HaptiStylus: A Novel Stylus Capable of Displaying Flow and Rotation Effects

by

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This is to certify that I have examined this copy of a master's thesis by

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and have found that it is complete and satisfactory in all respects,

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ABSTRACT

With the emergence of pen-enabled tablets and mobile devices, stylus-based interaction has been receiving increasing attention. Unfortunately, styluses available in the market are all passive instruments that are primarily used for writing and pointing. In this research, we describe a novel stylus capable of displaying certain vibro-tactile and inertial haptic effects to the user. Our stylus is equipped with two vibration actuators at the ends, which are used to create a sensation of up and down flow along the stylus. The stylus is also embedded with a DC motor, which is used to create a sense of bidirectional rotation about the long axis of the pen. Through two psychophysical experiments, we show that, when driven with carefully selected timing and actuation patterns, our haptic stylus can convey flow and rotation information with high accuracy. Results from a further psychophysical experiment provide insight on how the shape of the actuation patterns effects the perception of rotation. Finally, experimental and subjective results from our interactive pen-based game show that our haptic stylus is effective in practical settings.

ÖZET

Kalem ile kontrol edilebilen tablet ve mobil aygıtların ortaya çıkması ile birlikte, dijital kalem kullanılan ara-yüzler ve insan ile olan etkileşimi artarak önem kazanmaktadır. Ancak, mevcut dijital kalemler pasif aygıtlar olup yalnızca yazma ve seçme gibi aksiyomlar için kullanılmaktadır. Bu araştırmada, kullanıcılara titreşim ve eylemsizlik prensibi kullanılarak dokunsal geribildirimler verebilen yeni bir dijital kalem sunulmaktadır. Tasarlamış olduğumuz bu dijital kalem, uçlara yakın olarak yerleştirilmiş iki adet titreşim motoru sayesinde kalemin uzun ekseninde aşağı ve yukarı yönde akma efekti oluşturabilmektedir. Ayrıca, gövdeye entegre edilmiş olan DC motor sayesinde kalemin uzun ekseni etrafında her iki yöne dönme efekti oluşturabilmektedir. Önerilen dokunsal hisler, iki ayrı psiko-fizik deneyi ile test edilmiş ve denekler belirlenmiş olan parametrelerde yüksek başarı oranları ile verilen hisleri algılamışlardır. Bir başka psiko-fizik deneyinin sonuçları ile DC motorun çalıştırılma şeklinin dönme hissinin algılanması üzerinde etkisi olduğunu gösterilmiştir. Son olarak, tasarlamış olduğumuz dijital kalem, kullanıcının görsel ve dokunsal algılar ile etkileşim halinde olduğu kalem bazlı bir oyunda test edilmiş ve deneyin sonuçları da verilen dokunsal his duyusunun kullanıcılar tarafından etkin bir şekilde algılandığını göstermektedir.

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NOMENCLATURE

ISOI	Inter stimulus onset interval
ω_{max}	Angular velocity
τ	Torque
ANOVA	Analysis of varience
CW	Clockwise
CCW	Counter clockwise
NVH	No visual and haptic
OH	Only haptic
OV	Only visual
VH	Both visual and haptic
MVH	Mismatch between visual and haptic

Chapter 1

INTRODUCTION

The emergence of tablets and mobile devices makes stylus as a popular input device. Although the stylus is a favored input device; the sense of touch is missing. Haptics, sense of touch, conveys information through tactile channel and enables the electronic devices to generate tactile feedback [1]. In this research, we introduce HaptiStylus, a stylus that can display haptic effects through the tactile channel for immersive and enhanced interaction.

HaptiStylus is equipped with two vibration motors positioned at the ends of its casing. Asynchronous actuation of these motors results in a sensory illusion known as “apparent tactile motion” [2]. With appropriate combination of stimulus duration and inter-stimulus onset interval (ISOI) of the vibration actuators, we show that a flow effect can be displayed along the body of the stylus.

The other effect that HaptiStylus is able to display is rotation effect about the long axis of the stylus. A high torque rated DC motor, positioned underneath the fingers enables us to create a sense of clockwise and counter clockwise rotation. Powering up the DC motor leads to a torque on the casing of the stylus until the motor reaches its maximum rotational speed. When the voltage pulse is cut off, due to the law of inertia, the motor displays a reaction torque in the opposite direction on the casing. In our primary studies, we showed that the torque created during startup dominates over the reaction torque, and creates a sense of rotation in the intended direction [3]. Here, we further investigate the effects of the input waveform patterns on the torque created by the motor and the perceived sense of rotation.

In this thesis, we report detailed results from three psychophysical experiments that explore the effects of timing and actuation patterns on the perception of flow and rotation effects. In particular, we explore the main effects and interactions of parameters including duration of actuation, inter-stimulus onset interval for the flow effect, and the onset/offset durations and input waveform patterns for the rotation effect. In addition, we report results from our assessment of our haptic stylus in a game designed to take advantage of the proposed haptic effects in an interactive virtual environment setup. This assessment is carried out by a more compact version of our stylus (HaptiStylus 2.0), which is fitted with a Bluetooth module for communication and an active stylus tip to enable fine grained tracking on a digitizing tablet. The results of three psychophysical experiments and the game indicate that, with carefully selected parameters, we can create highly perceptible flow and rotation effects. We do so not only in a targeted perception experiment, but also in an immersive game where users' primary focus is not on perceiving effects, but is on the game dynamics.

Chapter 2

LITERATURE REVIEW

2.1 Overview

There are a few studies in literature about displaying haptic effects on styluses through tactile channel. The proposed haptic styluses mostly include single haptic actuator and are capable of displaying simple tactile effects to the user. Lee et al. developed the first novel haptic stylus that displays forces along the longitudinal axis of the stylus by a solenoid actuator at the tip [4]. Kyung and Jun-Seok designed Ubi-Pen which provides vibration stimulus on the body of the stylus and additionally, displays texture information at the fingertip through an embedded pin array [5]. Wintergerst et al. proposed a stylus with a magnetically operated brake structure at the tip capable of displaying tactile illusions by controlling the level of friction [6]. Withana et al. suggested a haptic stylus that dynamically changes its effective length to display the illusion of submerging into the display [7]. Finally, Kamuro et al. proposed a pen-shaped ungrounded device to provide kinesthetic feedback through fingertips [8]. Our work complements this body work by the virtue of focusing on an entirely different set of effects (flow and rotation effects).

2.2 Flow Effect

There are bodies of work that focus on displaying flow effects. Sherrick and Rogers were the first to create the tactile illusion of continuous motion also known as apparent tactile motion by adjusting stimulus duration of actuators and inter-stimulus onset interval (ISOI) between two actuators [2]. Kim et al. introduced sensation of vibration flow between two vibration actuators by adjusting magnitude of vibration and timing of the actuators [9]. Israr and Poupyrev proposed an algorithm that displays continuous two-dimensional dynamic tactile effect at the user back through matrix of vibration actuators [10]. In addition to magnitude and timing parameters, Lim et al. used frequency modulation to display apparent tactile motion between both hands [11]. Tan and Pentland proposed a wearable tactile directional display by using a sensory phenomenon known as sensory saltation [12]. All these systems have focused on situations where the stimulus is displayed to the user through actuators that directly contact the human skin. In our case, however, the actuators do not come in direct contact with the skin, and vibrations are transmitted indirectly through the stylus casing. Furthermore, our work is the first to explore the apparent tactile motion illusion with a stylus form factor.

2.3 Rotation Effect

Other authors have suggested achieving rotation effect through various means. For example, Amemiya and Gomi generate direction cues through abrupt actuation of a rotating flywheel [13]. Porquis et al. proposed to create a torque illusion by altering strain energy distribution on the fingertip while holding a stylus [14]. Based upon gyroscopic effect, Winfree et al. proposed iTorqU 2.1 including a flywheel inside of two-axis gimbal to create directional torque feedback [15]. Unlike these studies, we use consecutive torque pulses through a motor attached to the casing of the stylus to generate the sense of bidirectional rotation.

Chapter 3

METHOD

3.1 Design of HaptiStylus

Our haptic stylus consists of a plastic cylindrical casing and three physical actuators: one DC motor for creating a sense of rotation, and two vibration actuators for generating flow effects. Two physical embodiments of our design are shown in Figure 3.1. The pen in Figure 3.1(a) was designed as a low-cost embodiment, which doesn't include any circuitry inside, whereas the embodiment in Figure 3.1(b) was designed as a standalone device with an embedded digitizing stylus tip, control circuitry for actuators, and a Bluetooth module for wireless communication (Table 3.1). The first design was used to evaluate the effectiveness of our approach for generating flow and rotation effects, which was further verified with the second design in a more practical computer game setting. The second design was also used to further investigate how the perception of rotation effect is influenced by the shape of the waveform that drives the actuators.

