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Speed-accuracy tradeoff of fingertip force control with visual/audio/haptic feedback

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ABSTRACT

Fitts' law has been widely used in the human-computer interaction (HCI) field, especially for Graphical User Interface (GUI) design. However, most studies on Fitts' law were performed with motion control tasks under visual feedback while only a few endeavor to measure human force control behavior. How quickly humans can exert a constant force with a required accuracy and whether this speed-accuracy tradeoff obeys Fitts' law still needs to be explored. In this paper, human capabilities for controlling absolute magnitudes of fingertip force with discrete visual/audio/haptic feedback cues were observed and compared. Eighteen participants applied constant forces by pressing a force sensor with their index fingers in the three feedback modes respectively. Response time of 24 pairs (4×6) of Magnitude-Tolerance conditions were measured. The results showed that the response time obeyed Fitts' law within a certain range of force accuracy in all the three feedback modes, while the Linear speed-accuracy tradeoff model was almost superior for the force control process than the Meyer formulation and the Shannon formulation. The response time in the audio feedback mode was the shortest among the three feedback conditions. The results may be used as guidelines for applications that rely on accurate and quick force control under different feedback conditions such as fast tapping tasks on a touch screen.

1. Introduction

Recently, a new patent on force-sensitive input structure for electronic devices (Morrell et al., 2016) was publicized by Apple Inc. The patent revolutionized the conventional concept of keyboard input structure. The new generation of keyboard for MacBook will be a flat surface beneath which includes a sense layer. The sense layer can detect a force and its location exerted on the flat surface. This keyboard uses force input as a preliminary interface, and it can detect on-off input command regardless of multiple input force levels. In another case, in the iPhone 6s/6s plus produced by Apple Inc. (2015), force input technique was applied into it, which was known as 3D touch. The core component of the 3D touch technique is force touch sensors, which can detect not only the finger movement along *x*-axis and *y*-axis (e.g. swipe) but also the exerted force along z-axis (e.g. press). More importantly, this technique can discriminate as many as three levels of input force, i.e. tap, long press and heavy press, which corresponds to three different input commands. These new concepts illustrate the possibility of using force input as a tool to enlarge the communication bandwidth between humans and computers. Three force levels were used in the above example. If we aim to divide a certain force range into more than three levels, we need to quantitatively measure the human ability of controlling the accuracy within a certain force range (Mizobuchi et al., 2005).

In order to fully utilize the human force control ability as an input channel for computer devices such as touch screens or touch pads, we should first understand the quantified performance of human force control behavior. Quantified study of the speed-accuracy tradeoff may promote understanding of biological and neurological process of muscle control, including the bandwidth, accuracy, and stability of muscle control behavior. Exploring the speed-accuracy tradeoff in force control is essential for a great deal of potential basic applications, such as force control based human-computer interaction (HCI) design or pressure based password design.

Fitts' law provides a general speed-accuracy tradeoff model of the human motion control process, which provides a quantitative relationship between movement time, target distance, and target width. Fitts' law has been widely used for designing human-computer interfaces (Fitts, 1954; Mackenzie, 1992; Soukoreff and MacKenzie, 2004; Wright and Lee, 2013). However, most studies on Fitts' law have focused on movement, such as wrist flexion and rotation, hand movements, and head movements (Plamondon and Alimi, 1997). As force control and motion

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control always coexist, their close relationship inspired us to study the relevance of Fitts' law for human force control behavior. The potential reasoning that underlies the transfer of Fitts' law to force control could be attributed to the similarity between force control and motion control. Both of these recruit perception and executive control through the haptic channel, and require planning and adjustment of muscle tension. Therefore, it is an interesting topic to explore whether force control tasks display similar behavior to the motion control tasks in terms of speed-accuracy tradeoff.

In an effort to improve the data-to-model fit, lots of researchers have proposed variations on Fitts' law, such as the logarithmic model, or have introduced new models derived from different principles (Mackenzie, 1992; Soukoreff and MacKenzie, 2004). Fitts' law turned out to be a robust human performance model. However, it does not sit well for all. Besides the Shannon formulation of Fitts' law (logarithmic form), the Meyer formulation (power form) and the Linear trade-off formulation (linear form) are also used to describe human movement (Guiard and Beaudouin-Lafon, 2004; Mackenzie, 1992). Each form is appropriate for modeling movement behavior in certain circumstances. The Shannon formulation reflects the fundamental property of human motor performance on rapid aimed movements. The Meyer formulation divides the specified target region into a primary submovement and an optimal secondary corrective submovement (Meyer et al., 1988). The Linear formulation fits better for temporally constrained movement while the Shannon formulation fits better for spatially constrained movements (Wright and Meyer, 1983).

For the study on the speed-accuracy tradeoff of fingertip force control, Raghu Prasad et al. (2013) measured the response time (RT) to reach a target force with an allowable tolerance using index fingertip under visual feedback, and the R-squared value of Fitts' model fitting was as high as 0.993 in their results. They showed that a force-based virtual movement task with visual feedback can be well described by Fitts' law, which extended Fitts' law to fingertip force based tasks. Previous works have verified that the process of force control with visual feedback obeys Fitts' law (Li et al., 2015; Raghu Prasad et al., 2013), but which formulation is more appropriate and suitable for modeling force control with audio or haptic feedback is largely unknown.

In this paper, we aim to study how quickly a human can control absolute magnitudes of fingertip force in a given feedback mode, i.e. to measure the response time (RT) to reach a target force (A) with a specific tolerance range (W), and how the RT may vary under different A and W combinations. During the force control tasks, different sensory channels including visual, audio and haptic could be used to provide feedback cues for the user to adjust the force. There is no doubt that the feedback modality can modulate the speed-accuracy tradeoff. In this paper, the influence of feedback modality on force control performance was observed and compared, including visual/audio/haptic feedback mode. The experiment was designed to explore the following specific questions:

(1) Does fingertip force control performance obey Fitts' law in different feedback modes (i.e. audio, haptic, or visual)? Furthermore, how significant is the difference in the performance between the three feedback modes?
(2) Among the three speed-accuracy tradeoff models, the Shannon formulation, the Meyer formulation, and the Linear tradeoff formulation, which one is the most appropriate to model the fingertip force control/adjustment process?

The work presented here is an extension of earlier work (Li et al., 2015). Our previous experiment was a 5×4 A-W conditions design in two feedback modalities (audio and visual). In the present experiment, we performed a more detailed set of A-W conditions (4×6), and compared users' performance and preferences on the three feedback modalities (visual, audio, and haptic). This extension affords a more thorough investigation of the relationship between the speed-accuracy tradeoff model and the fingertip force control task in different feedback modalities and the influence of single sensory modality on the force control task. The haptic feedback condition is useful for scenarios when visual or auditory feedback is not available, such as for visually impaired people, or for environments with strong lighting such as using a mobile device in the sunshine on a summer afternoon, or for environments with big noises such as using a mobile device at a party. From the perspective of fundamental research, it is also valuable to explore the difference between haptic sensory modality and visual/auditory modalities for assisting accurate and quick force control tasks. The research results maybe helpful for selecting efficient feedback modalities for designing effective interacting paradigms.

Furthermore, in the current paper, we performed correlation analysis using the three formulations of the speed-accuracy tradeoff model. We aim to compare which formulation can lead to a higher fit for the proposed accurate and quick fingertip force control task. In our previous work, we found that the Shannon formulation and the Meyer formulation lead to a fit value of less than 0.95 (Li et al., 2015). In order to find a model that can lead to a higher fit for the force control task, we added the third model, the Linear formulation, to observe whether this formulation will produce a higher fit than the Shannon formulation and the Meyer formulation. In addition, the approach of presenting feedback signals was deliberately improved in this work, so as to make the comparison among the three modalities more consistent and convincing.

