Manual Detection of Spatial and Temporal Torque Variation through a Rotary Switch

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Abstract—We report three experiments on manual detection of torque variations experienced through a rotary switch. The experiments were designed to investigate whether torque perception was determined by the spatial or by the temporal characteristics of the rotary switch. In Experiment I, manual detection thresholds of torque variation were measured with raised sinusoidal torque profiles that varied in spatial period from 2.8 degree to 180 degree per cycle. In Experiment II, the same was measured for torque profiles that varied in temporal frequency from 2 to 300 Hz. Experiment III was similar to Experiment 1 except that the participants were required to turn the rotary switch at two different speeds for each of seven spatially specified torque profiles (spatial period: 2.8 degree to 90 degree per cycle). A comparison of the thresholds obtained in Experiment III and those in Experiments I and II suggests that the detection of torque variations depends on the spatial, not temporal, specification of the torque profiles. Our results can potentially shed new light on the design and engineering specification of rotary switches.

Index Terms—Haptic interface, rotary switch, spatial and temporal torque variation, torque perception.

1 Introduction

This study focuses on a group of common haptic objects known as switches. Switches come in many shapes and forms in our everyday life. They not only serve important functions but also color our daily experience. The way a headlight switch looks, feels, and sounds inside an automobile, for example, influences our perception of not only the quality of the switch itself but the automobile as a whole. What then, are the perceptual attributes of switches? What makes one switch feel different from another? What engineering metrics can predict the haptic percept of a switch? How can a target percept for a switch be translated into engineering design specifications for mass production?

Traditionally, switch performance has been characterized by torque versus travel profiles (see Fig. 1 for a hypothetical engineering specification). Manufacturers of switches are often given such profiles (the solid piecewise straight line in Fig. 1) with tolerances (the dashed lines in Fig. 1). We argue that these profiles are not sufficient to describe the perception of the resultant switches. Due to manufacturing tolerances, high- as well as low-frequency noise components in the switch's torque versus travel profile contribute to the way the switch feels to the hand that manipulates it. For example, with some noise added to the profile (the jagged curve in Fig. 1), the switch will still pass the inspection as long as the jagged line stays within the tolerance boundaries defined by the two dashed lines. However, the two switches corresponding to the piecewise straight line and the jagged curve feel quite different: the former smooth and the latter rough. Our work was motivated by the desire to quantify the minimum levels of torque variations that can be felt. These levels can then be used as engineering guidelines to set manufacturing tolerances so as to limit undesired torque variations or noise.

Many studies have investigated the feel of switches and ways of emulating switches with electromechanical devices. Adachi et al. [1] studied the perceived quality of virtual push buttons using rating scales and found that the introduction of a click (a sudden reduction in force) improved the crispness of the buttons. MacLean was perhaps the first to propose the idea of using a haptic interface to capture the force-distance characteristics of a switch and of using the same haptic device to emulate the switch [2]. In the studies that followed, an instrumented haptic object was used as an expressive media for multimodal communication [3] and for manipulating digital media [4], and the dynamics of mechanical knobs were captured and played back [5] using special-purpose haptic interfaces. Other researchers have also simulated knobs and buttons [6] and used instrumented probe to measure and model the force characteristics of an automobile gearshift lever [7], computer keyboard keys [8], and push-button switches [9], [10], [11]. Hasser and Cutkosky [12] modeled the dynamics of a human hand holding a haptic knob in a simple pinch grasp as a second-order system. Such a model can lead to better algorithms for the stable control of an active electromechanical switch. Realizing the importance of haptic interfaces in an automobile, car manufacturers have embraced the idea of controllers with active haptic feedback [13]. Examples include the iDrive system co-developed by Immersion Corp.

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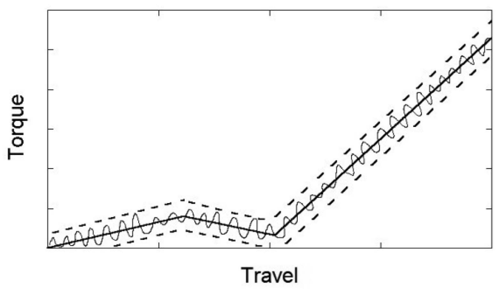

Fig. 1. Hypothetical engineering specifications of a detent switch. The solid piecewise straight line and the jagged line represent two specifications that both lie within the tolerance region defined by the dashed lines.

and BMW,[1] the Haptic Scroll Wheel in a Nissan concept car, and a high-torque rotary switch for vehicular instrument control [14]. New commercial products are continuing to be developed that explicitly address the cost/performance tradeoff [15] and the issue of cognitive load associated with the use of multifunctionality devices [16]. Despite all these efforts, however, much work still remains for fully understanding the physical and perceptual attributes of a switch. Recently, Weir et al. [17] performed a systematic measurement of the physical characteristics of linear push switches operated by human hands. The data are presented in a "haptic profile" that captures the feel of a switch during its operation, and minimizes the variability due to human button-pushing actions. Reisinger et al. [18], [19] proposed and tested the hypothesis that an energy versus angular travel profile is a better metric than a torque versus angular travel profile for describing the haptic perception of rotary switches. We build on these earlier studies to further characterize the physical and perceptual characteristics of a switch that is independent of user actions.