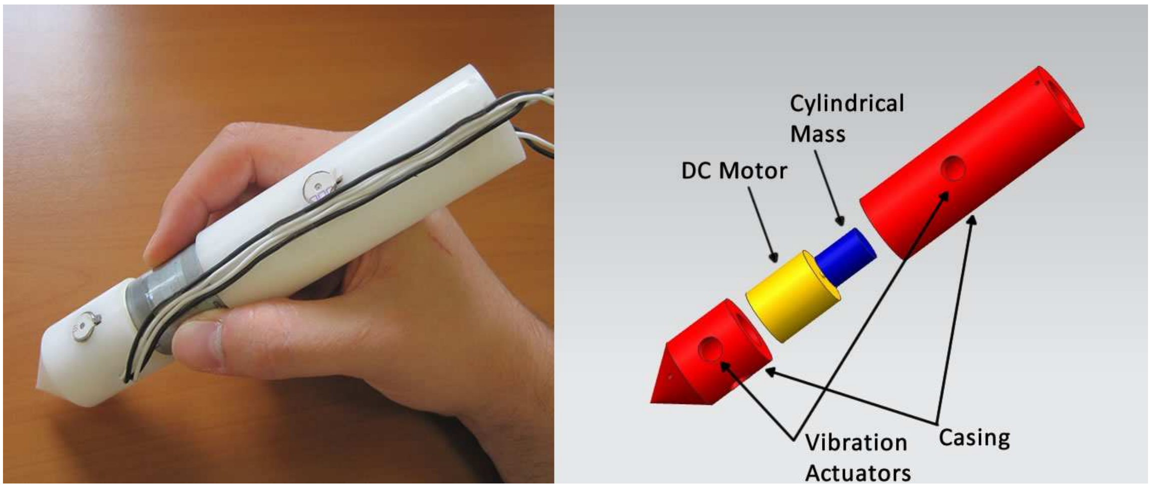
To generate vibro-tactile stimulus, we utilize eccentric rotating mass (ERM) to display a flow effect through the stylus. Coin type ERM actuators are compact, lightweight and have a larger frequency and amplitude bandwidth when compared to other vibration actuators. Two coin type ERM actuators are positioned close to the ends of the styluses (Figure 3.1). We used specialized haptic drivers to improve the performance of the vibration actuators. The vibration actuator drivers offer shorter start-up duration (0.1 ms) using only a single-ended pulse width modulation (PWM) input signal. The use of specialized driver circuits proved to be critical for achieving the targeted effects.

In order to display the rotation effect, we used a DC motor. The DC motor is positioned to coincide with the position of the fingers while holding the stylus. Our preliminary studies showed that using specialized circuitry to drive the DC motor is also critical for displaying the targeted haptic feedback. Hence, we used special purpose motor drivers for both designs (Table 3.1).

Components	HaptiStylus 1.0	HaptiStylus 2.0
Haptic Driver	DRV8601, TI	DRV 2603, TI
DC Motor	Generic	Re-max 13, Maxon
DC Motor Driver	L293D, ST	DRV 8835, TI
Microcontroller	ATtiny2313-PDIP	ATtiny2313-QFN
Communication	Wire	Bluetooth 2.0
Dimensions	Ø30mm, L=170mm	Ø18.5mm, L=192mm

Table 3.1: Physical components and specifications of both HaptiStylus designs

a)



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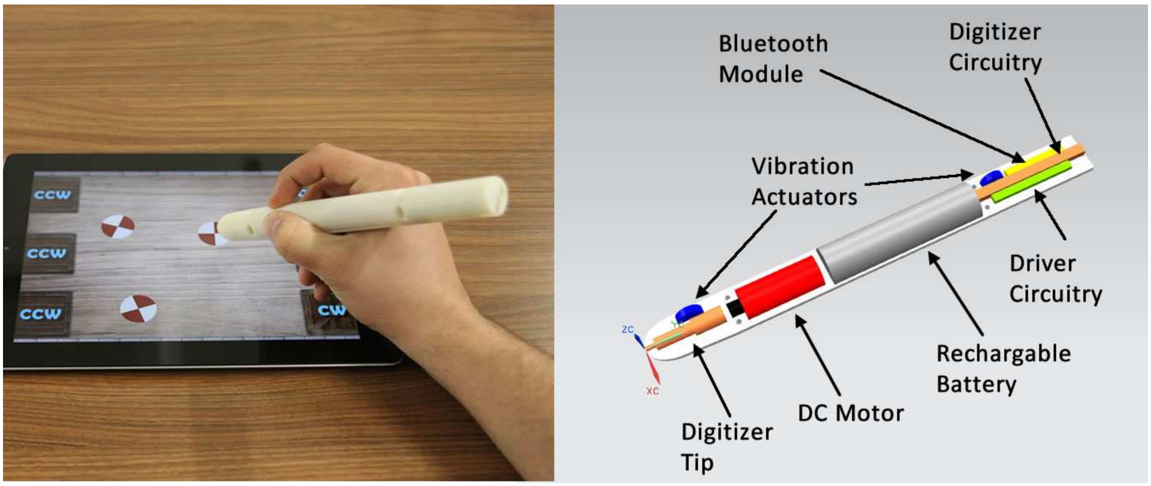


Figure 3.1: a) Physical components of HaptiStylus 1.0
b) Physical components of HaptiStylus 2.0

3.2 Generation of Tactile Effects

The HaptiStylus can generate two tactile effects: (1) up-and-down flow effect along the stylus, (2) rotation effect about the long axis of the stylus.

3.2.1 Flow Effect

We achieve the flow effect by actuating the two vibration motors while preserving a carefully selected delay between their actuation times. Sherrick and Rogers observed that actuating two vibration motors placed in close proximity of the skin leads to one of three sensations depending on the delay between the start-up times of the actuators [2]. In particular, depending on this delay, defined as the inter-stimulus onset interval (ISOI), subjects perceive either a single stationary target, two discrete stationary targets or a single moving target as shown in Figure 3.2. When ISOI is too small, it leads to the perception of a single and stationary stimulus (Figure 3.2 / Single Stationary). If the ISOI value is too large, it leads to the perception of two discrete stimuli near the actuators (Figure 3.2 / Discrete). Using a set of carefully selected ISOI values it is possible to create the sensation of stimulus moving from one vibration motor to the other (Figure 3.2 / Continuous).

Previous studies focused on identifying optimal stimuli duration and ISOI values for generating a flow effect, but focused only on sensation through human forearm and back [10, 12]. To our knowledge, our work is the first to investigate the perception of flow on a stylus through human hand and fingers. Moreover, earlier studies only considered the cases where the vibration motors are in full contact with the skin. Here, we show that humans can perceive the sense of flow even when there is no direct contact with the vibration motors.

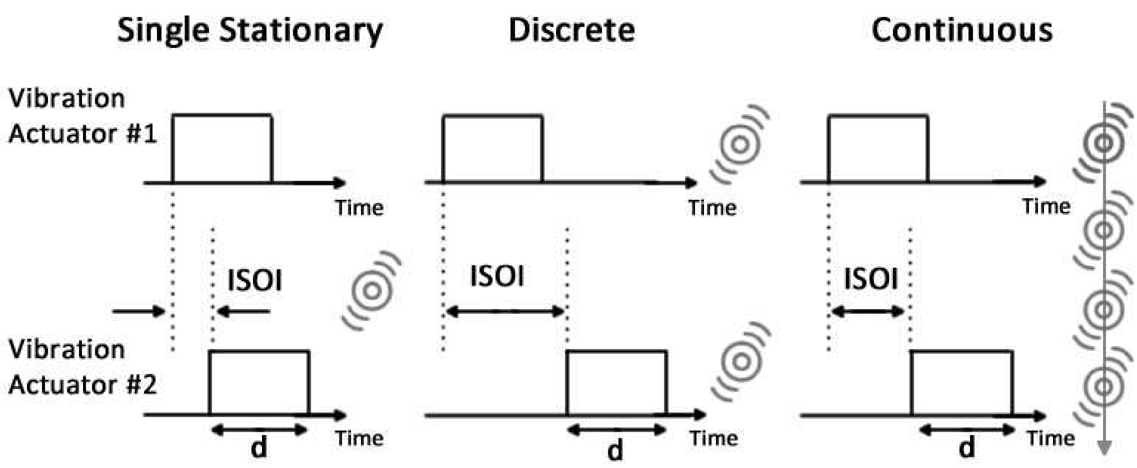


Figure 3.2: Effect of ISOI for constant duration (d) on flow effect

3.2.2 Rotation Effect

Unlike torque feedback devices, a stylus is an ungrounded apparatus, thus it is not possible to generate torque feedback using conventional means (e.g., grounded motors). Instead, we attempt to induce a sensation of rotation by powering the DC motor along the casing of the stylus through discrete pulses. This creates a short, but perceivable sensation of rotation about the axis of the pen (Figure 3.3). The torque generated by a motor is proportional to derivative of the angular velocity as well as the total inertia of the rotating armature.

The phenomenon that leads to the rotation effect is closely related to what happens when a DC motor is powered up. When a DC motor is first powered up, the rotor experiences non-zero angular acceleration until it reaches a terminal angular velocity ω_{max} (i.e, during the on-time state). This non-zero acceleration causes a corresponding torque τ in the casing of the motor in the reverse direction, which approaches to zero as the angular velocity approaches ω_{max}. When the motor is powered off, (i.e, during the off-time state), a reaction torque is generated in the opposite direction. Generating successive pulses with carefully selected frequency and duration creates a sense of rotation that is perceivable by the user. We report a comprehensive analysis of the effects of these parameters in the evaluation section.

Another parameter that affects the perception of rotation is the shape of the waveform that drives the DC motor. Based on this observation, which became evident in our preliminary experiments, we designed and conducted a controlled psychophysical experiment to compare three alternative waveforms. The results are reported in the evaluation section.

