the error rate. We observed that, in contrast to the affirmative feedback studies mentioned above, there has been relatively little research on the effects of various types of error feedback.

There are many examples of steering tasks in GUI environments, not only hierarchical menu selection, but also computer-aided design, writing, drawing, surgical training, computer gaming and other simulated environments and so on. Here we give some scenarios to show the merits of error feedback.

Menu selection is a traditional steering task in GUI environments. In this scenario, users want to select an item. When the menu button in menu bars is pressed, the pull-down menu appears and users can navigate through this menu and sub-menus. If the cursor is out of the area of pull-down menu and sub-menus, error feedback is triggered to alert users and prompt them to make corrections. Error feedback can not stop until the cursor returns to the inside of tunnel or the user clicks the left button to end the task.

In a cardiac intervention therapy scenario, a guide wire is pushed through a blood vessel from the leg to the heart. Haptic guidance is often used to simulate the different forces of vessels. Based on the results of our paper, vibrations should also be added to prompt the user. The distance between the top of the guide wire and the vessel's walls can be detected. If the top of the wire is too close to the vessel walls, error feedback will be triggered.

In calligraphy practice, children are taught how to write beautiful characters. Tracing paper with standard sharp letters is used; this is a kind of visual feedback. Traditionally, after tracing the characters, children will be given comments by teachers, indicating where they should be more careful when writing particular characters. This post hoc feedback can prove inefficient sometimes. In order to get a better effect, we can apply real-time tactile feedback on the pen, when the pen tip is outside of the printed trajectory (area). In addition, we may create a "pre-warning" buffer area which prompts users before a mistake is made. Given this potential, it is important to have a detailed understanding of different error feedback modalities to inform future software designers.

In driving simulation scenarios, if a car moves too close to the edge of the road, error feedback is used to prompt drivers. This kind of feedback is already used to good effect to warn drivers who unintentionally drift between lanes.

In this paper, we review related work and then an experiment is reported which investigates the effects of multimodal feedback on human performance in steering tasks. Several parameters are measured to evaluate accuracy and speed. We conclude with a discussion of our results, implications for feedback design and directions for future work.

2. Related Work

A high demand for visual attention is imposed on computer users. This not only causes fatigue, but it also prohibits the performance of secondary activities. The increasing requirement to present a large amount of information to the user also challenges the capacity and effectiveness of visual modality. It becomes necessary to expand the interaction bandwidth by introducing alternative or additional sensory modalities, and many devices [10)–16)] have been developed to enable this. For example, Luk, et al. [11)] created a handheld display platform to provide tactile feedback for users. EarPod [16)] enables eyes-free menu selection with the help of reactive auditory feedback, and its performance is comparable to traditional visual techniques in terms of both speed and accuracy. Poupyrev, et al. [14),15)] applied tactile feedback not only to desktop computing but also to mobile devices. Liao, et al. [10)] developed a pen with multimodal pen-top feedback, which effectively helped users detect errors early and provided support for interface discovery.

Akamatsu, et al.[3] used a multi-modal mouse to confirm that the cursor was on a target during pointing tasks. Although the overall response times did not change, final positioning time with tactile feedback improved significantly. In another paper, Akamatsu, et al.[4] concluded that tactile feedback could reduce selection times. Tactile and force feedback improved performance when the interface contained small targets. Jacko, et al.[5],[6] conducted a series of experiments to examine the effects of multimodal feedback on the performance of senior adults whose visual health varies a lot. Multimodal feedback was triggered when a file icon was correctly positioned. In drag-and-drop tasks, non-visual and multimodal feedback demonstrated significant performance gains over sole visual feedback for both Age-Related Muscular Degeneration (AMD) and normally sighted senior users.

Five different task activities were analyzed in a meta-analysis. Burke, et al.[2] compared the effects of uni-modal and bi-modal feedback on user performance. The effects of workload, and the number of tasks were considered. Error rate, performance score, and reaction time were analyzed. The results showed that bi-modal feedback improved performance and reduced reaction times, however it had little effect on error rates.

To investigate the effect of force feedback in steering tasks, Dennerlein, et al.[9] used a mouse that employed a force to pull the cursor to the center of the tunnel. Results showed that force feedback improved movement times by 52%. A combined steering and targeting task of navigating through a tunnel and then clicking on a target also showed that force feedback can reduce times to complete such a task. In order to investigate the interaction between the tactile and visual modalities, Campbell and Zhai[8] used an IBM Trackpoint mounted with an actuator and put virtual bumps in the tunnel. When the cursor entered or left a bump, a tactile pulse was triggered to guide the user through the tunnel. They concluded that user performance was enhanced by tactile feedback and that it is important to ensure that the visual feedback corresponds to the tactile feedback.