The remainder of this paper is organized as follows: in Section 2 we introduce the related work on force control. Section 3 describes the details of the force control experiment procedure and methods in each of the three feedback modes. The results of the experiment are shown in Section 4. Discussion of the results and data analysis are provided in Section 5. In the last section, we present conclusions and future work.

2. Related work

In addition to a large amount of previous work on human motion ability, many researchers have studied the human capability of maintaining a constant force in different ranges. Mai et al. reported that subjects could maintain an isometric grasping force of 2.5 N to within 6% of a target level using only tactile and kinesthetic feedback over a time interval of 20 s, and that the error rate could decrease to 1.5% if visual feedback was additionally employed (Mai et al., 1985). Srinivasan and Chen measured the human ability in controlling normal force of contact applied by the index fingerpad. Three target force profiles were used in their experiments: constant, linear ramps and sinusoids. In the case of constant force ranging from 0.25 N to 1.5 N in 0.25 N steps, they found that, when visual feedback was absent, the average absolute error increased with the target force magnitude and was generally between 11 to 15% of the target force values. When visual feedback was present, the error reduced significantly and remained approximately constant at 0.039N±0.006SD for all the target force values (Srinivasan and Chen, 1993). Although these works did not study Fitts' law, they investigated the difference between different feedback modalities that indicated that visual feedback can improve performance. Gupta et al. (2016) defined and developed a Direct Manipulation-enabled Tactile display with gesture-based input. One of their experiments validated that its target acquisition performance also obeys Fitts' law. In addition, they found that, with less than five minutes of visual aid in the beginning, participants not only were able to perform direct manipulation in a tactile menu without visual aid, but they also improved their speeds while preserving a relatively high accuracy for target execution, which indicated that the combination of visual and tactile feedback may improve performance.

There are numerous studies focused on the correlation between Fitts' law and motion control behavior. But only a few works have been performed to study the correlation between Fitts' law and force control behavior (Bi et al., 2013; Kim et al., 2010; Raghu Prasad et al., 2013). Park et al. (2011) compared the myocontrol and force control based on Fitts' law, finding that both myocontrol and force control could be modeled using Fitts' law. Scheme and Englehart (2013) proposed a 3-D Fitts' law test as an alternative to using virtual limb environments for evaluating real-time myoelectric control performance. From their work, the myoelectric prosthetic control scheme was shown to obey Fitts' law. Kim et al. (2010) studied the application of Fitts' paradigm to grasping tasks in individuals with chronic stroke, and they concluded that Fitts' law can be applied to the dynamic force application of stroke subjects' affected hand. Billon et al. (2000) found that Fitts' law was also valid in the realm of isometric force control.

The force control can be exerted by different part of the human body. Akamatsu et al. (1995), Kim et al. (2010), Park et al. (2011), and Scheme and Englehart (2013) studied the force control ability using the whole arm. Lundy-Ekman et al. (1991) and Piek and Skinner (1999) investigated the finger force control ability in clumsy children. Some other researchers studied the force control ability in older adults including grip force (Claudino et al., 2013; Lowe, 2001), tri-digit finger-pinch force (Keogh et al., 2007), and precision pinch grip force of the thumb and index finger (Cole, 1991). These works revealed that the ability of accuracy force control is different between healthy people and patients.

Holding a target force level for a certain period of time has practical applications such as in a long press of a virtual button or drag-and-drop interaction on a touch screen (Ahmaniemi, 2013). Linear mapping has been adopted as a straightforward approach to map pressure to the motion of a visual cursor (Ramos et al., 2004). Hwang et al. (2013) inferred that inhomogeneous dividing of the force range could be considered as a potential method to improve input accuracy. Shi et al. (2008) compared several mapping methods and found that adaptive division of the pressure range could produce lower error rates and maintain a similar speed than the even division method. A quantitative model on speed-accuracy tradeoff in force control may lay a foundation for estimating the minimum response time, identifying the optimal force range and corresponding subdivision levels within that range, and thus for developing an optimal mapping function to translate the input force to the movement of the visual avatar, as well as to determine the optimal mapping function for pressure-based input widgets.

However, all of above work was performed in visual feedback mode. To the best of our knowledge, there has been no previous work on studying the correlation between the response time (RT) and the index of difficulty (ID) in fingertip force control ability with audio/haptic feedback. It is also unknown how force control performance will vary under different feedback channels.

In addition, the "click" behavior was not clearly defined in previous force control tasks. In the tasks designed based on Fitts' law, it was very important to end a trial by defining explicit "click" behavior. Ramos et al. (2004) investigated the human ability to control the level of pressure and compared the response time (RT) under four techniques for confirming selection. Their results showed that the dwell metaphor (maintaining the cursor/force within the target region for a prescribed amount of time) had the lowest error rate. Cechanowicz et al. (2007) investigated the use of a uni-pressure and dual-pressure augmented mouse. Their results showed that pressure-levels have a significant effect on trial completion time. Many force based applications expected the production of producing a target force accurately and maintaining the magnitude within a tolerance range for a certain time. Taking all these factors into account, the dwell method was used to take the place of the "click" behavior in this paper.

To find out the relationship between response time (RT) and other independent variables, the three typical formulations of speed-accuracy tradeoff model were used to analyze the recorded data.

In HCI, the Shannon formulation of Fitts' law (Mackenzie, 1992) is most frequently used, which is defined as

$$RT = a + b \cdot \underbrace{log_2(A/W + 1)}_{ID} \tag{1}$$

where a and b are regression coefficients, A/W is the signal-to-noise ratio, and ID is the index of difficulty.

Meyer et al. (1988) proposed an optimized dual-submovements model and verified its validity of better explaining Fitts' law. And they extended it to an optimized multiple-submovements model including one, two, three, or more submovements later (Meyer et al., 1990). The optimized dual-submovements model can be formulated as follows,

$$RT = a + b \cdot \sqrt{A/W} \tag{2}$$

where a and b are regression coefficients.

Schmidt et al. (1979) found linear tradeoff between speed and accuracy which can be formulated as follows,

$$RT = a + b \cdot A/W \tag{3}$$

In this paper, the influence of the signal-to-noise ratio (A/W) and the index of difficulty (ID) on the response time (RT) were systematically analyzed. Furthermore, the index of performance (IP, equal to the reciprocal of the slope of the regression line, 1/b) was analyzed.

In our experiment, as defined in Fig. 3(b), the dependent measure "response time (RT)" refers to the reaction time of perceiving the stimuli plus the response time of adjusting the output force, but does not include the dwell time.

Based on the above analysis of the literature, how quickly a human can reach a target force within a required tolerance range in audio/haptic feedback using fingertip is unknown, and how it will vary under different feedback modes is also unclear.

3. Methods

3.1. Participants

Five female and thirteen male healthy volunteers of 23–30 years old (mean 26 years) from Beihang University participated in the experiment. All of them were right-handed and had no hearing disorders, visual impairments, or somatosensory disorders. All participants gave written consent to participate in the study and each of them received ¥50 (about $8) upon completion of the experiment.

3.2. Apparatus

A Six-Axis Force/Torque Sensor (ATI Nano17, ATI Industrial Automation Inc. US) was used to measure the force exerted by the right index finger of participants as shown in Fig. 1(a) and (b). The force sensor was mounted on a large aluminum plate that provided a stable fixed base for the sensor. The resolution of the force sensor was 0.003 N, and the sampling rate was 500 Hz.