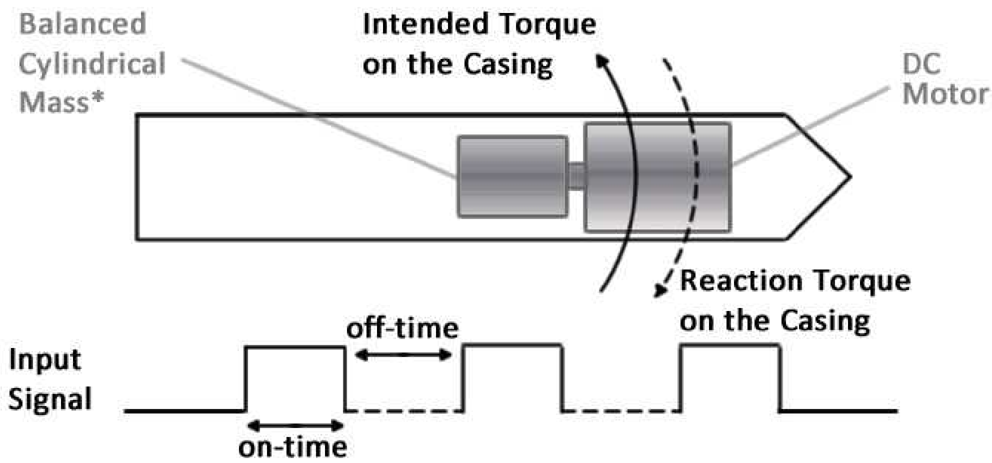


Figure 3.3: During on-time, motor generates torque about intended direction and during off-time, reaction torque is generated on the casing (*Balanced cylindrical mass was used for HaptiStylus 1.0 to achieve greater amount of intended torque)

Chapter 4

EXPERIMENTAL RESULTS

For each tactile effect, we conducted separate psychophysical experiments to determine the effective values of stimulus parameters. Experimental methods and general procedures for the experiments were the same and during the first two experiments, the HaptiStylus 1.0 was used. Two separate groups of 10 subjects participated to the experiments. In the first experiment, 5 female and 5 male participated with the average age of 24±2 and in the second experiment, 6 female and 4 male participated with the average age of 24±3. The participants did not have any known sensory impairments and they were all right handed. During the experiments, participants used their right hand to hold the stylus and left hand to enter their responses by pressing the keys on the keyboard. The subjects sat comfortably on a chair facing towards the computer screen displaying the experimental protocol and put on headphones that played “sounds of nature” to block auditory cues. In the second experiment, a visual barrier was placed to prevent the subjects from visual cues by seeing their hand and the stylus.

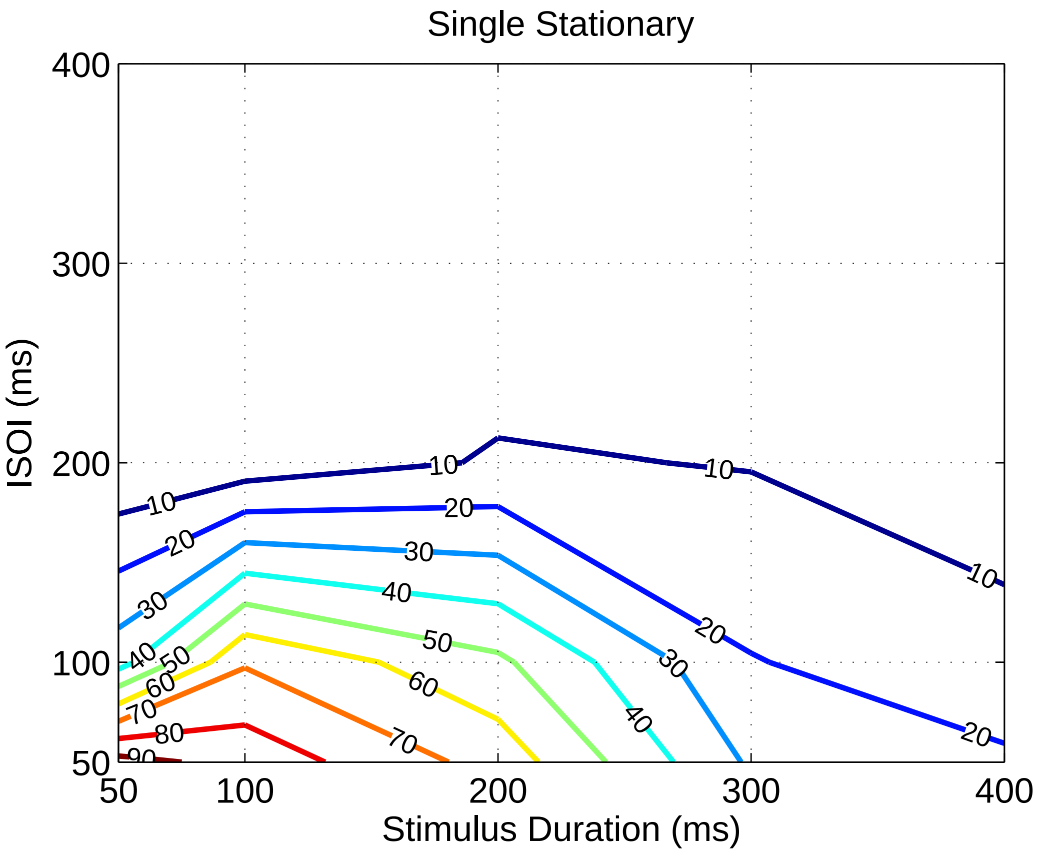
4.1 Experiment I

The goal of the first experiment is to determine the effective values of stimulus duration and ISOI for displaying the tactile flow effect. Depending on our preliminary studies, we selected five different values, 50, 100, 200, 300, and 400 ms, for stimulus duration and ISOI. Along the long axis of the pen, the flow effect moves from the tip of the stylus to the end of the stylus and vice versa. The experiment consisted of a total of 500 trials: 50 trials (5 stimulus durations x 5 ISOIs x 2 directions) with 10 repetitions for each trial. The subjects completed the experiment in two sessions with a break of at least 3 hours between the sessions and each session took no more than 20-25 minutes. The subjects were asked to characterize the tactile stimuli displayed through the vibration motors as “single stationary”, “discrete”, and “continuous” for each trial. To eliminate any bias during the experiment, the trials in each session were randomized. Before starting each session, a training session was applied to the subjects and during the training session, all possible combinations of the parameter values were presented.

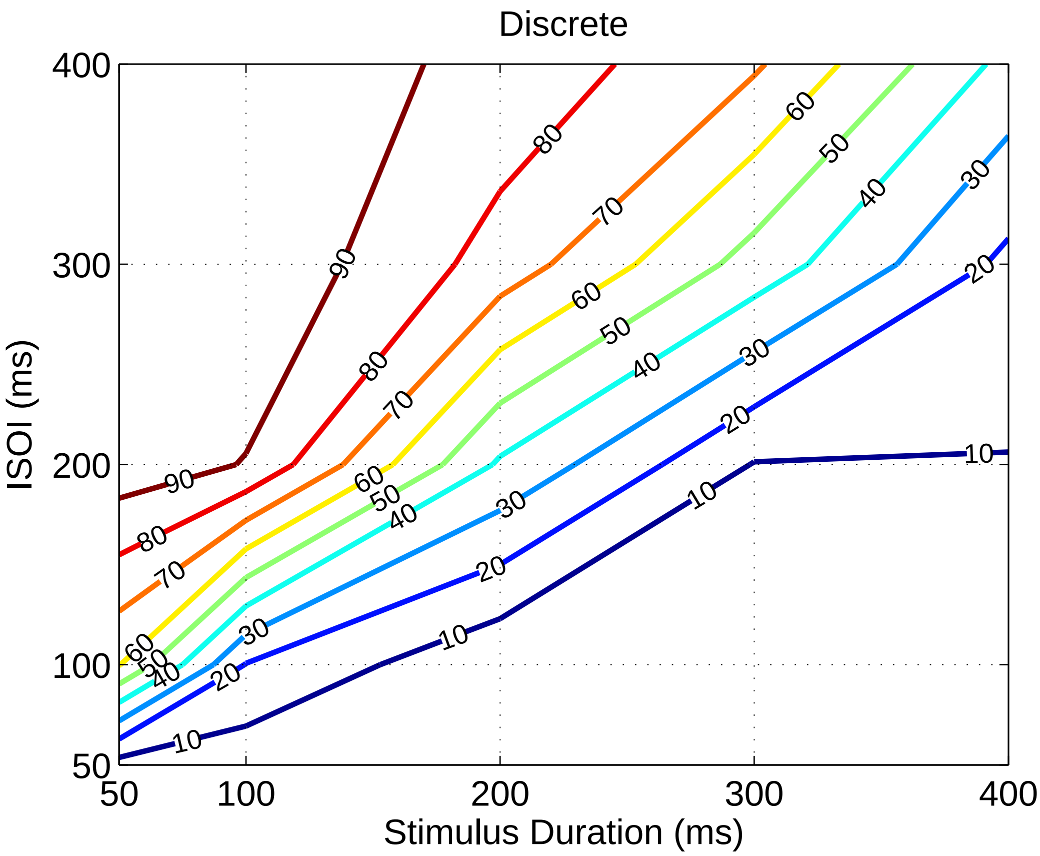
4.2 Experiment II

The goal of the second experiment is to determine effective values of on- and off-time durations of the input voltage pulses for displaying rotation effect. Depending on our preliminary studies, we selected six different values, 25, 75, 175, 275, 375, and 575 ms, for on- and off-time durations. About the long axis of the stylus, rotation directions of “clockwise” and “counter-clockwise” were presented during the experiment. The experiment consisted of a total of 720 trials: 72 trials (6 on-time x 6 off-time x 2 directions) with a 10 repetitions for each trial. The subjects completed the experiment in three sessions with a break of at least 2 hours between the sessions and each session took no more than 20-25 minutes. The subjects were asked to differentiate the directional rotation as “clockwise” and “counter-clockwise” in each trial. Before starting each session, a training session was applied to the subjects and presented all possible combinations of the parameter values.