In summary, our literature review indicates that little work has been done on the study of the relationship between the modalities of error feedback and user performance in steering tasks. This study offers an important basic understanding in this field of HCI literature.

3. Pilot Study

We conducted a pilot study with eight participants to determine suitable feedback parameters for the experiment. A pen with an attached motor was used in the experiment. We wanted to determine the input voltage that would provide maximum comfort and effectiveness for users. Different input voltages (2.0 V to 3.6 V) supplied to the motor, which mapped to different amplitudes of vibration, were chosen as input parameters. During the pilot study no participants complained that the vibration was significantly disturbing. After summarizing the experiment results and subjective evaluations, most of the participants preferred tactile feedback supplied at 3 V. The vibration motor can reach full speed within 60 milliseconds. Compared with the movement time of task, this time delay of motor is not significant and can be ignored. Audio feedback is also discussed. Firstly, we chose the Windows XP Error sound found in the Windows XP Operating System. However, some participants complained that the sound was too loud. We changed it to the sound of Windows XP Notify. Visual feedback was in the form of color change. The results gave us the required data to choose appropriate parameter values for our experiment.

4. Experiment

4.1 Apparatus

The experiment was conducted on an IBM ThinkPad X41 Tablet PC, running Windows XP and using a stylus as the input device. The screen size was 12.1-inches with a resolution of 1,024 × 768 pixels. The experimental software was developed with Java. In order to supply tactile feedback, a vibration motor (2.0 V to 3.6 V, SE-4F-A3A1-X0, manufactured by Shicoh Engineering Co., Ltd. Japan) was mounted on the stylus. The size of the motor was 4 × 10.9 mm. The rated speed was 8,400 rpm. We used adhesive tape to attach the motor to the tail of the stylus, 2 cm from the end. The stylus was about 13 cm long in total. This product was a brushless and geared motor supplied with 3.0 Vdc as

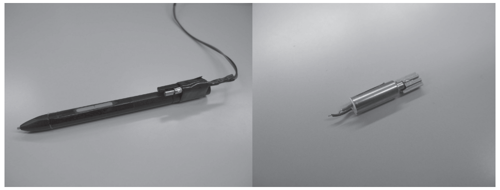

Fig. 1 Stylus with an attached motor and the motor.

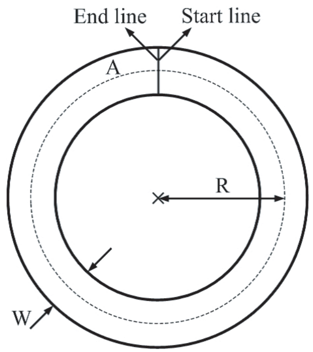

Fig. 2 Experimental task.

determined in the pilot study. The electrical signal was supplied by an AD/DA converter card (CSI-360116, manufactured by Interface Co., Ltd. in Japan) and was controlled by the Tablet PC. The motorized pen [17] is shown in **Fig. 1**.

4.2 Participants

Twelve right-handed university students (10 males, 2 females, aged from 21 to 32 years) participated in the experiment. All participants had normal or corrected to normal vision and reported that they each had normal hearing. Eleven of the participants had previous experience using a stylus. All of them had medium-to expert level computer experience.

4.3 Task & Procedure

There are two kinds of traditional steering task. In general, straight steering represents linear movement and circular steering represents non-linear movement. Our experiment uses a steering task through a circular tunnel (see **Fig. 2**). The circular steering task is more complex than the linear movement task. For a circular tunnel, the movement amplitude A is equal to the circle's circumference $2\pi R$, where R is the radius. According to the steering law [7] developed by Accot and Zhai, the index of difficulty for steering through a circular tunnel is $ID = 2\pi R/W$. The task completion time MT can then be expressed in the formula: $MT = a + b\ ID$, where a and b are empirically determined constants.

If the stylus moved out of the boundaries of the tunnel during the task, feedback is presented to the user to indicate an error. We used three modalities for error feedback: visual, auditory, and tactile. Visual feedback turned the steered trajectory (trail) to red when an error occurred. Auditory feedback was a notifying sound that played repeatedly. Tactile feedback was supplied by the vibration of the motor. In all three cases, the error feedback continued until the stylus returned to the tunnel. We also included a baseline condition where there is no feedback.