As far as human perception is concerned, the basic proximal stimulus delivered by a rotary switch is torque variation characterized in spatial or frequency domain. Therefore, it is important to first establish the human detection thresholds to torque variations as a first step toward a better understanding of how to design switches with desired percepts. One of the earliest studies on torque sensitivity was conducted by Woodruff and Helson [20]. Using a steel rod mounted on two ball-bearing assemblies, they measured Weber fractions for torque discrimination using different knob sizes and varying weights suspended from the rod. Jandura and Srinivasan measured the discrimination threshold for two constant torques using a custom-built instrumented screwdriver [21]. The two studies were similar in that they examined our ability to discriminate two *constant* torque levels. Our recent work has found, however, that humans are extremely sensitive to small-amplitude torque variations (Experiment 1 in [22]) superimposed on a low-frequency large-amplitude torque signal. The example shown in Fig. 1 further underlines the contribution of high-frequency components of the torque profile in forming a percept. Therefore, in addition to measuring the thresholds for detecting a constant torque change, it is also important to measure the thresholds for detecting dynamic torque variations over a large range of frequencies. Following the typical methodology for measuring detection thresholds as a function of stimulus frequency [23], [24], we have used sinusoidal torque variations in the present study to measure the torque-amplitude detection thresholds over a range of frequencies.

To design the stimuli, we needed to decide first whether torque variations should be specified in spatial or temporal frequency. Manufacturers typically provide design specifications in the spatial domain (i.e., in the form of torque versus travel curves) to their suppliers. However, depending on how fast a switch is turned, the proximal stimuli delivered to the hand is likely to vary in the temporal domain for the same spatial profile of the switch. It is therefore important to ask the question of whether thresholds depend on the spatial or temporal characteristics of torque variations. Our approach to answering this question was to measure detection thresholds for a set of torque stimuli designed in the spatial domain but turned at different speeds (Experiment III). We reasoned that if thresholds were determined by the spatial torque profile, then torque thresholds obtained at different turning speeds should be the same. If, however, thresholds were determined by the temporal torque profile, then different thresholds would be obtained at different turning speeds. Furthermore, by recording the actual speed at which a switch was turned and subsequently converting the spatial frequency to temporal frequency, we should be able to match the thresholds obtained from turning the spatial switch at different speeds to the thresholds obtained by using torque variations at the corresponding temporal frequencies. This approach required the availability of detection thresholds for torque variations specified in both spatial and temporal frequencies. To the best of our knowledge, however, such data did not exist prior to the present study. Therefore, they were estimated first in Experiments I and II, respectively.

The main objective of the present study was to investigate whether people are able to extract the correlation between simultaneous changes in angular displacement and torque profile. Put in another way, our participants had access to two temporal signals during active turning of a rotary switch: $\alpha(t)$ (angular displacement) and $\tau(t)$ (torque variation). We sought to find out if detection thresholds for torque variations depended on the temporal signal $\tau(t)$ alone or on the spatial signal $\tau(\alpha)$. Three experiments were conducted, as described below.

2 General Methods

This section covers the methods that are common to all three experiments in the present study. Methods that are specific to each experiment are presented later in the respective sections.

2.1 Apparatus

The experimental apparatus consisted of a rotary motor (Maxon RE25 118752), an optical encoder (Computer Optical Product, CP950, 4,096 counts per revolution), a power amplifier (Trust Automation 115), and a transformer (CUI MPS100-24), as shown in Fig. 2. A rotary (headlight) switch was attached to the end of the motor shaft. A

1. http://www.bmw.com/com/en/insights/technology/technology_guide/articles/idrive.html?search_type=index&article=idrive.

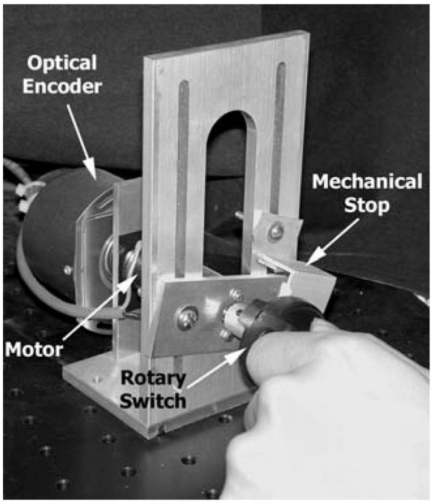

Fig. 2. Experimental apparatus used in the present study.

mechanical stop was used to ensure that the switch always started from the same position. A small torque in the clockwise direction (as seen by the participant) kept the switch against the mechanical stop when the participant was not actively holding or turning the switch. The participant held the switch with the thumb and the index finger of the left hand in a pinch grasp, and always turned the switch in the counterclockwise direction, as seen by the participant. The resistive torque stimuli (defined to be positive in the clockwise direction) were programmed to follow a predefined torque versus angular position (Experiments I and III) or torque versus time (Experiment II) profile. The angular position was defined to be 0 degree when the switch rested against the mechanical stop and increased as the switch was turned in a counterclockwise direction. The effective range of motion (where torque was nonzero) was 90 degree. This was accomplished by dropping the resistive torque to zero at the end of the initial 90 degree travel. The participant stopped turning the switch when no torque was felt. A small torque was then applied to the switch in the clockwise direction to bring it back to the mechanical stop. The torque values were calibrated using a switch-perception measurement system developed at Ford. A force/torque sensor (model mini40; ATI Industrial Automation, Apex, NC) coupled to the switch knob on one side and driven by a stepper motor on the other was used to collect the force output of the playback device under various velocity and acceleration profiles.

2.2 Procedure

The participant sat in front of a table with the apparatus on the left and a computer monitor and a keyboard on the right. During the experiments, the participant was instructed to rest the left elbow on the table in a comfortable position, and to hold the switch with the left hand in a pinch grasp. A black curtain was used to block the view of the apparatus and the participant's left hand. The participant wore a noise-reduction earphone to mask any sound emanating from the motor.