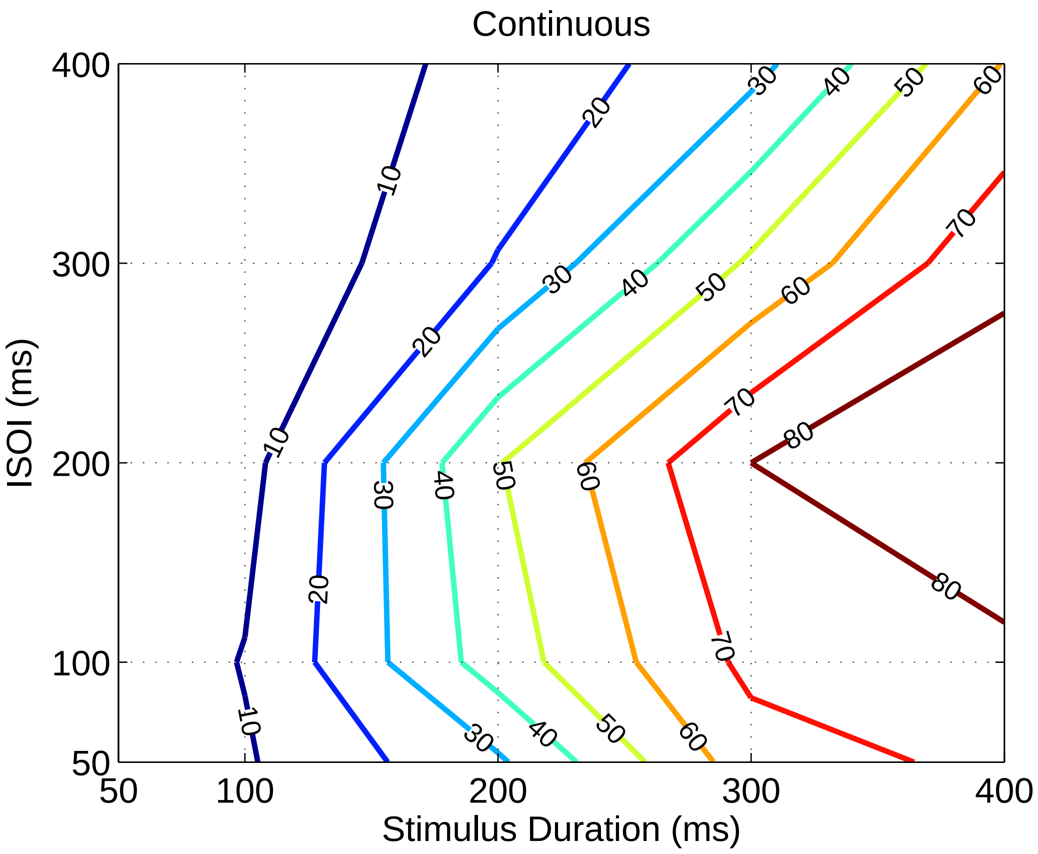
a)


Single Stationary
ISOI (ms)
Stimulus Duration (ms)
400
300
200
100
50
50
100
200
300
400
10
20
30
40
50
60
70
80
90

b)


Discrete
ISOI (ms)
Stimulus Duration (ms)
50
100
200
300
400
50
100
200
300
400
90
80
70
60
50
40
30
20
10

c)


Continuous
400
300
200
100
50
50
100
200
300
400
ISOI (ms)
Stimulus Duration (ms)
10
20
30
40
50
60
70
80

d)

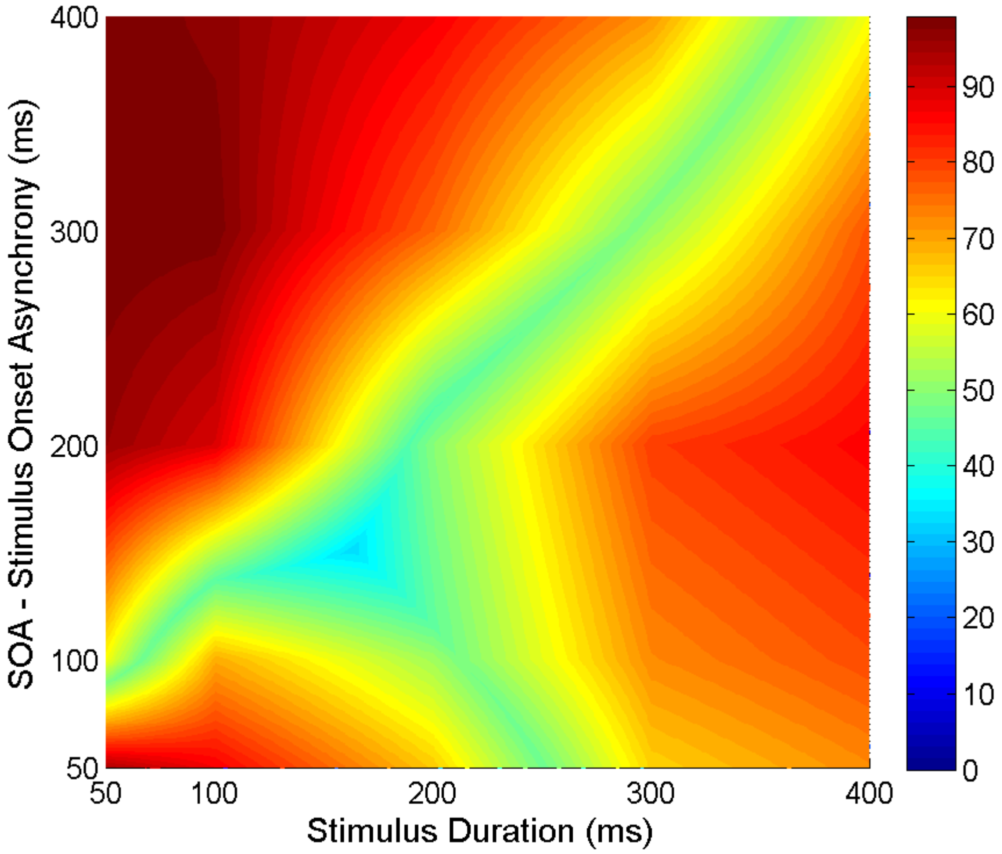


Figure 4.1: Tactile Flow Effect: Mean percentage of votes for two directions of flow. The contour graphs on the top row display the percentage of the votes given by users to each rating class (single stationary (a), discrete (b), and continuous (c)) for combinations of various ISOI and stimulus duration values. The bottom graph combines these plots and shows the rating of the most dominant effect at each point in terms of percentages. Note how the valleys in the combined plot clearly divide the space into three distinct regions corresponding to distinct effects.

4.3 Results

Figure 4.1 shows the results of the first experiment. Using the mean percentage of votes for two directions of flow (from tip to the end of the stylus or vice versa), the concise graph shows the effect of stimulus duration and ISOI values on the perception of vibrotactile stimuli. The figure also clearly illustrates the three perceived effects by the subjects: the bottom left region representing the “single stationary”, the top left region representing the “discrete”, and the middle right region representing the “continuous” stimuli.

We investigated the effects of stimulus duration, ISOI, and the direction of tactile flow on the perception of three possible cases. The responses of the subjects were also analyzed by a Three-Way Repeated Measures Analysis of Variance (ANOVA) and the significance level of $\alpha=0.05$ was used throughout the analysis. Due to our analysis, duration of vibration stimulus is a significant factor [$F(4,36)=102.64$, $p<0.05$] for perceiving the flow effect. Paired t-tests suggested that the perception accuracy of the tactile flow effect is higher as duration of stimulus increases ($p<0.05$). The ANOVA analysis also suggested that ISOI was a significant factor on perception of the flow effect [$F(4,36)=7.18$, $p<0.05$]. Paired t-tests and Figure 4.1(c) suggest that the ISOI values between 50 and 200 ms were perceived as “continuous” stimuli. The direction of the tactile flow as a third parameter had no effect on the perception of the tactile flow affect due to results of the analysis [$F(1,9)=0.03$, $p=0.86$]. In conclusion, the analysis results show that stimulus duration and ISOI are effective parameters on perceiving the flow effect whereas the direction of flow has no effect.

The Figure 4.2 shows the effect of on- and off-time durations on the perception of rotation effect displayed in the second experiment. On the graph (mean percentage of votes for two directions of rotation), the color diagram represents the accuracy of successfully perceived directional rotation by the subjects. Further analysis was utilized with Three-Way Repeated Measures Analysis of Variance (ANOVA) to investigate significant parameters of this haptic effect such as on-time duration, off-time duration and direction of rotation. A significance level of $\alpha=0.05$ was used throughout the analysis. The analysis results suggested that both on- and off-time duration of stimulus are significant factors effecting the perception of rotation effect and the quantitative results of on-time duration [$F(5,45)=4.49$, $p<0.05$] and off-time duration [$F(5,45)=13.32$, $p<0.05$], respectively. As shown in Figure 4.2, the subjects have identified more successfully the directional rotation effect at higher values of on- and off-time durations. ANOVA analysis also suggested that the direction of rotation has no effect on the perception [$F(5,45)=0.03$, $p=0.86$]. In conclusion, the perception of rotation effect only depends on the on- and off-time duration parameters.

In addition to the results presented above, further analysis of the flow effect reveals that the stimulus duration and flow direction factors interact ([$F(4,36)=141.85$, $p<0.05$], multi-way ANOVA). In particular, optimal stimulus duration depends on the direction of the flows effects (e.g., longer durations yield higher accuracies for the downward flow effect). This observation is noteworthy, because it suggests that exploring optimal duration parameters for the two directions independently is worth the effort.

Similarly, in addition to having main effects, the on- and off-times also interact. In other words, while perceiving sensation of rotation, on- and off-time do not collectively explain all the influence of test values. The variations of percentages of successful votes in Figure 4.2 can be based on this interact (i.e. percentage of successful votes for fixed 275ms and 375ms on-time values). Further investigation of relationship between the perception and independent variables are beyond the scope of this study.

The Experiment-I also revealed that the effective parameter values for obtaining apparent tactile motion in a hand-held stylus differs from the values reported in previous studies performed on the human forearm and the back [2, 10]. This result can be explained by the differences in the sensitivities of the human hand, the fingertips, the forearm and the back.