The direction of the circular steering task was always clockwise. At the beginning of each trial, the tunnel was displayed in the center of the screen. Once the stylus crossed the start line, the color of the drawn trajectory turned from green to blue as a signal that the task had begun. The user then steered the stylus through the circular tunnel. The trial ended once the cursor crossed the end line. Then the next trial was presented.

Before the experiment, the task was explained to the participants and they were asked to perform some warm-up trials in each operational bias until they were familiar with both the steering task and the different kinds of feedback and felt that they could begin the experiments. Participants could adjust the volume of the auditory feedback themselves. The participants were seated and instructed to perform the tasks as fast and as accurately as possible. Participants were allowed to have a rest between trials.

We measured the movement time MT (time taken to move from the start line to the end line). To measure the accuracy of the trajectory produced, we calculated its lateral standard deviation SD (standard deviation of the distances between trajectory points and the center of the circular tunnel) and out of path movement OPM (percentage of trajectory points outside the tunnel boundary). For both SD and OPM, higher values indicate lower accuracies. In this paper, we use the OPM to measure the out of path movement. This metric was previously used by Kulikov, et al.[18]. During the period of one trial in this experiment, we recorded the coordinates of sample points per 10 milliseconds. The number of sample points and the number of times the pen-tip moved out of the tunnel between these sample points were collected. The value of OPM was calculated by these two parameters. For example, if 100 points were sampled and 14 of those points were outside the Constraint lines, then OPM would be 14.

4.4 Design

We used a fully crossed within-subject factorial design. The independent variables were: *tunnel width* W (12, 20, 30, 40, 50, 60 pixels), *tunnel amplitude* (300, 600, and 800 pixels), and *feedback type* (no feedback (NONE), auditory (A), tactile (T), visual (V), auditory + visual (AV), visual + tactile (VT), auditory + tactile (AT), auditory + visual + tactile (AVT)). Each participant performed the experiment using all 8 feedback types in sequence. The presentation orders of the feedback types were counterbalanced across participants.

All participants conducted the experiment in sitting postures. Within each *feedback type*, the participant performed all combinations of *tunnel widths* and *tunnel amplitudes* 3 times each and presented in random order.

In summary, the experiment consisted of:

12 participants ×
8 feedback types ×
6 tunnel widths ×
3 trials ×
3 tunnel amplitudes =
5,184 times in total.

The experiment took approximately 30 minutes per participant. After the experiment, participants completed a questionnaire to rate their subjective preferences for the feedback types.

4.5 Hypotheses

H1. Feedback type will affect movement time, especially when the task is difficult.

H2. Feedback type will affect accuracy.

H3. The single tactile feedback outperforms other individual feedback modalities.

5. Results

Repeated measures of analyses of variance were used to assess the effects of multimodal error feedback (eight kinds) on movement time, standard deviation and out of path movement.

5.1 Movement Time (MT)

An ANOVA test showed that there was no significant effect ($F_{7,77} = 0.575$, $p = 0.774$) from *feedback type* on the movement time MT. The index of difficulty ($ID = 2\pi R/W$) for the tasks had a significant main effect ($F_{14,154} = 91.666$, $p < 0.001$), with higher ID corresponding to longer MT. There was no significant interaction effect from *feedback* × ID ($F_{98,1078} = 1.118$, $p = 0.212$). The overall means for MT were 1,567, 1,657, 1,600, 1,601, 1,588, 1,582, 1,595, and 1,619 ms for the NONE, A, T, V, AV, VT, AT, and AVT feedback (see **Fig. 3**). The movement time with NONE feedback was the shortest among these feedback types.

The regression analysis on MT and ID indicated that they followed a linear relationship with each *feedback type*, as predicted by the steering law ($R^2 > 0.97$ in all cases).

5.2 Standard Deviation (SD)

The overall mean of SD is 4.62 pixels (see **Fig. 4**). The main effect of feedback type was statistically significant ($F_{7,77} = 2.148$, $p = 0.048$) on SD. There was also a significant effect ($F_{14,154} = 110.05$, $p < 0.001$) of ID on SD. There was no significant interaction effect from *feedback type* × ID

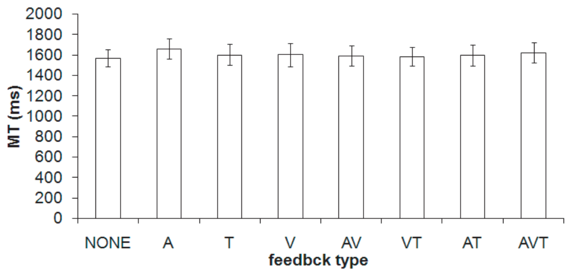

Fig. 3 Mean MT by different feedback types (with standard error bars).