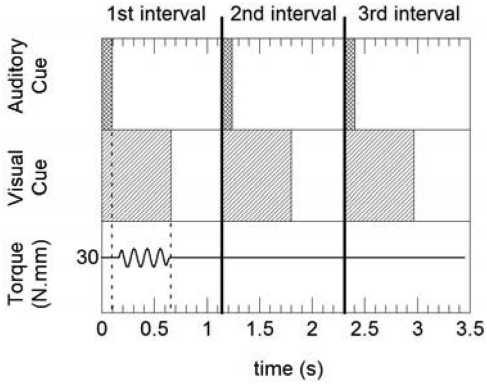

Fig. 3. Timing diagram of a three-interval trial in Experiment II.

Detection thresholds were determined with a three-interval forced choice (3IFC) paradigm combined with a one-up-three-down adaptive procedure, following the recommendation in [24] (see also [25] and a review of adaptive procedures [26]). Thresholds obtained this way correspond to the 79.4 percentile point on a psychometric function [25]. On each trial, the participant felt three stimuli: two of the stimuli were of constant torque (30 $\mathrm{N \cdot mm}$) and the other contained a sinusoidal torque variation superimposed on the constant torque. The constant torque of 30 $\mathrm{N \cdot mm}$ was selected based on the considerations that it was clearly perceivable and that it was not too high to cause fatigue for a typical experimental run that lasted at most 15 minutes. The participant's task was to indicate which of the three intervals ("1," "2," or "3") contained the varying torque. The magnitude of the sinusoidal torque ripple was reduced after three consecutive correct responses and increased after each incorrect response. The initial torque-ripple magnitude was always set to be higher than the anticipated detection threshold. It changed initially by 4 dB and then by 1 dB after the first three reversals. A reversal occurred when the torque-variation magnitude changed from increasing to decreasing, or vice versa. An experimental run was terminated after 12 reversals at the 1-dB step size. Each run typically lasted 70 to 90 three-interval trials.

The timing diagram for a trial in Experiment II is shown in Fig. 3. On each trial, a 100-ms 2-kHz auditory tone indicated the beginning of the first of the three intervals for the trial. A 650-ms visual signal (a text string on the computer monitor) indicated the current interval ("1st," "2nd," or "3rd interval"). The visual and auditory signals had the same onset time (see shaded areas in Fig. 3). The haptic stimulus began 150 ms after the onset of the auditory and visual signals and lasted for 500 ms. The offset of the visual signal coincided with the offset of the haptic stimulus, thereby serving to indicate the end of the haptic stimulus. This was necessary when the two reference (constant torque) intervals were presented consecutively. After a short pause of 500 ms, the auditory and visual signals for the next interval started all over again. The interval during which torque variation occurred (1st interval in the example shown in Fig. 3) was randomly selected from the three intervals. The timing diagrams for Experiments I and III are similar to that shown in Fig. 3, but with the abscissa specified in angular displacement instead of time.

TABLE 1
Participant Information

	S1	S2	S3	S4	S5	S6	S7	S8
Exp.I	√	√	√	√	√	√		
Exp.II	√		√		√	√	√	√
Exp.III	√		√			√		

A "√" indicates participation in the corresponding experiment.

A brief training procedure was conducted at the beginning of each run. After entering the experimental parameters for the run, the participant was given an opportunity to feel either stimulus alternatives (constant or varying torque) by selecting the corresponding icon on a computer monitor. The training was self paced and lasted as long as the participant wished. Data collection began immediately after the participant terminated the training. No correct-answer feedback was provided during the experiments. Each run typically lasted 10-15 minutes in duration. We conducted one run per participant for each experimental condition in each of the three experiments, from which six estimates of detection threshold were obtained (see Section 2.3 below; also [24]). We repeated the runs during which data failed to converge as judged by the experimenter, which happened infrequently. A 5-minute break was enforced between runs to prevent fatigue.

2.3 Data Analysis

Detection threshold was estimated by averaging the peak and valley torque values at the last 12 reversals. To estimate the standard error of the threshold, six estimates of the threshold were calculated from the six pairs of the peaks and valleys at the 12 reversals, and the corresponding standard error was obtained [24].

2.4 Participants

A total of eight participants (two females) took part in one or more of the three experiments. Table 1 shows which participants were tested in each of the experiments. Participants S1-S4 were coauthors of this paper. The age of the participants ranged from 22 to 49 years old and averaged 32 years old. Except for S1 who was left handed, the participants were right handed by self-report. They reported no sensorimotor impairment with their left hands.

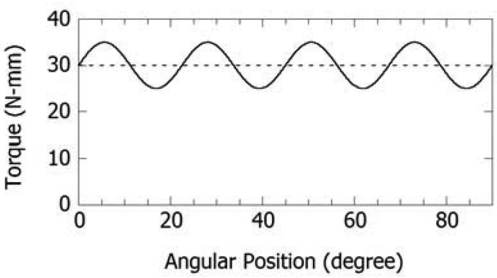

Fig. 4. An illustration of $\tau(\alpha)$: raised sinusoidal torque variations defined in the spatial domain (Experiment I). Shown are the torque offset (dashed line) and the sinusoidal torque variation (solid curve) with a spatial period of 22.5 degree.