The experiment included three parts. Each part was performed in single-channel feedback mode, i.e. only a visual/audio/haptic feedback signal was provided in each feedback mode. A pair of head-mounted earmuffs (Peltor H10A, 3M Inc., US) was used to exclude the surrounding noise during all three parts. An eyeshade was used for shielding all visual signals in the audio/haptic feedback mode. A haptuator (TL-002-14R, Tactile Labs Inc. Canada) was used for providing vibrotactile stimuli between the thumb and index fingertips of the non-dominant hand in the haptic mode as shown in Fig. 1(c). A sinusoidal signal with adjustable frequency and amplitude was used to drive the haptuator. A 21 inch computer monitor was used in the visual feedback mode.

The experimental software was developed in Microsoft Visual Studio 2008 using the C++ language and ran on a 2.20 GHz Intel(R) Core(TM) 2 Duo CPU E4500 PC with the Windows 7 operating system.

3.3. Procedures

The participant sat by the lab table in front of the force-measuring platform at a convenient height. As shown in Fig. 1(b), all participants were required to press the force sensor with a consistent hand posture while their forearms were comfortably supported on the table. As shown in Fig. 2, each participant was required to wear a pair of head-mounted

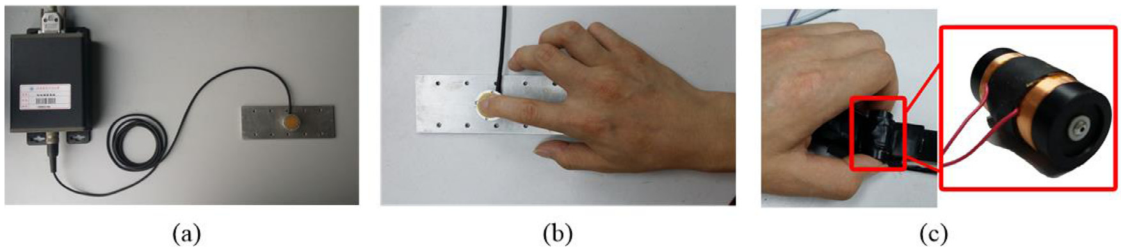

Fig. 1. Force/Torque sensor system. (a) Six-axis force/Torque sensor system. (b) The posture of pressing on the force-measuring platform. (c) Haptuator.

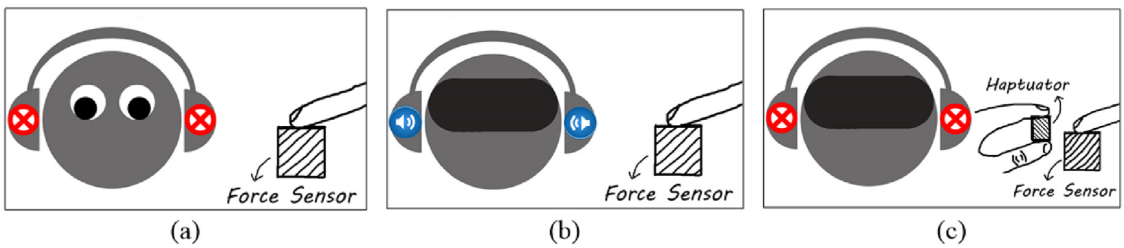

Fig. 2. A sketch of the experiment. (a) Sketch of the experiment in the visual feedback mode. (b) Sketch of the experiment in the audio feedback mode. (c) Sketch of the experiment in the haptic feedback mode, during which the haptuator is held in the left hand while force sensor is pressed by the right hand.

earmuffs for eliminating surrounding noise in all three parts of the experiment, and to wear an eyeshade for eliminating visual distractions in the audio/haptic feedback mode.

Using a counterbalanced design on the experimental sequence of the three feedback modes, participants were randomly divided into six groups which included three participants respectively in each group. In detail, each group corresponded to one kind of experimental sequence. There were six possible sequences, which aimed to make sure that the experimental results were not biased by the experimental sequence among the three feedback modes.

The three parts of the experiment were performed on three consecutive days for each participant, and the experimental procedure in each mode was explained to the participants by a text description before each part. Then the participants practiced freely for five minutes to get familiar with the system.

The target force (A) was chosen from the set (1, 2, 3, 4 N) while the tolerance range (W) was chosen from the set (0.3, 0.4, 0.5, 0.6, 0.7, 0.8 N). The tolerance range was defined symmetrically with respect to the target force, that is, (A±0.15, A±0.2, A±0.25, A±0.3, A±0.35, A±0.4 N). Therefore a total of 24 pairs (4 × 6) of A-W conditions were generated. A random sequence of conditions was assigned to each participant with the restriction that each condition occurred only once. For each feedback mode, participants needed to complete all the 24 A-W conditions that appeared randomly, and each condition was repeated ten times (trials) consecutively. For an upcoming trial with a new A-W condition, there were no explicit cues to prompt the changed target force and target tolerance, and participants needed to explore and adapt to the new A-W condition by themselves.

The sampling rate for the force measurement and all three kinds of feedback signals display was 500 Hz. Therefore, the changing command of the feedback signal could be produced within 2 ms, which could meet the real-time measurement requirement. Furthermore, we measured the latency of the vibration motor, it was about 1 ms. It was much smaller than the average value of the observed response time.

As shown in Fig. 3(b), the available force range can be divided into three regions: Upper region, Target region and Lower region.

In summary, the experiment consisted of:

18 participants ×
3 feedback modes ×
24 A-W conditions ×
10 repetitions (trials)
= 12,960 force control trials.

The participant first placed his/her right index finger over the force-measuring platform and prepared for starting to exert pressure on it. The participant was required to increase the normal pressure to enter the target region (a target force with a tolerance) as soon as possible, and then maintain the force for a certain dwell time. If the pressure jumped out of the target region before the dwell time was up, the participant needed to adjust his/her pressure to enter the target region again until the dwell time was up, then the trial was completed successfully. During the trial, real-time feedback signals were provided to correct the relative difference between the actual force and the target force. After completion of a trial, the participant lifted his/her right index finger and prepared for the next trial.

When the whole experiment was finished, each participant was asked to fill out a questionnaire, and all of them were asked to rank the three feedback modalities according to their preferred task difficulty level.

In the visual feedback mode, the position of the visual stimuli was in the center of the monitor with 60 cm of distance from the user, which led to a visual angle of 15° below eye level. Before the formal experiments, all the participants took a simple test on discriminating the three levels of each feedback mode. The test results showed that all the participants could discriminate them easily and instantaneously.

3.4. Visual/Audio/Haptic feedback cues

As shown in Fig. 3(a), three kinds of feedback modality signals were provided separately: color signal, tone signal, and vibration signal. In visual feedback mode, three colors (sub-types) were used to notify participants about their force levels. In the audio and haptic feedback modes, three tones and three vibrating patterns (sub-types) were used to notify participants. There are many ways and forms of feedback cues that can be used in each feedback modality. This paper is focused on the comparison of different feedback modalities as long as the three sub-type cues in the same feedback modality can be discriminated easily. We conducted a pilot study to ensure that all the participants could discriminate the three kinds of feedback cues in each modality correctly. For each modality, a participant performed a session including 100 trials. The kind of feedback cues was randomly generated for each trail. And we also ensured that no two adjacent trials had the same cues. In each trial, the participant was required to verbally report the kind of feedback cues as he/she recognized. A participant was allowed to perform the formal

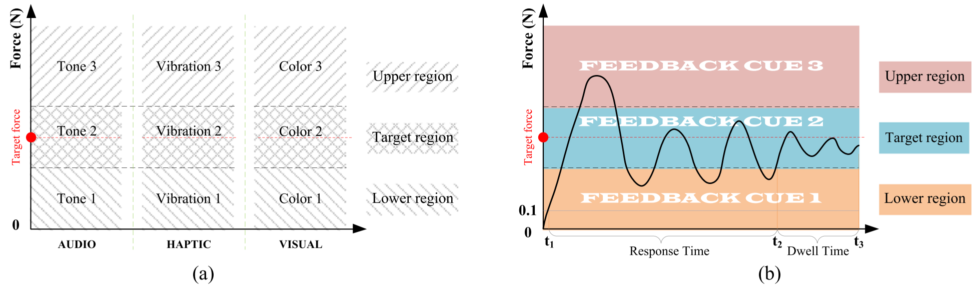

Fig. 3. Feedback cues and the sketch of one trial. (a) Feedback cues. (b) The sketch of one trial. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Parameters used for generating feedback cues in the three sensory modalities.