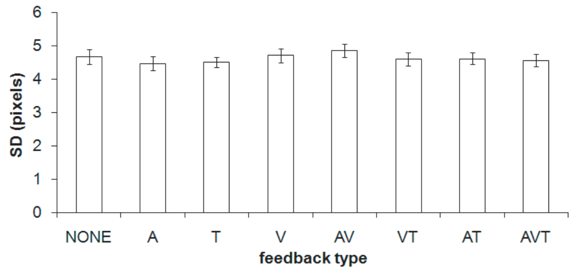

Fig. 4 Mean SD with different feedback types.

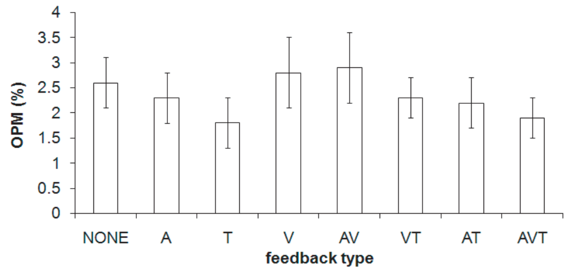

Fig. 5 Mean OPM with different feedback types.

($F_{98,1078} = 0.876,\ p = 0.796$). Pair-wise comparison tests showed that the participants produced significantly lower SD ($p < 0.05$) with the A feedback and T feedback compared with the other feedback types and significantly higher SD ($p < 0.05$) with AV and V compared with the other feedback types. There was no significant difference in SD between A and T, or between AV and V. The baseline performance with NONE feedback was between these two extremes, however this difference was not statistically significant.

5.3 Out of Path Movement (OPM)

The overall mean of OPM was 2.35% (see **Fig. 5**). The main effect of feedback type was statistically significant ($F_{7,77} = 3.458,\ p = 0.003$) on OPM. There was also a significant effect ($F_{14,154} = 13.942,\ p < 0.001$) of ID on OPM. There was no significant interaction from $feedback\ type \times ID$ ($F_{98,1078} = 1.034,\ p = 0.395$). Pair-wise comparison tests showed that the participants produced significantly lower OPM ($p < 0.05$) with the AVT feedback and T feedback compared with the other feedback types and significantly higher OPM ($p < 0.05$) with NONE, V, AV and VT compared with the other feedback types. There was no significant difference in OPM between AVT and T, or between NONE, V, AV and VT.

Summarizing the experimental data, we showed that different modalities of feedback significantly affected human performance in steering tasks in terms of accuracy but not in terms of completion time. From the results of OPM and SD, we concluded that users performed the task most accurately with tactile (T) feedback, and least accurately with AV (auditory + visual) and V (visual) feedback.

5.4 Subjective Evaluation

According to the results of the questionnaire, the majority of participants (8/12) preferred AV feedback to indicate an error condition. The reason is that "hearing the sound feels comfortable and gives a clear warning. Compared to sole auditory feedback, the additional visual modality makes cursor movement more accurate". Some participants (7/12) disliked tactile feedback because "vibration from the motor disturbed the movement of the pen-tip", but, one participant highly praised the direct and active response delivered by tactile feedback. Some participants (7/12) disliked AT and AVT feedback, because they felt "the combination of auditory feedback and tactile feedback confused them".

5.5 Steering Law Analysis

Each of the feedback modalities fit the steering model with correlations greater than 0.97. As mentioned before, there was no significant effect from feedback type on the movement time MT. The indexes of performance ($IP = 1/b$) for different feedback types are similar.

6. Discussion

In the experiment, the analysis of SD and OPM shows that $feedback\ type$ affects accuracy significantly. The simple tactile error feedback (T), outperforms the other error feedback types and combinations in steering tasks. In contrast to H1, no significant effect of $feedback\ type$ on MT was found. However, Forlines and Balakrishnan [19] found that $feedback\ type$ did have a significant effect on completion time in their study on pointing and crossing tasks. Although Aka-

Table 1 Steering law models with different feedback.