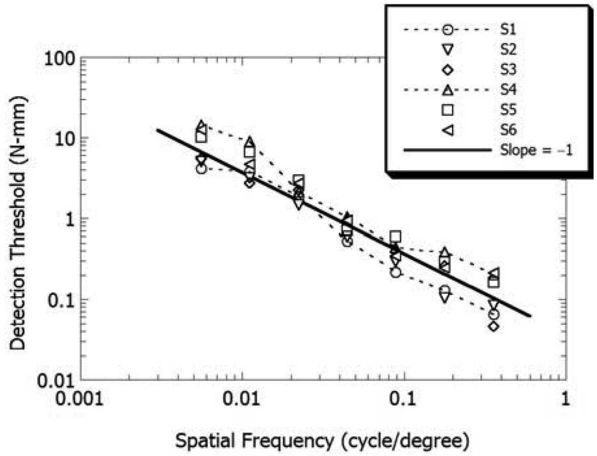

Fig. 5. Detection thresholds for raised sinusoidal torque variations defined in the *spatial* domain (Experiment I). Shown are individual participant's data as well as a fitting line with a slope of −1 (see text for details). For clarity, only the data points of S1 (with the lowest thresholds) and S4 (with the highest thresholds) are connected by dashed lines. The standard errors (not shown) are smaller than the symbol size.

3 Experiment I: Detection of *Spatial* Torque Variation

The first experiment measured detection thresholds for torque variations specified in the *spatial* domain when the rotary switch was actively turned.

3.1 Methods

The haptic stimulus was either a constant torque of $30\ \mathrm{N \cdot mm}$ or a raised sinusoidal torque variation defined in the *spatial* domain. Fig. 4 shows a varying-torque stimulus with a spatial period of 22.5 degree; or equivalently, a spatial frequency of 0.044 cycle/degree. Seven spatial periods equally spaced on a logarithmic scale were tested: 2.8, 5.6, 11.25, 22.5, 45, 90, and 180 degree/cycle. Note that at 180 degree/cycle and with a total displacement of 90 degree, only half a cycle of torque variation was presented to the participants. For ease of comparison with data from subsequent experiments, the spatial periods were converted to their corresponding spatial frequencies: 0.006, 0.011, 0.022, 0.044, 0.089, 0.179, and 0.357 cycle/degree. The ordering of the seven spatial frequencies in the experiment was randomized for each participant. The participants were allowed to turn the switch at whatever speed they desired.

3.2 Results

The detection thresholds obtained from the six participants are shown in Fig. 5 as a function of spatial frequency. For each participant, detection thresholds decreased as the spatial frequency of the torque variations increased, indicating that it was easier for the participants to detect a fast-varying torque than to detect a slowly varying one. The individual thresholds decreased from $14.34\ \mathrm{N \cdot mm}$ (S4 at 0.006 cycle/degree) to $0.05\ \mathrm{N \cdot mm}$ (S3 at 0.357 cycle/degree). A one-way analysis of variance (ANOVA) performed on the thresholds revealed a significant effect of spatial frequency $[\mathrm{F}(6, 245) = 91.76, \mathrm{p} < 0.0001]$.[2]

2. Alternatively, one threshold from each participant was used in a one-way ANOVA. The effect of spatial frequency was still highly significant $[\mathrm{F}(6, 35) = 14.31, \mathrm{p} < 0.0001]$.

TABLE 2
Linear Regression Analysis of Detection Thresholds in Fig. 5 on a Log-Log Scale (Experiment I)

	S1	S2	S3	S4	S5	S6
slope	–1.10	–1.07	–1.07	–1.06	–1.04	–1.04
std.err.	0.08	0.05	0.11	0.10	0.08	0.09

Listed are the slope and its standard error for individual participants.

The thresholds averaged across all participants varied from 8.64 to 0.13 $\mathrm{N \cdot mm}$ (28.8 percent to 0.43 percent, respectively, of the reference torque of 30 $\mathrm{N \cdot mm}$) as spatial frequency increased from 0.006 to 0.357 cycle/degree. This represented a 66-fold decrease in the threshold over a 64-fold increase in the spatial frequency of the torque variations. The data were well fit by a straight line with a slope of -1 on a log-log scale (solid line in Fig. 5). A linear regression analysis confirmed that the slopes of the best-fitting lines were about -1 for all six participants (Table 2). Therefore, the detection thresholds were inversely proportional to the spatial frequency; or equivalently, proportional to the spatial period.

The fact that the detection threshold versus spatial frequency data followed a straight line of slope -1 on a log-log scale implied that the thresholds probably depended on the maximum rate of change in the torque profile (Fig. 4). Assuming that the angular turning velocity followed a typical bell-shaped curve, then the torque versus time profile $\tau(t)$ would be different from the torque versus angular-position curve $\tau(\alpha)$ shown in Fig. 4. A natural question that arose was whether detection thresholds depended on the *spatial* or *temporal* characteristics of the torque variations. Therefore, the next experiment investigated the relation between detection threshold and *temporal* frequency.

4 EXPERIMENT II: DETECTION OF *TEMPORAL* TORQUE VARIATION

The second experiment measured detection thresholds for torque variations specified in the *temporal* domain when the rotary switch was held stationary.

4.1 Methods

In Experiment II, a torque ripple was programmed to be a small-amplitude sinusoidal function superimposed on a constant torque offset of 30 $\mathrm{N \cdot mm}$ (see Fig. 6). The sinusoidal torque ripple was specified by its magnitude ($\mathrm{N \cdot mm}$), *temporal* frequency (Hz) and duration (500 ms). To eliminate any possible step change in torque magnitude at the beginning or end of a stimulus, a Hanning window consisting of a 50-ms rise time and a 50-ms fall time was applied to the torque signal (note the slightly decreased amplitude in the first positive peak and the last negative peak in Fig. 6). The Hanning window was necessary in Experiment II because the torque waveforms were no longer guaranteed to begin and end at 30 $\mathrm{N \cdot mm}$. Ten *temporal* frequencies were tested: 2, 4, 8, 16, 32, 64, 128, 200, 256, and 300 Hz. They were selected to be equally spaced on a logarithmic scale except for the 200- and 300-Hz signals that were added in anticipation of low thresholds at these frequencies. The ordering of the 10 temporal frequencies during the experiment was randomized for each participant.