Modality	Cue	Region	Function values	Signal type
AUDIO	BASE	others	NA	NA
	Tone 1	Lower	*dAmp*=40, *dFreq*=20,000, *c*=127, *m*=*i*ˆ2*10, *n*=0.03	Continuous
	Tone 2	Target	*dAmp*=40, *dFreq*=10,000, *c*=127, *m*=*i*, *n*=1	Continuous
	Tone 3	Upper	*dAmp*=40, *dFreq*=20,000, *c*=127, *m*=*i*, *n*=1-*i*/4096	Continuous
HAPTIC	BASE	others	NA	NA
	Vibration 1	Lower	*dAmp*=40, *dFreq*=10,000, *c*=100, *m*=*i*, *n*=*i*ˆ3/100	Continuous
	Vibration 2	Target	*dAmp*=40, *dFreq*=20,000, *c*=0, *m*=*i*/10,000, *n*=1	Continuous
	Vibration 3	Upper	*dAmp*=40, *dFreq*=20,000, *c*=0, *m*=*i*/10, *n*=1	Continuous
VISUAL	BASE	others	GRAY80: rgb (204,204,204)	Continuous
	Color 1	Lower	GRAY20: rgb (51,51,51)	Continuous
	Color 2	Target	ORANGE: rgb (255,165,0)	Continuous
	Color 3	Upper	RED: rgb (255,0,0)	Continuous

Note: NA, not applicable.

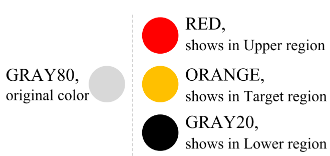

Fig. 4. Signal disk with changeable color in the visual feedback mode. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

experiment after he/she could recognize the kind of feedback cues correctly in all trials in a complete session. And all the participants passed the discrimination test once.

To keep consistency among the three sensory modalities, all three kinds of feedback cues were designed to be discrete signals. Compared with continuous feedback, discrete feedback produces lower perception workload to the user. We assume this simple pattern of on/off feedback signal may be useful in some scenarios when the information processing workload is already at a high level.

In the visual feedback mode, a signal disk with changeable colors was presented to participants on the computer monitor as shown in Fig. 4. There were four kinds of colors (GRAY80, GRAY20, ORANGE, RED) for the signal disk. The definition of the used colors were shown in Table 1. All the colors were emitted by one signal disk at different times. As shown in Fig. 4, the original color (BASE) of the signal disk was GRAY80. If the fingertip force was within the target region, the signal disk turned to ORANGE, if it was within the lower region, the signal disk turned to GRAY20, and if it was within the upper region, the signal disk turned to RED. When a trial was completed, the color of the signal disk returned to GRAY80. There were two breaks during each visual feedback session to avoid fatigue, that is each one third of the session was followed by a two-minute rest, and similarly in the audio/haptic feedback modes. Before each break and at the end of the session, a window popped up which indicated that it was rest time or the session was over.

Different from the continuous feedback signal of using a dynamic circle to denote the real-time pressure force in our previous work, a discrete feedback signal of using three different colors was adopted in the current study. In this way, we aimed to ensure the presenting styles of visual/auditory/haptic channels were consistent, i.e., all three feedback channels utilized discrete signals to denote the three states of the actual pressure force.

In the audio and haptic feedback mode, there were three different tones (TONE1, TONE2, TONE3) and three different vibrating patterns (VIBRATION1, VIBRATION2, VIBRATION3) provided for participants respectively. The audio and haptic cues were defined by the sinusoidal Eq. (4), which was used to define the synthesized sounds cues and vibration cues by using the DirectSound application programming interface (API).

$$f = c + dAmp \cdot \sin(20 \cdot \pi \cdot dFreq \cdot m) \cdot n \tag{4}$$

where *dAmp* is the amplitude in the unit of dB, *dFreq* is the frequency in the unit of Hz, *c* is a constant intercept, *m* and *n* are *i* related expressions, *i* is used in forloop in the codes, and $i \in [0, 4096]$, π=3.14.

The detailed values of the variables in the sinusoidal equation under different conditions in different sensory modalities were described in Table 1. The reason for selecting these values to synthesize those feedback cues was straightforward, i.e., to ensure the cues representing the three regions can be discriminated easily and correctly for all participants. Similar to the visual feedback, when the fingertip force fell into the Target region, TONE2 (in the audio feedback mode) or VIBRATION2 (in the haptic feedback mode) was presented to participant. When the fingertip force overshot into the Upper region, TONE3 (in the audio feedback mode) or VIBRATION3 (in the haptic feedback mode) was presented to participant. And when the fingertip force fell into the Lower region, TONE1 (in the audio feedback mode) or VIBRATION1 (in the haptic feedback mode) was presented to participant. When a trial was completed, all the audio/haptic cues vanished. Before each break and at the end of the session, a piece of music was played which indicated that it was rest time or the session was over.

Table 2
Three-way ANOVA on response time (RT) with the three factors of amplitude (A), tolerance (W), and feedback modality (M).

Factors	*F*	*p*
A	F (3, 51)=121.23	*p*<.001
W	F (5, 85)=49.53	*p*<.001
M	F (2, 34)=3.59	*p*<.038
A×W	F (15, 255)=4.21	*p*<.001
A×M	F (6, 102)=2.08	*p* = .06
W×M	F (10, 170)=1.52	*p* = .14
A×W×M	F (30, 510)=1.05	*p* = .39

3.5. Data analysis and statistics

All data was entered into a Microsoft Excel 2010 spreadsheet. SPSS software version 21.0 (SPSS Inc., Chicago, IL, USA) was used for statistical investigation, and Matlab R2013a (Mathworks Inc., Natick, MA, USA) was used for data analysis. The differences between the six groups were evaluated by using one way ANOVA to observe the possible effect of experimental sequence on the performance. A three-way ANOVA on response times (RT) with the factors amplitude (A), tolerance (W), and feedback modalities (audio, haptic, visual) using Bonferroni correlation was performed to explore the difference among different levels of each factor. A *p*-value of less than .05 was considered statistically significant. The response time (RT) did not include the dwell time.

4. Results

4.1. Response time for varied force magnitude

Fig. 5. shows the relationship among the response time (RT), tolerance (W), and the target force (A) in the three feedback modes respectively. As shown in Table 2, a three-way ANOVA on response time (RT) with the three factors of amplitude (A), tolerance (W), and feedback modality (M) showed that there was no interaction effect among these three factors ($F_{A\times W\times M}(30, 510) = 1.05$, $p = .39$). There exists a significant interaction effect between A and W ($F_{A\times W}(15, 255) = 4.21$, $p < .001$), but not between feedback modality and amplitude ($F_{A\times M}(6, 102) = 2.08$, $p = .06$), and there is also no interaction effect between feedback modality and tolerance ($F_{W\times M}(10, 170) = 1.52$, $p = .14$). But for each of the three factors there was a significant effect on RT, i.e. for amplitude ($F_A(3, 51) = 121.23$, $p < .001$), for tolerance ($F_W(5, 85) = 49.53$, $p < .001$), and for feedback modality ($F_M(2, 34) = 3.59$, $p < .038$).