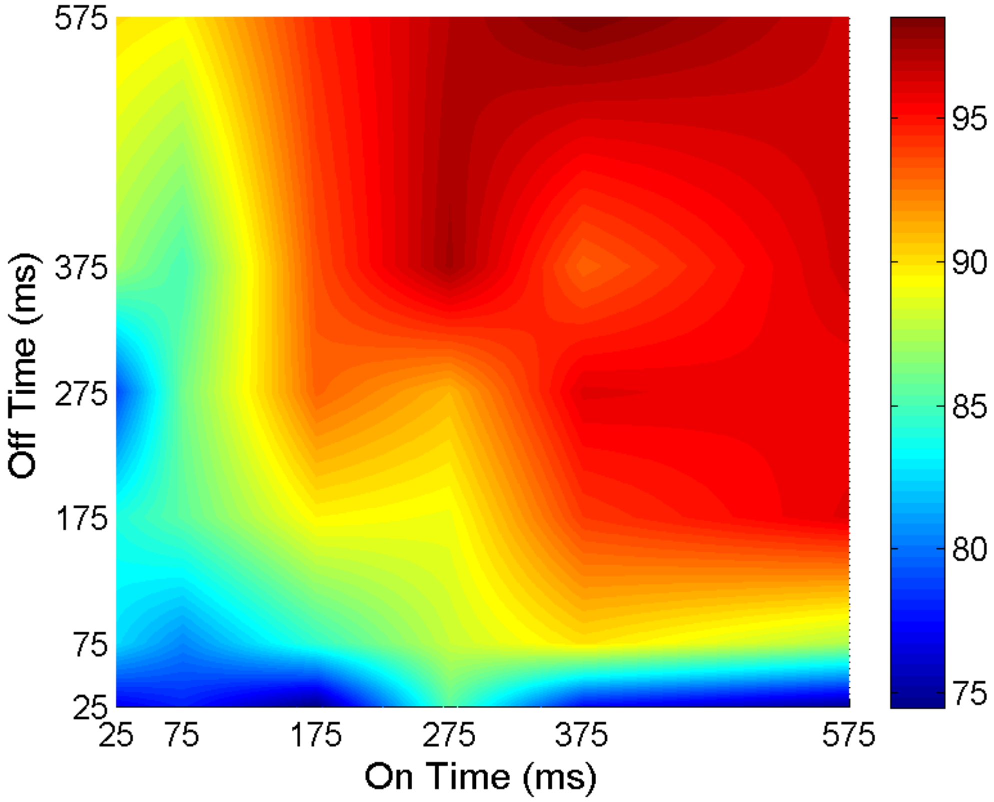


Figure 4.2: Rotation Effect: Mean percentage of votes for two directions of rotation. The color bars next to the plots indicate the accuracy of perceived direction.

Chapter 5

WAVEFORM USER STUDY

Rotation effect is successfully generated by square shaped input pulses as described in the second experiment. In this experiment, we further investigate how various input waveform patterns affect the perception of the rotation effect. Due to our preliminary studies, we carefully selected three significant input voltage waveforms to investigate in the third user study. As shown in Figure 5.1, three waveform patterns are tested during the experiment; square shape, increasing pattern and decreasing pattern. The goal of the user study is to determine the most effective waveform to display rotation effect through the HaptiStylus 2.0.

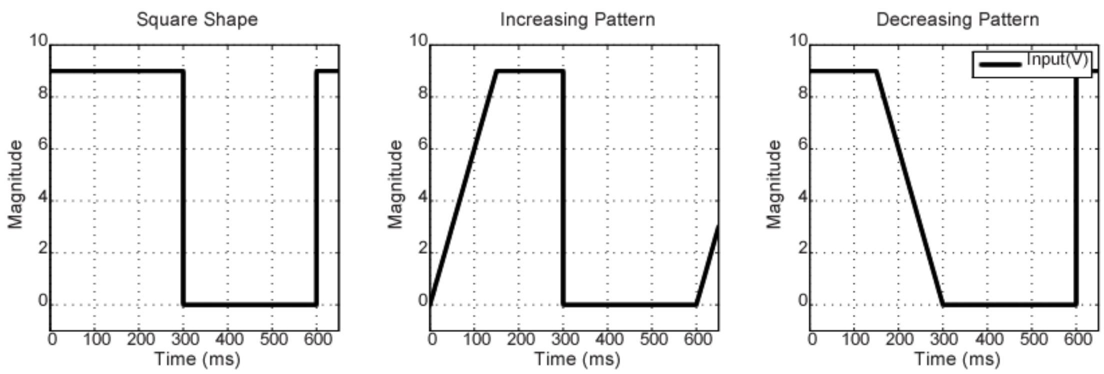


Figure 5.1: ”Square Shape”, “Increasing” and “Decreasing” input waveform patterns for rotation effect

5.1 Experiment III

The same experimental procedures were applied to the participants as second experiment and the experiment was conducted using HaptiStylus 2.0. There were 10 subjects (5 female and 5 male) and the average age of the subjects was 25±2, respectively. We selected three different values, 50, 200, and 350 ms for on- and off-time durations for two directions of rotation about the long axis of the stylus. There were a total of 180 trials in this experiment: 18 trials (3 on-time durations x 3 off-time durations x 2 directions) with 10 repetitions of each trial. The subjects completed the experiment in two sessions in the same day and each session took no more than 20 minutes. In each trial, the subjects were asked to differentiate if the torque displayed through the casing as “clockwise”, or “counter-clockwise” with respect to the long axis of the stylus. The trials in each session were randomized to eliminate any bias. Before starting the experiment, the subjects were presented a training session including all possible combinations of the duration values and waveform patterns.

5.2 Results

In Figure 5.2 concise graphs show the effect of input voltage waveform to the perception of directional rotation in the third experiment. In each plot, red colored region represents the parameter space in which the direction of rotation was perceived successfully by the subjects. We also analyzed the responses of the subjects by One-Way Repeated Measures Analysis of Variance (ANOVA). A significance level of $\alpha=0.05$ was used throughout the analysis. ANOVA results suggested that input voltage waveforms significantly affect the perception of rotation effect [$F(2, 26) = 41.96$, $p<0.05$]. The results also showed that subjects have identified the direction of rotation more successfully with decreasing pattern waveform compared to square shape input waveform. The results of the third experiment clearly suggest that, besides on- and off-time durations, input voltage waveform is another significant factor on perception of rotation effect. For example, at 200 ms on- and off-time values, the accuracies of the perceived direction are 90%, 78% and 95.5% for square shaped, increasing, and decreasing waveforms, respectively (Figure 5.2). The reason behind the increase from 90% to 95.5% percentage correct choice of directional rotation requires additional psychophysical experiments that are out of scope of this paper.

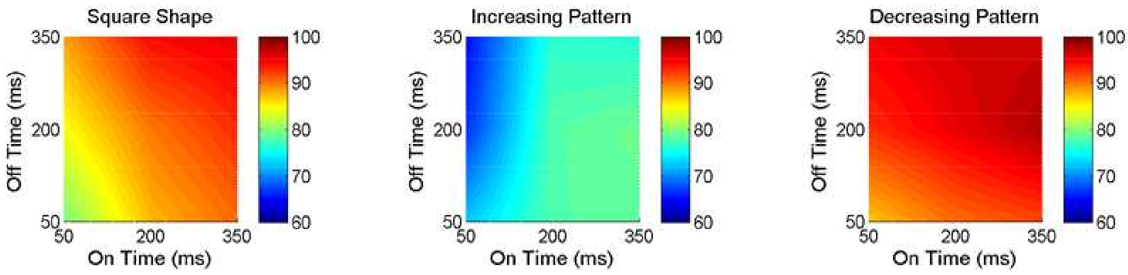


Figure 5.2: Percentage correct choice of ”Square Shape”, “Increasing” and “Decreasing” waveform patterns

Chapter 6

SPINNING TOP GAME

To evaluate the effectiveness of the proposed haptic effects in an application, we developed an interactive pen-based game in 2-D, called “Spinning Tops”, using a game engine (Game Maker, https://www.yoyogames.com/studio). We conducted the game with 15 subjects and the average age of the subjects was 23±5, respectively. During the game, tactile flow effect and rotation effect were displayed to the subjects through HaptiStylus 2.0. Due to the previous psychophysical experiments, the most effective parameters are selected while displaying both effects. As shown the Figure-8, the game scene involves 3 tops, spinning in 3 different speeds, 2 directions, and 3 boxes on each side to drop the tops. The boxes on the left and right were labeled as “CCW” and “CW”, indicating the direction of spin as “counterclockwise” and “clockwise”, respectively. The goal is to identify the spinning direction of each top, then drag and drop it to the appropriate box using visual and haptic cues. The subject selects the appropriate box based on the spinning direction of the selected top (hence it drags the top either to the left or right hand side), but one of three boxes must be available to drop the top. The direction of the spin (CCW versus CW) is conveyed to the user via the visual and tactile (rotation effect) cues while the availability of the box (open versus close) is conveyed to the subject through the haptic flow effect only. The box is open (closed) for the drop if there is a haptic flow from the distal (proximal) end of the stylus to the proximal (distal) end of the stylus.