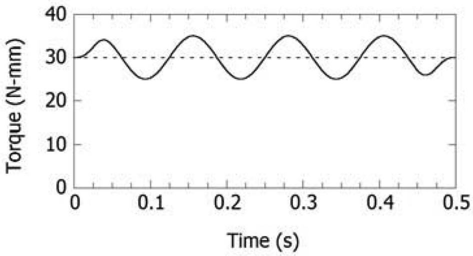

Fig. 6. An illustration of $\tau(t)$: temporal torque variations used in Experiment II. Shown are the torque offset (dashed line) and the sinusoidal torque variation (solid curve) at 8 Hz. Notice the slightly reduced amplitudes of the peak and valley at the beginning and the end of the signal, respectively, due to Hanning windowing.

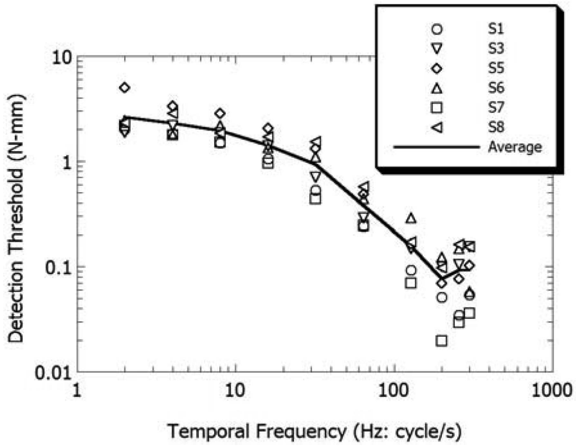

Fig. 7. Detection thresholds for raised sinusoidal torque variations defined in the *temporal* domain (Experiment II). Shown are the data for individual participants and the averages. The standard errors (not shown) are smaller than the symbol size.

The participants were instructed to turn the rotary switch slightly counterclockwise to take it off the mechanical stop, and to hold the switch still in space throughout the experiment. In other words, unlike the active turning motions required in Experiment I, a passive condition was used in Experiment II.

4.2 Results

Detection thresholds for the six participants over the frequency range 2-300 Hz, as well as the averages, are shown in Fig. 7. The data indicate a general decreasing trend for threshold as frequency increased, with the lowest thresholds occurring at the 200-300-Hz frequency range. Individually, detection thresholds ranged from 0.02 $\mathrm{N \cdot mm}$ (S7 at 200 Hz) to 5.04 $\mathrm{N \cdot mm}$ (S5 at 2 Hz), or 0.07 percent to 16.80 percent of the 30 $\mathrm{N \cdot mm}$ offset torque, respectively. A one-way ANOVA revealed a significant effect of temporal frequency: $\mathrm{F}(9, 350) = 153.43$, $\mathrm{p} < 0.0001$.[3]

The thresholds averaged across all participants (solid line in Fig. 7) started at 2.65 $\mathrm{N \cdot mm}$ at 2 Hz, reached a

3. Alternatively, one threshold from each participant was used in a one-way ANOVA. The effect of temporal frequency was still highly significant $[\mathrm{F}(9, 50) = 24.11, \mathrm{p} < 0.0001]$.

minimum of 0.08 $N \cdot mm$ at 200 Hz, and then appeared to increase slightly at higher frequencies. It is clear that the data shown in Fig. 7 did not follow a straight line on the log-log scale as the data in Fig. 5 did (Experiment I). Therefore, the data did not support the notion that the participants might have attended to the maximum temporal rate of change in torque ripples.

There is a striking similarity between the shape of the torque threshold curve obtained in Experiment II and the displacement threshold data available in the literature (e.g., [23]). This will be discussed further in Section 6.

To answer the question of whether the spatial or the temporal characteristics of the torque variations determined perception, in this case detection thresholds, the next experiment sought to create pairs of stimuli that were of the same spatial specification but differed in their temporal torque profiles. If thresholds remained the same for the stimuli despite changes in their temporal profiles, we would conclude that perception depended on the spatial, not temporal, characteristics of the torque stimuli. Conversely, pairs of stimuli that differed in their spatial characteristics but were similar in their temporal profiles were also created and tested. If we obtained similar thresholds for the stimuli despite their differing spatial specifications, we would then conclude that the temporal profiles of the stimuli determined perception.

5 Experiment III: Detection of Spatial and Temporal Torque Variations Using Different Turning Speeds

This experiment was designed to investigate the importance of spatial and/or temporal cues in determining torque perception thresholds. In a typical manipulation of the rotary switch, the temporal characteristics of the proximal stimuli are determined by the spatial definition of the rotary switch as well as the velocities at which the switch is turned. In order to answer the research question posted here, it was necessary to decouple the spatial and temporal attributes of a rotary switch. We did so by asking the participants to turn the switch at different speeds. With the detection thresholds measured in Experiment I (for *spatial* frequencies) and Experiment II (for *temporal* frequencies), we were now able to quantitatively address the issue of whether detection thresholds were determined by the spatial or temporal characteristics of torque variations.

5.1 Methods

Three participants (S1, S3, and S6) who had participated in both Experiments I and II took part in Experiment III. It was important that we had the torque detection thresholds from Experiments I and II for each participant, so that within-participant comparisons could be made with the thresholds obtained in Experiment III.