The post hoc tests using Bonferroni correction revealed that there was a significant difference of their effects on the response time (RT) among different amplitudes ($p < .001$). And there was a significant difference ($p < .01$) of their effects on the response time (RT) between any two of the three tolerance levels (W = 0.3, W = 0.4, W = 0.5), while there was no significant difference ($p > .05$) of their effects on the response time (RT) between W = 0.7 and W = 0.8.

A one-way ANOVA on RT for six groups showed no significant differences among groups ($F(5, 102) = 0.78$, $p > .05$), i.e. there was no significant effect of experimental sequence on the subjects' performance.

4.2. Correlation with Fitts' law

Fig. 6 shows the comparison of the response time (RT) in visual/audio/haptic feedback modes respectively. A two-way ANOVA on response time (RT) with the factors of signal-to-noise ratio (A/W) and feedback modality (M) was conducted to analyze their effects on the response time (RT). The results showed that both the signal-to-noise ratio (A/W, $p < .0001$) and the feedback modality (M, $p < .0001$) had a significant effect on the response time (RT). A further pairwise analysis

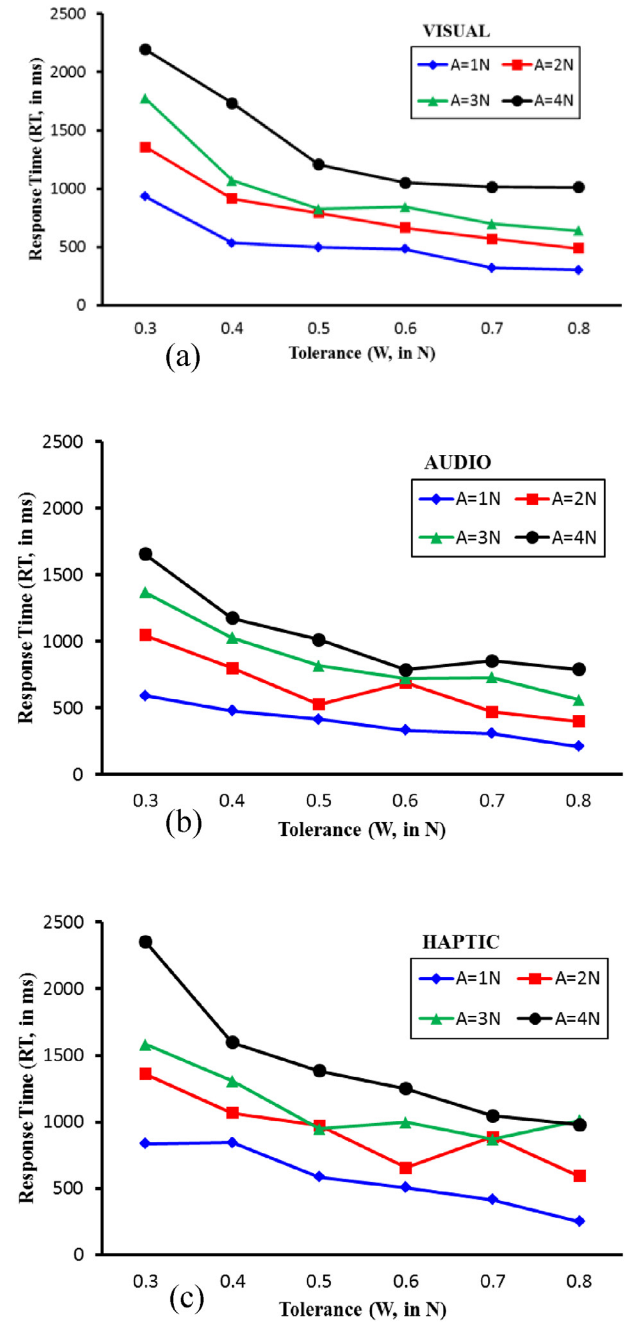

Fig. 5. The relationship among the response time (RT), tolerance (W) and the target force (A) in different feedback modes. (a) Visual feedback mode. (b) Audio feedback mode. (c) Haptic feedback mode. The error bars represent the standard deviation (SD).

using Tukey method showed that each two of the three feedback modalities had a significant difference (AUDIO-VISUAL, $p = .0001$; AUDIO-HAPTIC, $p < .0001$; VISUAL-HAPTIC, $p = .0049$). It indicated that, combined with Fig. 6, the response time (RT) in visual feedback mode was significantly longer than that in audio feedback mode ($p = .0001$), and significantly shorter than that in haptic feedback mode ($p = .0049$). In other words, for tasks with a same signal-to-noise ratio (A/W), participants generally produced the shortest response time (RT) in audio feedback mode, and the longest RT in haptic feedback mode.

Fig. 7 shows the curve fitting by different formulations of the speed-accuracy tradeoff model between response time (RT) and signal-to-noise ratio (A/W) in the three feedback modes respectively. R-squared, the coefficient of determination, indicated how well the actual values fit

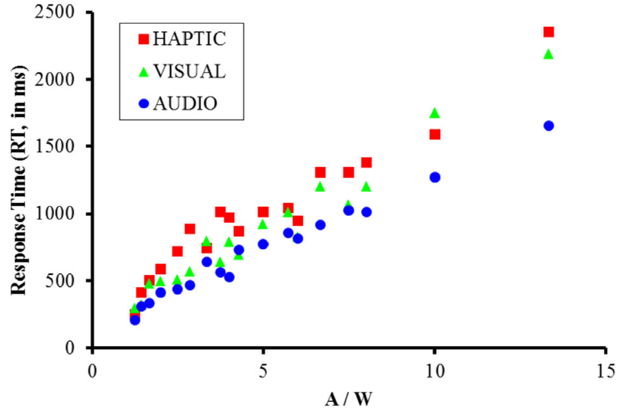

Fig. 6. Comparison of response time (RT) among visual, audio and haptic feedback modes.

Table 3
The parameters of curve fitting by different formulations of speed-accuracy tradeoff in three sensory modalities.

		a	B	R^2	IP (bits/s)
Shannon	**V**	−0.53	0.59	0.86	1.69
	A	−0.39	0.47	0.93	2.15
	H	−0.43	0.60	0.88	1.68
Meyer	**V**	−0.53	0.66	0.91	1.51
	A	−0.38	0.52	0.97	1.94
	H	−0.41	0.66	0.92	1.51
Linear	**V**	0.14	0.15	0.96	6.77
	A	0.16	0.11	0.98	8.85
	H	0.27	0.15	0.94	6.86

Note: V = visual feedback mode, A = audio feedback mode, H = haptic feedback mode; a and b are constant in (1), (2), and (3), R^2 is also known as the coefficient of determination; IP is the abbreviation for the index of performance; the values in the column of a, b, and R^2 are summarized from Fig. 6.

the corresponding regression plot. All the R-squared values fitted by the three formulations were above 0.86. As shown in Fig. 7, in all the three feedback modes, the R-squared values fitted by the Linear tradeoff formulation (V, visual; A, audio; H, haptic; [V, A, H] = [0.96, 0.98, 0.94]) were greater than those fitted by the Shannon ([V, A, H] = [0.86, 0.93, 0.88]) and Meyer ([V, A, H] = [0.91, 0.97, 0.92]) formulation, which indicated that the Linear model has the best fit in all the three feedback modes.