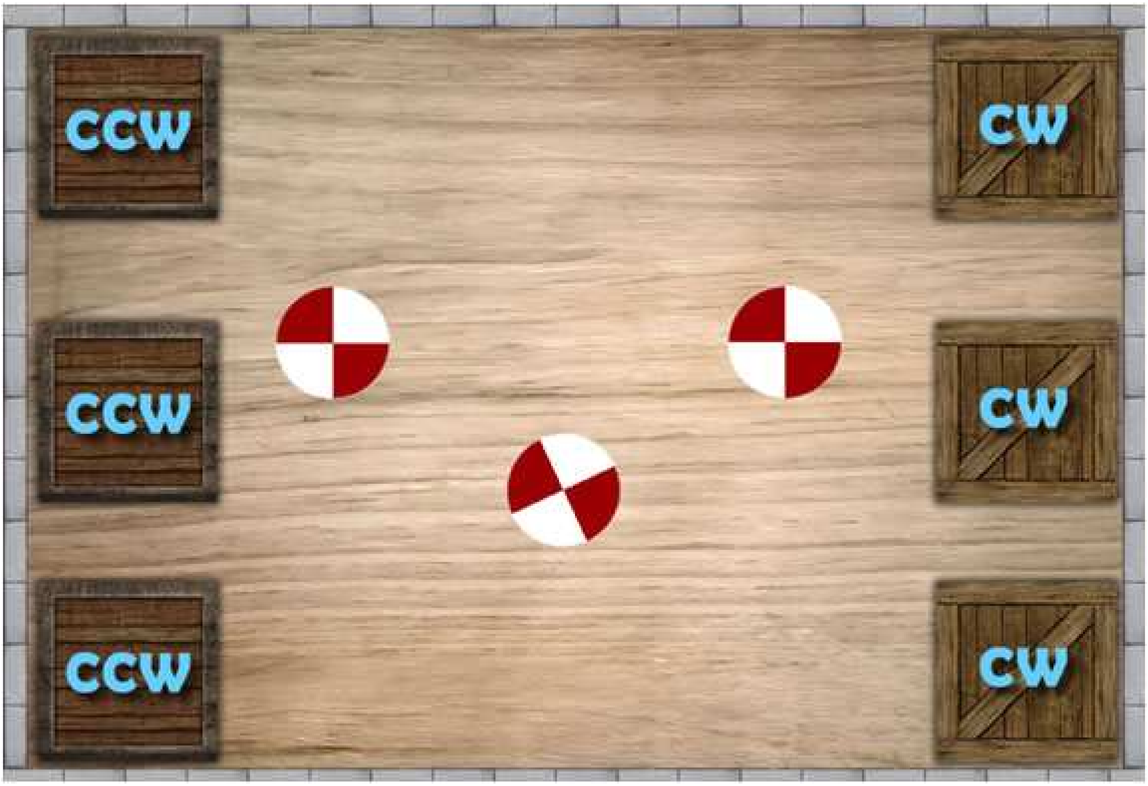


Figure 6.1: Screenshot of Spinning Top Game

6.1 Experiment I & Results

We investigated the effect of haptic cues on the perception of spin direction and availability of the boxes when the visual cues in the scene are not sufficient to make decisions about them. For this purpose, the tops were rotated 90 degrees per frame in the visual scene and the visual scene is updated at 30 frames per second. Since the symmetrical pattern on the surface of tops repeats itself every 180 degrees, the subjects could not differentiate the direction of spin.

The experiment was performed under two different sensory conditions: a) NVH: no visual and haptic cues were available to the subjects about the direction of spin (CCW vs. CW) and the availability of the boxes (open vs. close). b) OH: only haptic cues are displayed to the subjects about the direction of spin (via rotation effect) and the availability of the boxes (via haptic flow effect). There were 40 trials in this experiment (2 sensory conditions x 2 spin directions x 10 repetitions). The trials were displayed to the subjects in random order.

The results of Experiment I are given in Figure-9 under "NVH & OH" and "Flow Effect" subfigures. As shown in the figure, the subjects make random decisions under NHV condition (the percentage of correct response is 45 ± 13 % and 32 ± 10 % for the direction of spin and the availability of the box, respectively) Note that the expected percent correct response is 50% (one out of two directions) for the direction of spin and 33% (one out of 3 boxes) for the availability of the box. However, these values were increased to 81±19% and 65±24%, respectively when the subjects were provided with haptic cues (OH condition). Further analysis, One-Way Repeated Measures Analysis of Varience (ANOVA), suggests that percentage of correct choice of NVH and OH cases are significantly different [$F(1,14)=27.7$, $p<0.0001$].

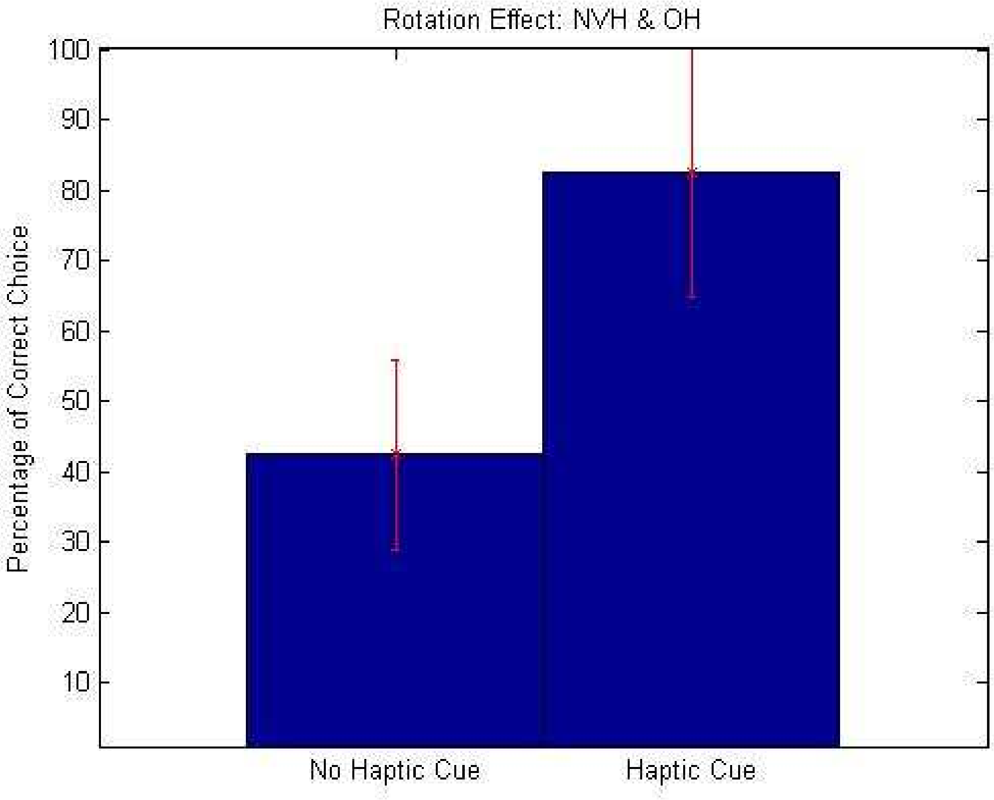


Figure 6.2: Percentage of correct choice for NVH & OH

6.2 Experiment II & Results

We investigated the effect of haptic cues on the perception of spin direction when there are already sufficient visual cues in the scene to make a decision about it. For this purpose, the tops were rotated at 45 and 135 degrees per frame in the CW direction and the visual scene is updated at 30 frames per second. When the tops were rotated at 45 (135) degrees per frame, it was visually perceived as they were spinning in the CW (CCW) direction (this is known as wagon wheel effect in literature). It was straightforward to differentiate the direction of spin by visually inspecting the scene.

The subjects played the game under 2 different sensory conditions: a) OV: only visual cues were provided to the subjects about the direction of spin, b) VH: Both visual and haptic (via rotation effect) cues were provided to the subjects about the direction of spin. As shown in Figure-9 / "OV & VH", the results suggest that the subjects were 100% and 98% correct in their response under OV and VH conditions and there is no significance between these two sensory conditions.

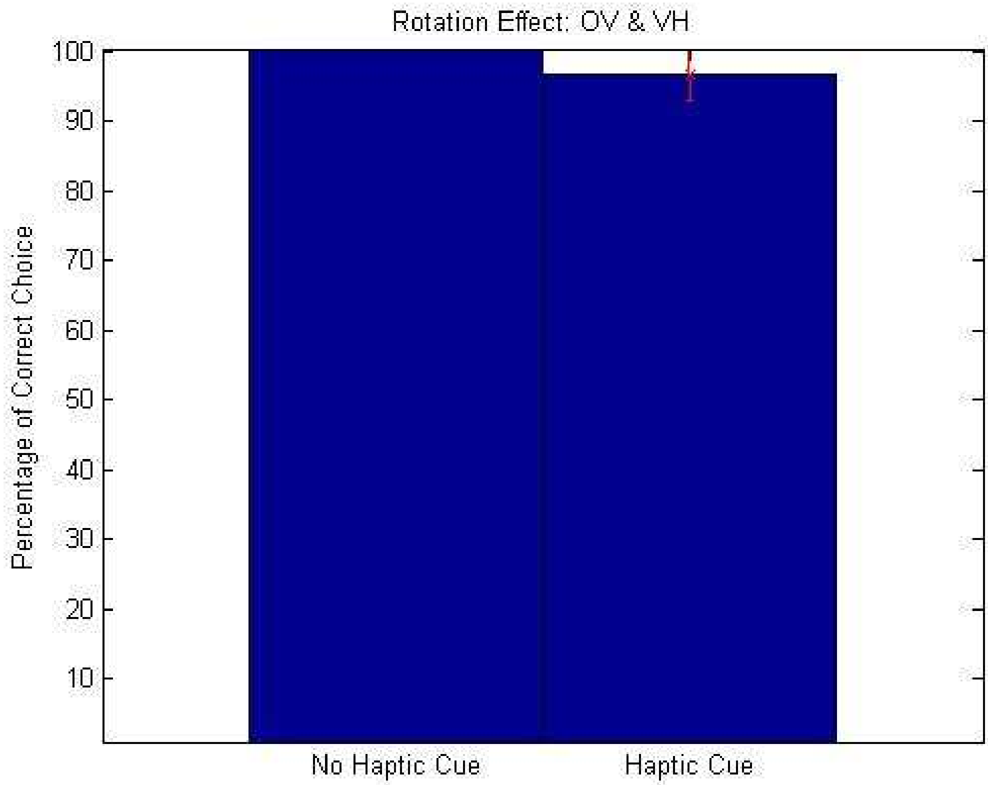


Figure 6.3: Percentage of correct choice for OV & VH

6.3 Experiment III & Results

We investigated the performance of the subjects when there is a mismatch between the visual and haptic cues. For this purpose, the tops were rotated at 45 and 135 degrees per frame in the CW and CCW direction. When the tops were rotated at 45 (135) degrees per frame, it was visually perceived as they were spinning in the CW (CCW) direction or vice versa. During mismatch between visual and haptic condition, the haptic cues were provided to the subjects in the direction opposite to the visually perceived one, hence causing a mismatch between the visual and haptic cues (MVH condition).

As shown in Figure-9 / “MVH”, under ambiguous sensory conditions, the subjects prefer the visual cues significantly more than the haptic ones in making a decision about direction of rotation. Also, One-Way Repeated Measures Analysis of Variance (ANOVA), suggests normal and MVH conditions are significantly different [$F(1,14)=38.7$, $p<0.0001$], respectively.