Feedback	Steering law model	R^2
NONE	MT = 64.7 ID + 87.5	0.98
A	MT = 64.7 ID + 177	0.99
T	MT = 67.9 ID + 47.7	0.98
V	MT = 67.3 ID + 61.8	0.98
AV	MT = 68.3 ID + 26.2	0.97
VT	MT = 67.8 ID + 32.1	0.98
AT	MT = 64 ID + 130.3	0.99
AVT	MT = 68.8 ID + 45.6	0.98

matsu, et al.[4] concluded the effect is more pronounced for small targets for the tactile condition, we cannot draw the same conclusion from the results of our experiment. These observations could be explained by their different usage of feedback. They used feedback as an affirmation, e.g., notifying the user when the tip of the cursor was on a target. Therefore the feedback was always in effect in every trial. By contrast, in our study we used feedback as an alarm to indicate errors. There are two possibilities in extreme cases. Firstly, if the tunnel is wide enough, no error occurs during the trial and no feedback was presented. Secondly, if the tunnel is too narrow, error activated feedback is very similar to "affirming" feedback. In summary, feedback type was irrelevant to the overall temporal performance in most cases.

On the other hand, feedback directly contributed to the reduction of errors in the task and therefore, feedback type has a significant effect on performance accuracy, and thus H2 is confirmed. Comprehensive analysis of OPM and SD confirms that the simple tactile feedback (T) outperforms or is similar to all other feedback types (both single and combined), thus confirming hypothesis H3. This phenomenon may also be explained from the following point. We used a direct input device in this study. Visual feedback is more or less unavailable when the target is covered by the hand or stylus (this particularly relates to the sitting posture and writing posture). Compared with audio feedback, tactile feedback is a real-time interactive modality. It transforms information through skin displacement both in space and time, while audio feedback is transmitted though the air and has some delay.

An interesting observation is the apparent disparity between the actual performance of the users and the subjective preferences of the users. Despite the fact that the majority of participants felt that tactile feedback disturbed the movement of the pen-tip, they all achieved the highest level of accuracy with tactile feedback. This could indicate that participants wanted to avoid triggering the vibration so that they performed the task more carefully, i.e., this probably explains why tactile feedback was so effective. Visual feedback does not impact the user forcefully and is the easiest to ignore. This may be the reason the lowest levels of accuracy are produced by the AV and V feedbacks. This trade-off between performance and comfort may guide us to choose the most suitable form of feedback in different scenarios. In addition, the different human response times for different sensory channels (with tactile being the fastest[20], while visual and auditory having more considerable delay) may have also contributed to the performance difference.

Considering these points, we suggest that error feedback mechanisms, as investigated in this paper, might be the most suitable applications for tactile feedback, where the feedback is presented intermittently to indicate abnormal situations rather than continuously to indicate normal situations. The results of our experiment confirmed the suitability of the tactile modality for this purpose, especially in the context of a steering task. Accot and Zhai[7),21] gave some examples of steering tasks. For example, drawing, writing, and steering in 3D space. Error feedback can be widely used to improve the performance of these tasks, or used as a training tool such as to teach handwriting.

Based on the result of our experiments, the simple tactile error feedback (T) outperformed the other feedbacks. The GUI is designed for visual feedback but audio feedback and tactile feedback are not considered. Campbell, et al.[8] also mentioned that today's GUIs may be not suitable for tactile feedback. A new user interface should be proposed to replace the ones we use now.

7. Conclusion and Future Work

Different tasks, workloads and feedback types in different forms may affect user performance. In this work, we conducted an experiment to investigate the effects of different modalities on error feedback in steering tasks. The results show that users perform most accurately with tactile error feedback. Our work provides insights and implications for the future design of multimodal error feedback mechanisms.

There are several different kinds of tactile feedback [22], such as force, pressure, texture, puncture, thermal, softness, wetness, vibrotactile sensations and so on. In the future, we will compare the different kinds of tactile feedback to evaluate the effects of the forms and strengths of auditory and tactile feedback, as well as expanding our investigation to other fundamental interaction tasks. Perception response times increase significantly with age so we will also investigate the age effect which is an important factor affecting performance with multimodal feedback.

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Editor's Recommendation

This paper investigates the relationship between various feedbacks and user performance in steering task, a fundamental task in GUI environments. The contribution of this paper is the proposed methods and the empirical data, which are highly useful to the field. (Shinichi Honiden FIT2009 Program Chair)

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