Table 3 shows the parameters of curve fitting by different formulations of the speed-accuracy tradeoff in three sensory modalities. By using Akaike information criterion (AIC) method, the Linear model is significantly better than the Meyer model ($p = .0014$, visual mode; $p = .0113$, audio mode) and the Shannon model ($p < .0001$, both of visual mode and audio mode) both in the visual feedback mode and in the audio feedback mode. In the haptic feedback mode, the Linear model is significantly better than the Shannon model ($p = .0021$) but not the Meyer model ($p = .0665$). However, the Meyer model is always significantly better than the Shannon model in the visual feedback ($p = .01389$), in the audio feedback ($p = .0010$), and in the haptic feedback ($p = .0313$). Statistically speaking, there is no significant difference between the index of performance (IP) obtained in any two different feedback modes (using Bonferroni correction, $p > .05$). However, based on the numerical value, the index of performance (IP) obtained in the audio feedback mode was the best among the three feedback modes under the same formulation of the speed-accuracy tradeoff.

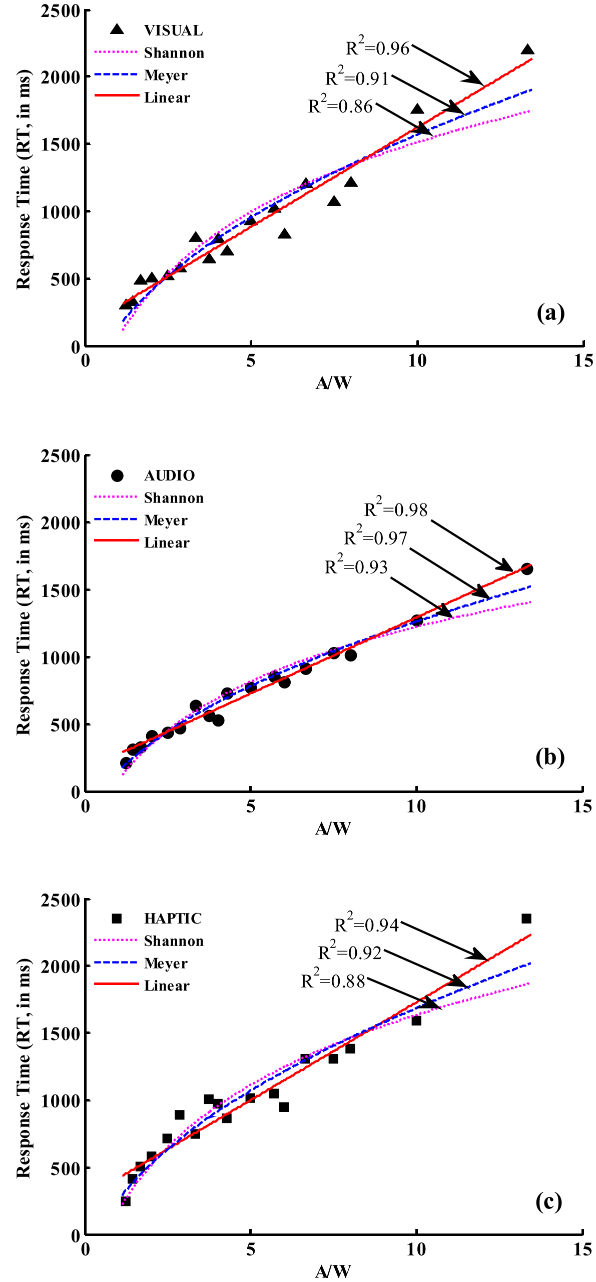

Fig. 7. Curve fitting by different formulations of speed-accuracy tradeoff model between response time (RT) and signal-to-noise ratio (A/W) in three feedback modes. (a) Visual feedback mode. (b) Audio feedback mode. (c) Haptic feedback mode.

4.3. Force adjustment strategy

There is an interesting phenomenon: in most cases, before the dwell period during each trial, the percentage of the fingertip force entering a target region by increasing (from Lower Region to Target Region) was much higher than that by decreasing (from Upper Region to Target Region). As shown in Fig. 8, for all the three modalities, the percentage of all trials entering the target region by increasing the fingertip force (Audio, mean 89%; Haptic, mean 89%; Visual, mean 90%) was higher than that by decreasing the fingertip force (Audio, mean 11%; Haptic, mean 11%; Visual, mean 10%). There was always have a significant bias on the "Increasing" strategy in all the three modalities (Audio, $t(17) = 48.159$, $p < .0001$; Haptic, $t(17) = 54.799$, $p < .0001$; Visual, $t(17) = 28.891$, $p < .0001$; bias standard was 0.5) by using one-sample *t*-test analysis. There was no significant effect of modalities on the force adjustment

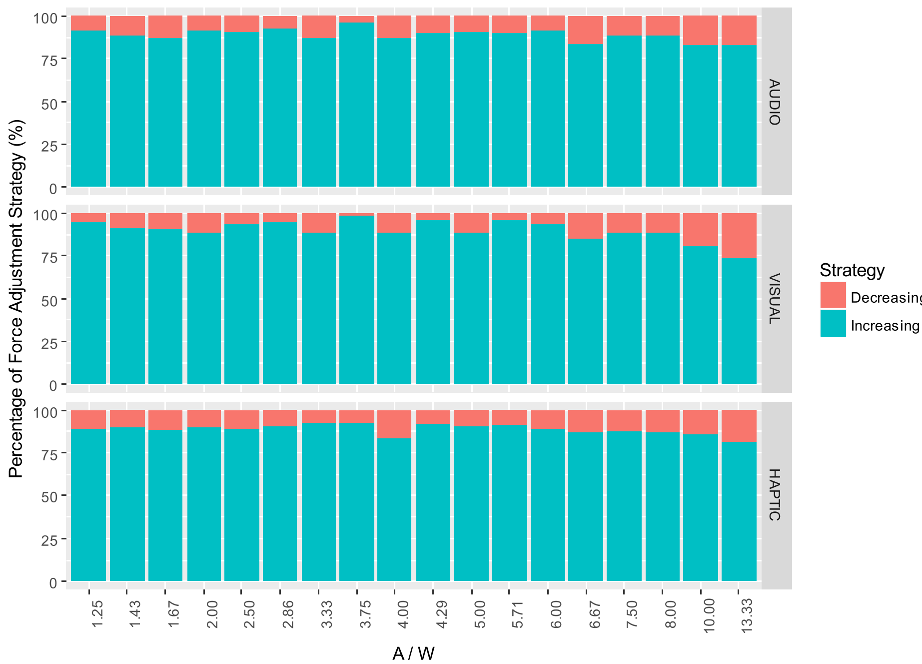

Fig. 8. The percentage of all trials that completed by force adjustment strategy of increasing/decreasing fingertip force.

strategy, i.e. the percentage of entering the target region by increasing the fingertip force ($F(2,34) = 0.0543$, $p > .05$).

This phenomenon may reflect two points. One is that all the participants preferred using an "increasing" strategy, that is, entering the target region from the lower region. On the other hand, the resolution of force control is higher when increasing than when decreasing, that is, humans may perform better in controlling force by increasing rather than by decreasing.

More interestingly, one participant was not consistent with the "increasing" strategy, and over 68% of his trials were completed by decreasing. However, he got the longest average of response time (RT) on the three sensory modalities among all participants.

4.4. Comparison among the three feedback modes

Fig. 9 shows the mean response time (MRT) in visual/audio/haptic feedback modes. MRT is the average response time of all the participants in the same feedback mode. From Fig. 9 we can find that audio feedback mode yields the shortest mean response time (MRT, 720±369 ms) while the haptic feedback mode yields the longest mean response time (MRT, 994±486 ms), and the visual feedback mode with the highest standard deviation (SD) yields a medium mean response time (MRT, 878±488 ms).

After participants finished the whole experiment, they were required to give an ordering of the three feedback modes according to their subjective feeling of the difficulty level, and the results are shown in Fig. 10. It shows that nearly 90% of participants thought that the audio feedback mode was easier than the visual feedback mode; nearly 70% of participants thought that the audio feedback mode was easier than the haptic feedback mode. And over 70% of participants thought that the visual feedback mode was more difficult than the haptic feedback mode.