Six spatial periods, equally spaced on a logarithmic scale, were tested: 2.8, 5.6, 11.25, 22.5, 45, and 90 degree/cycle. They were the same as those used in Experiment I, except that the 180 degree/cycle torque profile was eliminated because it contained less than a full cycle of torque variation for an angular displacement of 90 degree. Two turning speeds were achieved by asking the participants to make the 90 degree turn in 500 ms (slow) or 250 ms (fast), respectively. A metronome was used to provide the participant with a timing reference. The metronome was set to 120 and 240 beep/min for the slow and fast speeds, respectively. With this setup, participants had to complete one full 90 degree turn within the time period marked by two consecutive beeps. Listed in Table 3 are the equivalent temporal frequencies when the switch was turned at the nominal durations. With the parameters chosen for this experiment, each torque profile of a given spatial period corresponded to two nominal temporal frequencies, and each nominal frequency corresponded to two torque profiles with different spatial periods (with the exception of the 2- or 128-Hz signal that each corresponded to only one spatial period). To the extent that participants followed the metronome rhythm, we would be able to determine whether torque threshold varied with spatial frequency alone, temporal frequency alone, or both.

TABLE 3
Experimental Conditions in Experiment III

Spatial Period Θ (°)	Duration T (ms)	Nominal Frequency (Hz)
90	500	2
	250	4
45	500	4
	250	8
22.5	500	8
	250	16
11.25	500	16
	250	32
5.6	500	32
	250	64
2.8	500	64
	250	128

Training was provided at the beginning of each run. The participant was instructed to turn the switch such that resistive torque was felt between two consecutive beeps of the metronome. Data collection began when the participant was comfortable with turning the switch at the desired speed. The ordering of the 12 experimental conditions was randomized for each participant.

The angular position of the rotary switch was recorded at a sampling rate of 1 kHz. For each run, the turning durations for a full 90 degree turn for all trials (three per trial) were averaged. All trials with a duration of more than ± 3 standard deviations away from the mean were discarded. The remaining trials were used to calculate the average duration ($\bar{T}$). The estimated temporal frequency was subsequently computed as $90/(\Theta \cdot \bar{T})$ in Hz (cycle/s).

5.2 Results

The data from the three participants were analyzed individually. The detection thresholds obtained in Experiment III for slow (500 ms) and fast (250 ms) turning speeds are shown in Fig. 8 (open circles and open squares, respectively) in three separate panels for the three participants. There appears to be

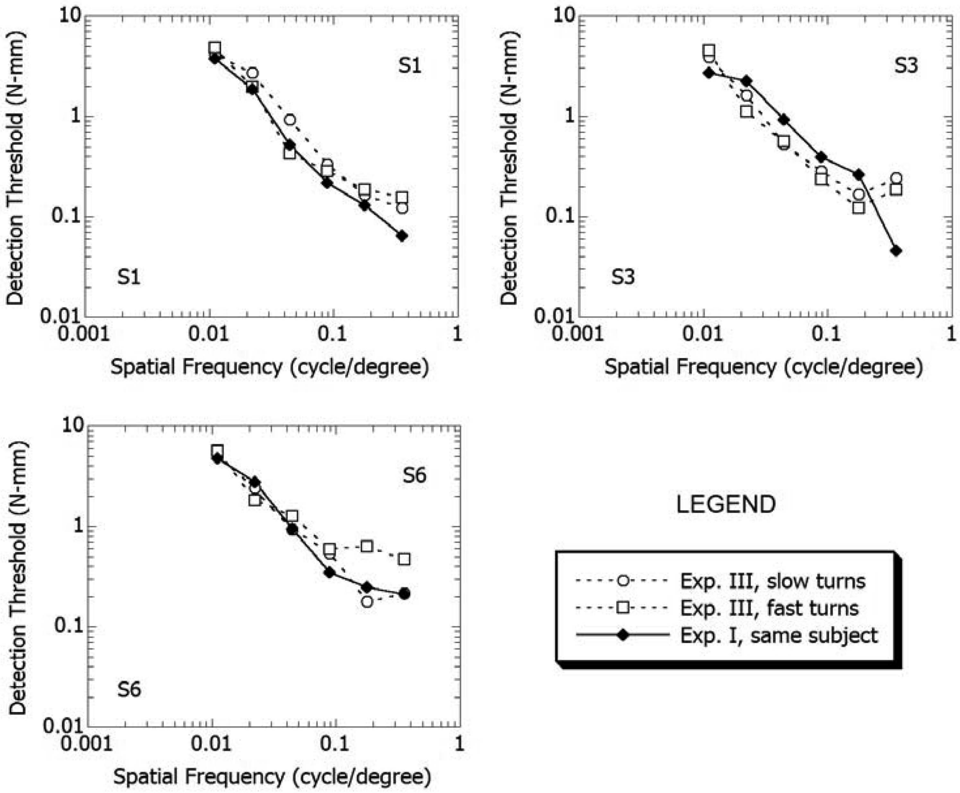

Fig. 8. Detection thresholds corresponding to slow and fast turns, obtained in Experiment III, as a function of spatial frequency. Data from the three participants are shown in three separate panels. Also shown in each panel are the thresholds obtained in Experiment I for the corresponding participant. The standard errors (not shown) are smaller than the symbol size.

no systematic difference between the thresholds obtained under the slow-turning and the fast-turning conditions, except for S6's data at the two highest spatial frequencies.