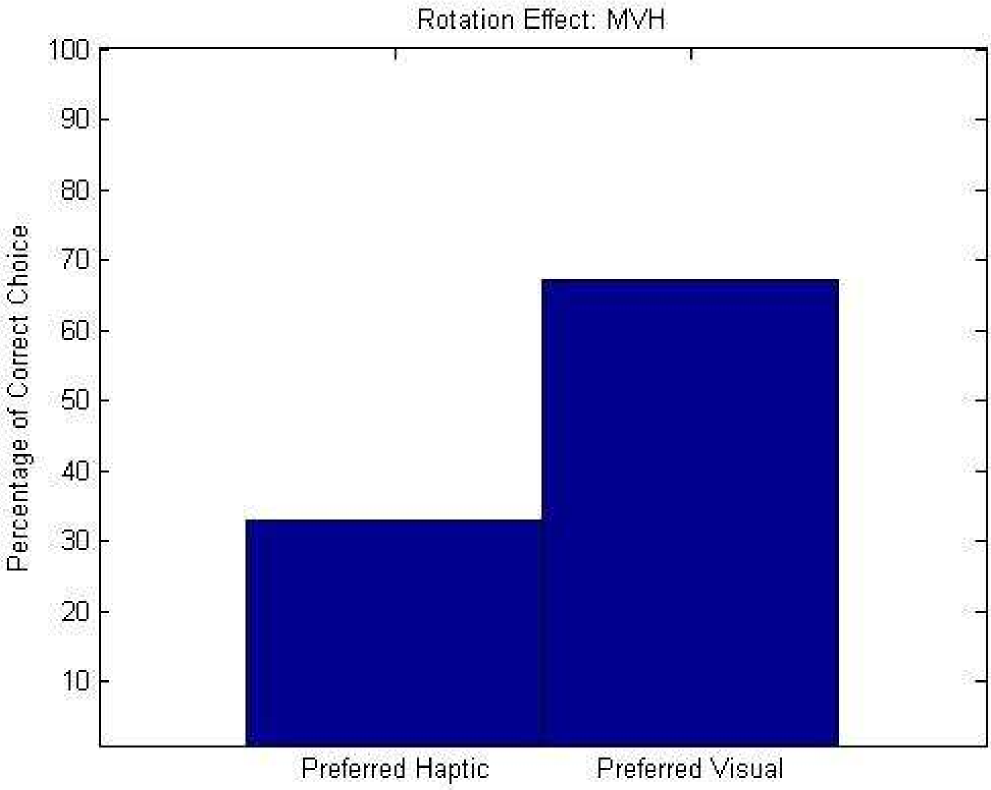


Figure 6.4: Percentage of subject preference for VH & MVH

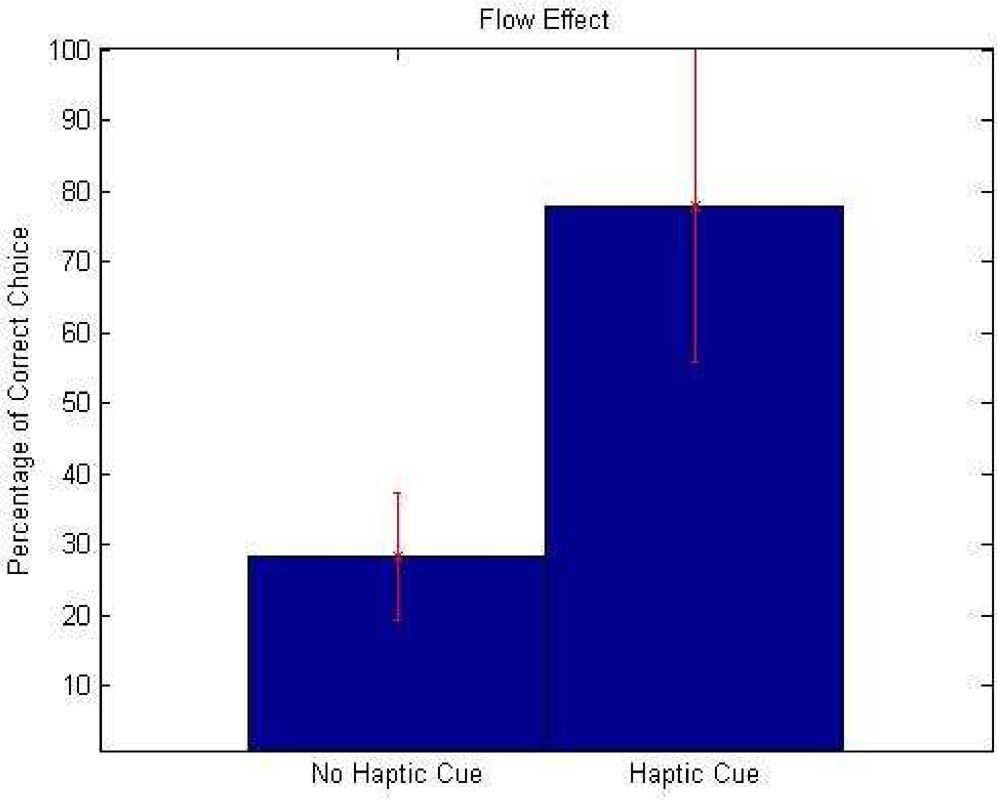


Figure 6.5: Percentage of correct choice for flow effect

Chapter 7

FUTURE WORK & CONCLUSION REMARKS

7.1 Future Work

In our experiments, we explored a comprehensive set of values for parameters that create a sense of rotation about the long axis of the stylus. However, we did not attempt to build a mathematical model of the relationship between the parameters and perception ratings. The challenge in relating input values directly to the perceived sensations lies in the fact that both the input parameters and the sensation ratings are discrete labels; however they are connected through a time varying torque signal, which is continuous. Hence, a feasible strategy might involve building a mathematical model of the relationship between input parameters and generated torque, as well as the relationship between the torque profiles and the perceived effects. In order to assess the feasibility of this idea, we collected torque data for combinations of input parameter values by attaching a torque sensor on the stylus casing. Preliminary results from a set of system identification experiments show that it is possible to obtain a mathematical model of the relationship between the input parameters and torque response. This leaves the task of relating the perceived user sensations to the displayed torque profiles as an interesting piece of future work. This may potentially lead to a framework for inferring optimal actuation parameters.

Another piece of future work involves improving the physical and ergonomic characteristics of the stylus. Although our second design is substantially more compact compared to our original stylus, more improvement is needed to achieve the form factor of a regular stylus. This is partly because all used parts (actuators and the batteries) were off-the-shelf items. Replacing these with custom-made versions with smaller form factors is likely to lead to an improvement. The improved form factor is likely to improve the ergonomic character of the stylus; however we believe that ergonomic factors deserve further exploration. A possibly direction might involve investigating parameters such as stylus length, center of gravity, casing texture, and pen-skin contact area.

7.2 Conclusion Remarks

We introduced a novel haptic stylus capable of displaying two tactile effects to the user: the flow effect and the rotation effect. The flow effect was displayed by asynchronously activating two vibration motors positioned two ends of the stylus. The rotation effect was displayed through a DC motor creating torque pulses in intended direction. We explored the effective parameter spaces for both tactile effects through psychophysical experiments and in an interactive pen-based game. The results of psychophysical experiments using both HaptiStylus designs proved that the proposed tactile effects are successfully perceived by the subjects with high accuracies.

Our design opens new avenues for exploration in the pen-based computing and haptics communities. We believe that HaptiStylus can be used in variety of mobile applications including games, entertainment, and education. For example, injection/discharge of fluids (e.g. simulating needle injection in a game), trajectory of a moving object towards/away to/from the scene (e.g. approaching a fire engine in a video scene), and penetration into a soft object (e.g. touching and feeling the softness of organs in the scene) can be displayed to a user using the flow effect. Similarly, opening and closing of valves and screws, sense of rotational inertia in spinning (e.g. feeling winds during climate visualization) and rolling of objects (e.g. flying an airplane in a game) can be conveyed to the user via the rotation effect. This is not an exhaustive list, but serves as evidence of abundant potential uses.

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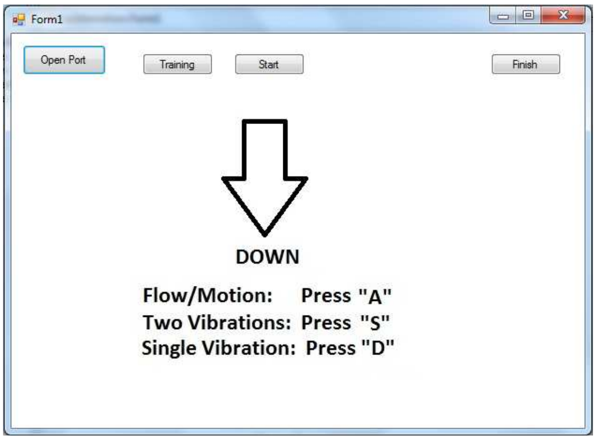
Appendix A

INSTRUCTIONS USED DURING THE EXPERIMENTS

EXPERIMENT I: FLOW EFFECT

- Please note that:
    - This study constitutes the central part in my research (it is a matter of graduation or not)
    - Hence, it will be appreciated if you focus on the task during the experiment
- The Experiment:
    - This experiment requires you to respond the sense of motion you get from the pen
    - You will use keyboard to answer questions
    - The aim of the experiment is to respond the given sensation as:
        - If this is a single vibration, illusion like motion or sequentially two vibrations at sides of the pen
        - İf it is motion or sequential, then which direction stimulus goes
- On the screen:
    - You will see this simple window on the screen



- Interface:
  - You will be using a pen with two vibration actuators on it
  - The pen will give you sensation of motion
  - You will be only holding the pen with one hand then answer the type of vibration and the direction using keyboard