In addition, most participants thought that frequent switching among different colors was uncomfortable and led to fatigue, and this indicated that strong dependence on the visual channel may easily cause visual fatigue (Akamatsu et al., 1995). Audio or vibration switches may be relatively more comfortable and acceptable, but this needs more evidence to be supported.

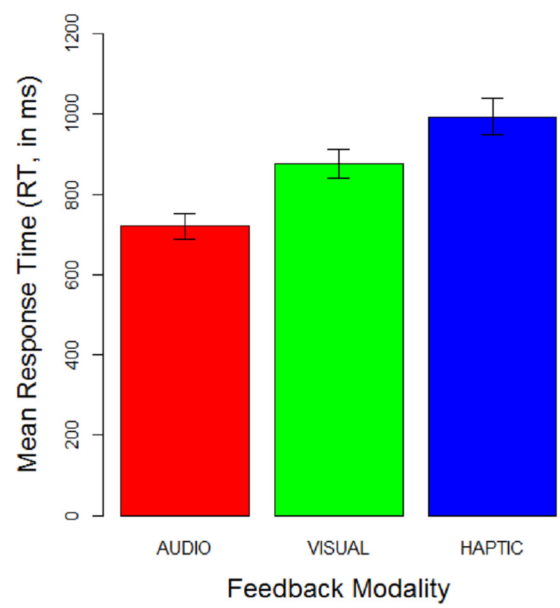

Fig. 9. The mean response time (MRT) in visual/audio/haptic feedback modes. Error bars: 95% confidence interval of the mean.

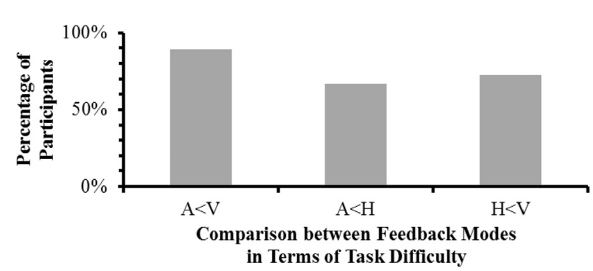

Fig. 10. Participants' preference among the three feedback modes in terms of task difficulty. The sign "<" means that "easier than". V = visual feedback mode, A = audio feedback mode, H = haptic feedback mode.

5. Discussion

During the whole experiment, all participants were required to use the index fingertip of their dominant hand (they were all right-handed). Because touch screens require you to be touching them, haptic feedback should be provided to the dominant hand that performs the foce control task. This could be realized by mounting the vibrating motor underneath the touch screen. Previous work has shown the feasibility of this idea (Ahmaniemi, 2013), and the result showed that the force control task can be performed well with vibrotactile feedback. In our experiment, the haptic feedback was provided to the left hand. The main reason is that it was hard to integrate the adopted vibration motor (i.e. the Haptuator) underneath the ATI force sensor. The advantage of providing haptic feedback on the other hand is to avoid possible distraction of the vibration feedback to the fine force control tasks. If the haptic feedback cues had been provided to the same hand, it could have made the force control unstable. A future study could compare the quantified difference of force control performance when the haptic feedback is provided to the same hand or a different hand.

The fingertip force control behavior with discrete feedback signals obeyed Fitts' law (the Shannon model) in all the three feedback modes. The result is consistent with previous force control studies on other muscles of the body (Akamatsu et al., 1995; Park et al., 2011; Scheme and Englehart, 2013) and our previous work (Li et al., 2015). The results may imply that Fitts' law was determined by the nervous system and was not affected by the feedback modes. The results further extended and strengthen the argument that the trade-off between speed and accuracy of the force control behavior is determined by the capacity of information transfer of the central nervous system (CNS), rather than the physical limitations of the arm or fingertips, such as inertia and mechanical compliance (Park et al., 2011).

As the formulas modeling human behavior are not unique, it is necessary to know which model can well-depict the force control behavior. As shown in Fig. 7, the Linear model has the best fit in all the three feedback modes among all the three models. Furthermore, by using the Akaike information criterion (AIC) method, the Linear model is always significantly better than the other two models in all the three modes except the Meyer model in the haptic feedback mode ($p = .0665$). These results validate that the proposed force control task could be better modeled by the Linear formulation. According to the conclusion in (Wright and Meyer, 1983), this implies that the force control tasks are to some extent similar to temporally constrained movements.

This result may provide helpful guidelines for designing the interaction tasks based on quick force control. For example, we could develop an attention training game that required accurate control of quick and repetitive force pulse with different design parameters (A, W, RT), in which the allowable reaction time RT in each trial could be determined to achieve an optimal difficulty level for a given force target (A and W) (Yang et al., 2016). The Linear formulation might provide smaller estimation errors when determining the parameters compared to the other two formulations.

According to Fig. 8, most of the trials were completed by increasing fingertip force. The "increasing" strategy may yield higher accuracy during force control movement than "decreasing", similar to the discovery by Fitts that flexor movements were more accurate than extensor movements (Fitts, 1954). This also could be explained by the force adjustment process which was always toward reaching a target force in our experiment. Regardless of which feedback mode was being conducted, due to the fact that the feedback signal was discrete, the participant took a conservative method to complete the trial slowly but steadily. One limitation of the current work is the design of the pressure control task, i.e. the users always needed to increase the force from zero to a certain force value. One interesting and unknown topic is whether users' performance is the same between increasing force to a certain force value and decreasing force to a certain force value. Furthermore, it is unknown whether both force increasing and decreasing tasks obey the Fitts' law. Rigorous studies are needed to explore whether there exists a kind of asymmetry behavior. These studies might provide insight about the biological differences between muscle flex and muscle extension processes.

The fingertip force control process obeyed Fitts' law only when the index of difficulty (ID) was within a specific range. According to the tendency in Fig. 5, the most difficult condition ($A = 4\,N$, $W = 0.3\,N$), similar to our previous work, also revealed an interesting future research topic. With a larger index of difficulty (ID), these three formulations of the speed-accuracy tradeoff model may not be suitable anymore and other new formulations need to be explored. The reason may be that the difficulty of this level has already approached the human limit for accuracy of controlling muscle. The biological evidence needs to be further explored.

The difference between the models lies in their different applications. The Shannon formulation focuses on rapid aimed movement, and the Meyer formulation focuses on the divided target region, and the Linear formulation focuses on temporally constrained movement. The reasons that lead to the difference may be that the force control process is more suitable to be modeled as a temporally constrained adjustment of muscle strength instead of a process involving divided target regions. In this paper, the response time (RT) in the visual feedback mode is significantly smaller than that in the haptic feedback mode but significantly higher than that in the audio feedback, and this tendency is more and more obvious as the difficulty increases. However, most participants thought the task in the visual feedback mode was more difficult than that in the haptic and audio feedback mode, although their performance using the haptic feedback mode was poorer than that using the visual feedback mode.

Compared to the work of Raghu Prasad et al. (2013), the coefficient of determination fitted by the Shannon formulation of Fitts' law in their experiment was relatively better (R^2=0.993) than that in our experiment. The first possible reason may be that the "click" behavior was different, i.e. Raghu Prasad et al. (2013) used a kind of quick release method while we adopted the dwell method. Secondly, in their experimental data, not all the A-W combinations were considered for curve fitting, which may lead to a change in the correlation coefficient.