Also shown in Fig. 8 are the thresholds obtained in Experiment I under self-paced condition (filled diamonds). There is generally a close match between the thresholds obtained in Experiment III (the two dashed lines) and those obtained in Experiment I (the solid line), except for S3's data at the highest spatial frequency of 0.357 cycle/degree and S6's fast-turning data at the two highest spatial frequencies of 0.179 and 0.357 cycle/degree. Therefore, there appears to be no systematic difference among the slow-turning, fast-turning (Experiment III) and the self-paced (Experiment I) conditions. Overall, there is strong evidence that the detection thresholds for torque variations were not affected by the turning speed.

A different pattern emerged in Fig. 9 when we compared the torque thresholds obtained in Experiment III (open symbols with dashed lines) with those obtained in Experiment II (filled symbol with solid line). The results of Experiment III were analyzed in terms of temporal frequency using the average turning durations computed from the data recorded during the experiment. It can be observed that the thresholds for fast turns (open squares) are systematically higher than the thresholds for slow turns (open circles), except for S3's data that crossed over at the higher frequencies. In general, the data from Experiment III show a different pattern than those from Experiment II. The most obvious difference is that the dashed lines (Experiment III) were mostly concave-up whereas the solid lines (Experiment II) tend to be convex-up over the same frequency region. Except for the points where the dashed lines and the solid line cross over, the thresholds obtained from Experiments II and III differ significantly at the corresponding temporal frequencies. Therefore, we conclude that the detection thresholds for torque variations are not determined by the temporal frequency of the stimuli.

A closer examination of the open symbols in Fig. 9 reveals that the three participants were able to follow the metronome signals closely. According to Table 3, although the six symbols on each dashed line corresponded to the same six spatial periods for the torque stimuli used in Experiment III, the slow-turning data points should nominally be at 2, 4, 8, 16, 32, and 64 Hz, and the fast-turning points at 4, 8, 16, 32, 64, and 128 Hz. Overall, the participants did a good job following the metronome signals so that a torque stimulus of a given spatial period was felt at two distinct temporal frequencies. Furthermore, it is clear that the open square symbols were offset from the open circles such that each open square appeared at roughly the same temporal frequency as the open circle representing the next (higher) spatial frequency at around 4, 8, 16, 32, and 64 Hz. Therefore, the close alignment of the data shown earlier in Fig. 8 could not have been due to the failure of the participants to vary the turning speed as instructed.

6 General Discussions

The present study was motivated by the need for engineering specifications of rotary switches with a consistent feel. We knew intuitively that the engineering tolerance specification

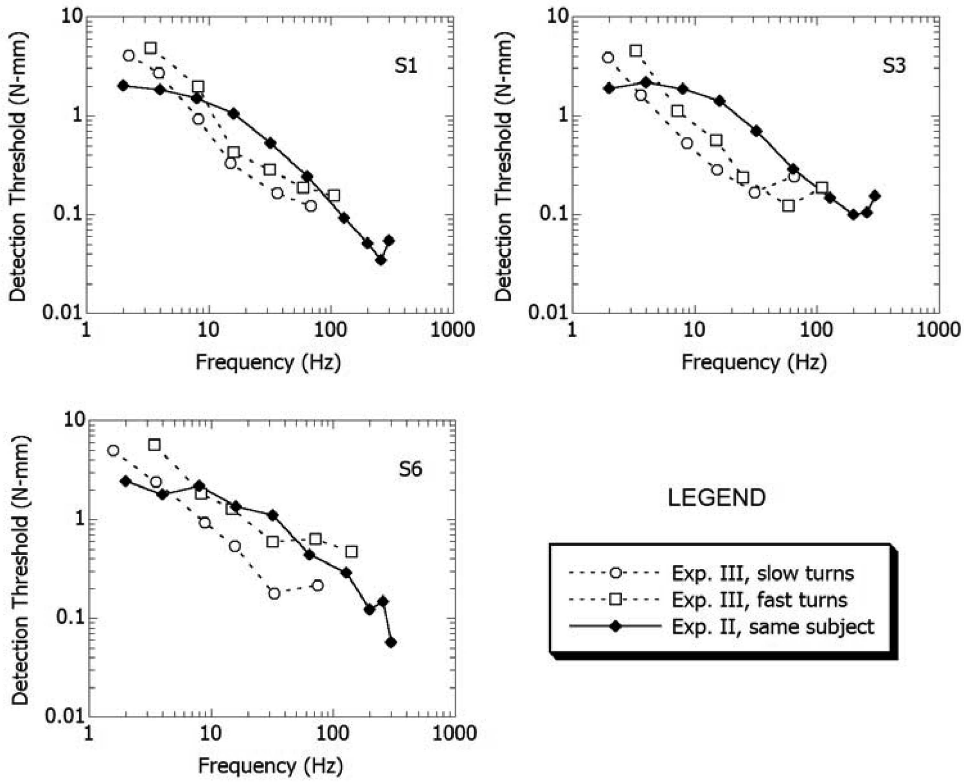

Fig. 9. Detection thresholds corresponding to slow and fast turns, as a function of temporal frequency. Data from the three participants are shown in three separate panels. Also shown in each panel are the torque thresholds obtained in Experiment II for the corresponding participant. The standard errors (not shown) are smaller than the symbol size.

for switch production should take into account the frequency contents of the torque versus travel characteristics, as illustrated in Fig. 1. Therefore, the first experiment of the present study measured the human detection thresholds over a range of spatial frequencies for a rotary switch. The results of Experiment I can be used to supplement the traditional torque versus travel specification for switch manufacturing. For example, given a switch specification such as the piecewise straight line shown in Fig. 1, the supplier can be further required to keep the high-frequency components in the torque profile below the human detection thresholds shown in Fig. 5. This approach is based on the assumption that the detection thresholds are determined solely by the spatial frequencies of the torque versus travel characteristics, $\tau(\alpha)$. The validity of this assumption was tested in Experiment III of the present study. Before that, it was also necessary to measure detection thresholds with torque stimuli specified in the temporal domain ($\tau(t)$, Experiment II), so that data from different experimental conditions can be compared.