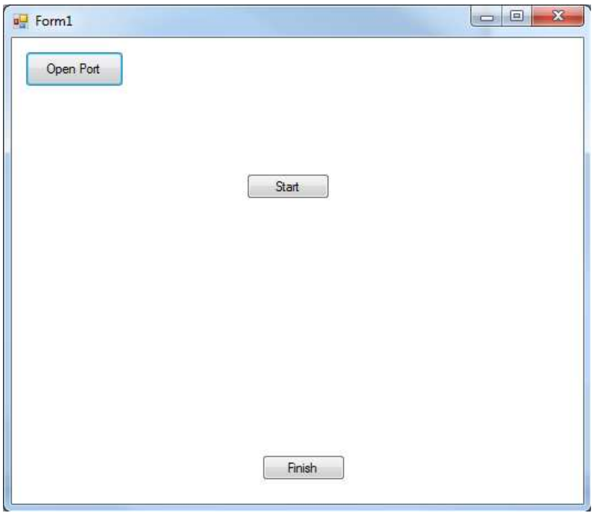
- Instructions:
  - Before starting experiment, there will be 2min training session. You will be presenting some of stimuluses
  - During the experiment, there will be 10 repetition of the test
  - Each repetition expectedly takes 2 min and there will be 2 blocks as following
    - 10 repetition (20min)
    - 10 repetition (20 min)
  - As you used to experiment, duration of a block will take less time
  - There will be 1-2 min break between each trial

- Hold the pen as showed below during the training session and the experiment

- Thank you for participation

EXPERIMENT II: ROTATION EFFECT

- Please note that:
    - This study constitutes the central part in my research (it is a matter of graduation or not)
    - Hence, it will be appreciated if you focus on the task during the experiment
- The experiment:
    - This experiment requires you to respond the sense of ratation you get from the pen
    - On the screen, you will see 3 buttons only
    - You will use keyboard to answer questions
    - The aim of the experiment is to respond the given sensation as if this is a clockwise rotation or a counter clockwise rotation
- On the screen
    - You will see this simple window on the screen



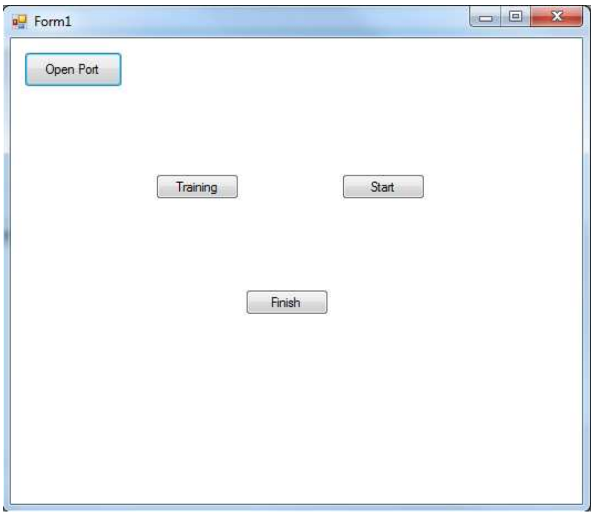
- Interface:
  - You will be using a pen with inertial feedback
  - The pen will give you a sensation of rotation in clockwise and counter-clockwise directions
  - You will be only holding the pen with one hand and answer the rotation direction with other hand using keyboard

- Instructions:
    - Before starting experiment, there will be 2min training session. You will be presenting some of stimuluses
    - During the experiment, there will be 10 repetition of the test
    - Each repetition expectedly takes 6 min and there will be 3 blocks as following
        - 3 repetition (18 min)
        - 3 repetition (18 min)
        - 4 repetition (24 min)
    - As you used to experiment, duration of a block will take less time
    - There will be 5-7 min break between each block
    - Hold the pen as showed below during the training session and the experiment

- I will be leading you for each block but when a block starts no more talking!
- Step 1:
  - Press “Open Port” button on the left top
- Step 2:
  - Press “Start” button at center
- Step 3: Use keyboard to answer
  - Press “D” for clockwise
  - Press “A” for counterclock wise
- Step 4:
  - Press “Finish” button at the below to finish a block
- Thank you for your participation

EXPERIMENT III: WAVEFORM USER STUDY

- Please note that
  - This study constitutes the central part in my research
  - Hence, it will be appreciated if you focus on the task during the experiment
- The experiment
  - This experiment requires you to respond the sense of rotation you get from the pen
  - You will use keyboard to answer questions
  - The aim of the experiment is to respond the given sensation as if this is a clockwise rotation or a counter clockwise rotation
- On the screen
  - You will see this simple window on the screen



- Interface
    - You will be using a pen with inertial feedback
    - The pen will give you a sensation of rotation in clockwise and counter-clockwise directions
    - You will be only holding the pen with one hand and answer the rotation direction with other hand using keyboard

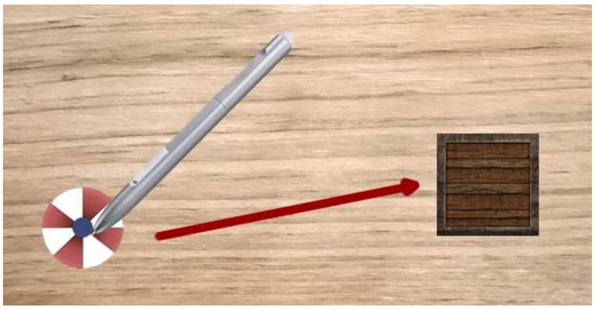
- Instructions
    - Before starting experiment, there will be 2min training session. You will be presenting some of stimuluses
    - During the experiment, there will be 10 repetition of the test
    - Each repetition expectedly takes 4 min and there will be 3 blocks as following:
        - 3 repetition (12 min)
        - 3 repetition (12min)
        - 4 repetition (17 min)
    - As you used to experiment, duration of a block will take less time
    - There will be 5-7 min break between each block
    - I will be leading you for each block but when a block starts no more talking!
    - Step 1:
        - Press “Open Port” button on the left top
    - Step 2:
        - Press “Start” button at center
    - Step 3: Use keyboard to answer
        - Press “D” for clockwise
        - Press “A” for counterclock wise

- Step 4:
    - Press “Finish” button at the below to finish a block
- Thank you for participation

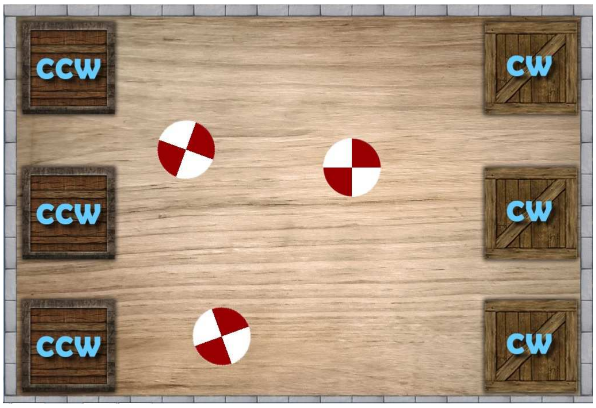
EXPERIMENT IV: SPINNING TOP GAME

PART I

- Please note that
  - This study constitutes the central part in my research
  - Hence, it will be appreciated if you focus on the task during the experiment
- Instructions
  - This game requires you to drop the spinning tops to the corresponding boxes
  - You will use a stylus (digital pen) during the game



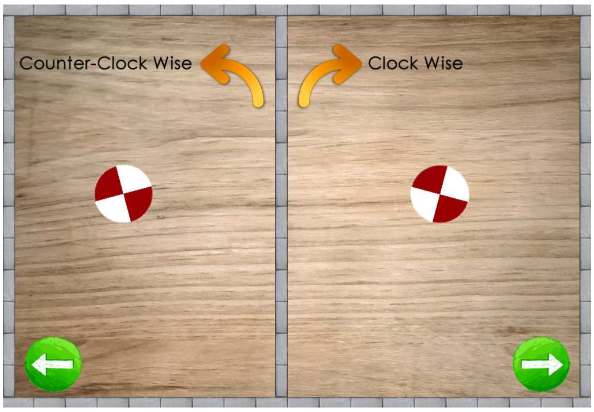
  - The aim of the experiment is to drag and drop the spinning tops into boxes according to their direction of rotation (CW or CCW)
  - The sense of direction of rotation will be given through visual channel only during the game



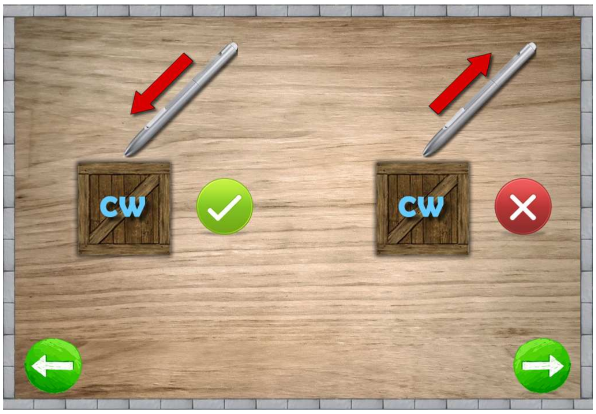
- Before starting experiment, there will be a training session with 2 repetitions to get used to the game
- During the game, there will be 10 repetitions for each part
- You will take a 2 min. break after 5th repetition

PART II

- Instructions
  - The aim of the experiment is to drag and drop the spinning tops into boxes according to their direction of rotation (CW or CCW)
  - The sense of direction of rotation will be given through visual and tactile channel during the game
  - On the next page, you will experience spinning tops in two directions



- During the game, sometimes the boxes do not accept the spinning tops
- Availability of the boxes will be given through tactile channel only
- If a box available, you will receive a flow effect from end to the tip of the stylus
- If a box is not available, in this case you will receive a flow effect from tip to the end



- Before starting the experiment, there will be a training session with 2 repetitions to get used to the game

- During the game, there will be 10 repetitions for each part
- You will take a 2min. bereak after 5th repetition

PART III

- Instructions
  - Same procedures will be applied as Part II
  - There won’t be a training session in this part