From the perspective of fundamental research, the obtained relationship between speed-accuracy tradeoff formulation and force control process provides important implications for the study of the biological behavior of muscles. The average response time in the haptic mode was larger than that in the other two modes. The possible reason could be a signal transmission delay from the signal detection to the force control execution. One possible reason may be due to the neurophysiological time delays (i.e. haptic information travels longer distances through relatively slow nerve fibers). As the perception and control signals are all controlled by contralateral hemispheres, the signal transmission delay might be different in the three feedback modes. In the haptic mode, command signals of the right index fingertip come from the motor control cortex in the left hemisphere, whereas the haptic feedback signal was received on the left hand. Therefore, the perceived haptic stimuli were first transmitted to the somatosensory cortex in the right hemisphere, and then the signals traveled through the corpus callosum to the motor control cortex in the left hemisphere, and finally arrived at the right index finger. The additional signal transmission delay through the corpus callosum may increase the response time (Marzi et al., 1991; Tettamanti et al., 2002; van der Knaap and van der Ham, 2011). In the visual feedback mode, the perceived visual signal may arrive at both the left and right visual cortex as both eyes are involved in the perception process, and thus the feedback signal might be directly mapped into force control signal without the involvement of the corpus callosum. Similar signal transmission pathways may occur for the audio channel as both ears are involved in the auditory perception process.

An interesting phenomenon is that the RT in the visual feedback mode is significantly higher than that in audio feedback, which is opposite to our previous work that used continuous visual feedback signals (Li et al., 2015). That is, in our previous work, the RT in the visual feedback mode was smaller than that in the audio feedback mode. The primary reason is that the presentation style of feedback signals in the previous and present work is slightly different. For the former, the design for the presenting style in the two feedback modes was continuous in the lower and upper region, but for the latter, the design was deliberately improved and the presenting style of all three feedback signals was consistent, that is, all of them were uni-dimensional and discrete. So it is likely that human eyes are more sensitive to continuous feedback signals than the ears, and conversely, the ears are more sensitive to the discrete feedback signal than the eyes. Besides the possible fatigue caused by switching between different colors, attention might be another reason leading to the difference among the three feedback modes. In the audio feedback mode, it seems that the participants were able to pay more attention to the audio signals and the force control task. The possible reason may be that external disturbances from visual channels were eliminated by using the eyeshade. However, the visual channel will inevitably receive plenty of information besides the expected visual feedback stimuli that will inevitably increase the noise in the feedback signal, and it is also easy for people to neglect the specific visual information by shifting their eye focus, or distraction, or closing eyes. Therefore, methods need to be taken to avoid these possible factors in the future study, for example, to present the visual cues in an immersive VR environment using a head-mounted display.

Based on the summary of the questionnaires, participants provided their subjective experience on the three feedback modalities, which showed that participants preferred to perform the task with the audio and haptic feedback rather than the visual feedback. To some extent, this indicated that there are some differences among the three different feedback modalities, and participants might have some preference on one of them. As the visual cue changes color while the other two cues change magnitude (tone or vibration), these differences may lead to slight difference for users during the perceiving process. It could be a future topic to explore better ways of designing feedback signals to ensure more consistent and rigorous comparisons among the three sensory modalities.

The results on haptic/visual/auditory feedback condition could be used for designing interaction tasks recruiting quick and accurate force control. One ongoing work in the authors' group is to develop a multi-sensory attention training game using fingertip force control (Yang et al., 2016). In order to motivate a high engagement level of the user to play the game, we need to compare which feedback modality may produce higher curiosity to the individual users and could exclude external disturbances during the training. As different users may have preferences on different sensation channels, haptic feedback may produce better training effects for some users than visual or auditory feedback. Furthermore, the haptic channel has the uniqueness of privacy. In order to use visual or auditory channels for attention training, usually an isolated and quiet room is needed to exclude external disturbances. Using haptic feedback, trainees could receive the haptic stimuli exerted on their body without additional requirements on the visual and auditory inputs. This feature provides the potential of using haptic training in ubiquitous environments such as travelling in a subway.

Another potential application of the haptic feedback condition is fast pressure-based command input for wearable devices such as a watch. Small-sized vibrotactile actuators could be integrated into the wearable wrist watch, and thus provide haptic feedback for users to perform quick and accurate fingertip force control task. As this type of device has a limited screen size, it is hard to display a virtual keyboard on the device. A promising input method could be using the pressure fingertips assisted by vibrotactile feedback, in which different magnitudes of the input force could be mapped onto different targets such as different characters. Based on the speed-accuracy tradeoff results of the current study, it could be an interesting research topic to evaluate the performance of this novel input method for supporting quick and accurate input of English characters on a wearable device.

6. Conclusions

In this paper, we studied the human capability of controlling absolute magnitudes of fingertip force within specified tolerance ranges in three feedback modes. Three models of human fingertip force control behavior were compared, i.e. the Linear model, the Meyer model, and the Shannon model. The result showed that the fingertip force control behavior with discrete feedback signals obeyed Fitts' law in all three feedback modes. The Linear model has the best fit in all three feedback modes among all three models. In addition, the Linear model is significantly better than the other two models in all three modes except the Meyer model in the haptic feedback mode, which implies that the force control task is to some extent similar to temporally constrained movements. The Linear formulation provides smaller estimation errors for modeling the human force control behavior than the other two formulations.

The findings of this study may provide guidelines for pressure-based input devices in several ways. For visually impaired users, a force-based interface may provide access for them to use devices with a touch screen. For these users it is necessary to know how fast and how accurate they can reach a target force with the guidance of audio feedback signals. For users with normal vision capability, novel input methods combining force control and motion control could be developed for touch screens to enlarge the communication bandwidth between human and computers. For example, the pressure force can act as the third dimensional command in addition to the two dimensional movement of the fingertip within the screen's surface. Based on the identified speed-accuracy tradeoff model of human's force control skill, it is possible to divide the pressure force range into several segments of varied target force and tolerance, while each force segment is corresponding to an average response time. These force segments might be mapped to the control of multiple widgets in a virtual environment (Cechanowicz et al., 2007; Raisamo, 1999), and each widget could be allocated an allowable response time. By this way, it is possible to provide guidance for designing pressure-based input widgets with high manipulation efficiency and accuracy. Last but not least, force control is more private and personal than motion control because there is no visible displacement of the fingertips during pressure adjustment. Taking advantage of this point, secure input methods for tablet devices could be invented for some particular interaction tasks such as password input, where each force segment could represent a digit of the password.

Several topics can be studied in future work. The effect of feedback types, i.e. continuous vs. discrete feedback, could be an interesting topic. The present work showed that force control using discrete feedback obeys Fitts' law, while R-squared is not as large as that in previous motion or force control tasks using continuous feedback signals. For the visual feedback mode, our previous works showed that continuous feedback information was better than discrete signals. For the audio and haptic feedback modes, it remains an open question to develop effective continuous feedback signals and investigate their effects on improving the response time of accurate force control tasks.

Furthermore, it could be interesting to study the difference between using a fixed or varied starting force in each trial. In our work, the starting force was always zero. For two trials that have the same difficulty level, but with different starting force magnitudes, the response time may be different. For example, even though the force step and the tolerance is the same for two trials ("from 1 ± 0.1 N to 2 ± 0.1N" or "from 2 ± 0.1 N to 3 ± 0.1N"), the response time might be different. This may bring the necessity to explore a more appropriate speed-accuracy tradeoff model to account for this difference. In addition, the force measured in this paper is orthogonal to the surface of the force sensor. It could also be interesting to explore whether tangential forces, torque, or pull force also obey the Fitts' law.

In the next step, we plan to develop an attention training game using the multi-sensory feedback signal, and perform a user study to compare the effect of different channels for modulating attention. Another future work is to develop a wearable wrist watch that uses pressure control of fingertips assisted by vibrotactile feedback to realize command input. We plan to evaluate the performance of this novel input method for supporting quick and accurate input of English characters on a wearable device.

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