Despite a wealth of literature on the detection thresholds for displacement as a function of (temporal) frequency, we were not aware of any such data on the detection of torque variations. The shape of the detection-threshold curve from Experiment II of the present study was consistent with a U-shaped trend with a minimum in the 200-300-Hz region (Fig. 7). This is very similar to the shape of the displacement threshold data widely available in the literature. Shown in Fig. 10 are the torque threshold curve reproduced from the average threshold data obtained in Experiment II (the solid line in Fig. 7) and the displacement threshold curve from the Bolanowski et al. study in [23, Fig. 1]. The torque and displacement thresholds follow the simple relation $20 \log \tau = 0.7 \times 20 \log x - 10$, where τ stands for torque threshold in $\mathrm{N \cdot mm}$, and x denotes displacement threshold in micrometers. It is apparent that, after proper scaling and shifting, these two curves roughly overlap over the frequency range 2-300 Hz. This simple relation

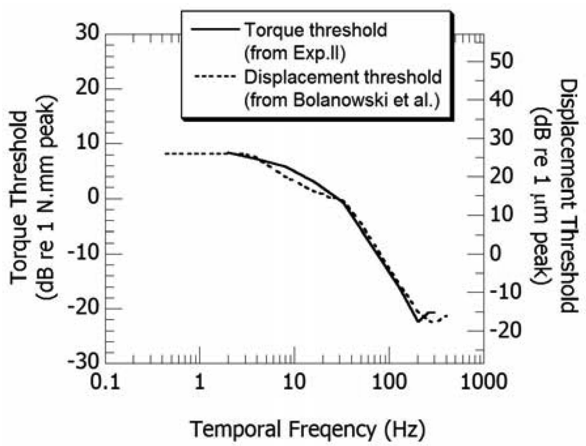

Fig. 10. Comparison of displacement threshold data (from [23]) and torque threshold data (from Experiment II of the present study). The torque thresholds were converted to dB as $20^* \log(\tau)$, where τ denotes torque threshold obtained in Experiment II. To align the two curves, the displacement thresholds (x) were scaled by 0.7 and then shifted down by 10 dB. See texts for further details.

between the two data sets (on a log-log scale) is remarkable considering that the experimental conditions in the two studies were quite different. In the Bolanowski et al. study [23], 700-ms stimuli were delivered through a contact area of 2.9 cm^2, the skin-surface temperature was held constant at $30^{\circ}\mathrm{C}$, and the body site involved was the thenar eminence (the protruding part on the palm just beneath the thumb). In the present study, 500-ms stimuli were used, there was little control over the contact area, the skin-surface temperature was not regulated, and the stimulation site involved the fingertip of the thumb and the side of the index finger. Despite these differences in experimental methods, however, the overall shape of the torque and displacement thresholds as a function of *temporal* frequency are quite similar. From the data shown in Fig. 10, estimates of the impedance of human skins can be derived (e.g., [27] and [28]), although this is beyond the scope of the present study.

Our results on torque-variation thresholds are more relevant than displacement thresholds when we consider tools and devices that are designed to deliver force and/or torque (e.g., switches, force-feedback displays, etc.). Although the detection thresholds for displacement have been extremely useful in estimating the perceived intensity of vibrotactile stimuli, they do not generalize well to situations involving the use of tools and everyday objects. A recent study on vibrations transmitted through a tool held in the palm of the hand found vibrotactile detection thresholds to be much lower than those reported earlier in the literature [24]. The higher sensitivity was attributed to the larger contact area between the tool and the skin of the palm, the direction of vibration (parallel as opposed to perpendicular to the skin surface), and the stimulation site (palm was found to be more sensitive to lateral vibration than fingerpads). Another study found that people are able to make consistent magnitude estimation of normal and tangential forces, as well as discriminate small differences in tangential forces, over a force range that is typical of those experienced during manual grasp and manipulation tasks [29]. The Weber fraction for tangential force, 16 percent, was consistent with those reported in the literature (e.g., [30] and [31]). In general, there is a need for more studies to assess detection thresholds associated with everyday tools with the objects held in a manner that is consistent with their typical use (despite a less controlled experimental setup). As far as we are aware, the results from Experiments I and II of the present study were the first to characterize human sensitivity to torque variations as a function of spatial and temporal frequencies.

Experiment III of the present study was designed to decouple spatial and temporal characteristics of rotary switches in order to discover the parameters most responsible for torque-ripple detection. This was accomplished by instructing participants to turn spatially identical rotary switches at different speeds. By comparing results of Experiment III with those obtained in Experiments I and II, we conclude that the detection of torque variation is determined by the spatial characteristics of the rotary switches based on the following observations. First, the detection thresholds associated with turning the same spatially defined rotary switch at two distinct speeds are essentially the same over a range of spatial frequencies. Second, the aforementioned thresholds are essentially the same as those estimated when the turning speeds were chosen by the participants and were therefore variable across participants and spatial frequencies. Third, when the data from Experiment III are converted from the spatial domain to the temporal domain, the torque thresholds were different when the turning speeds were such that two rotary switches with different spatial specifications resulted in the same temporal frequency. Fourth, the converted thresholds do not match those measured using torque stimuli with precisely controlled temporal frequencies.

A few issues need to be clarified further regarding the methodology of the present study. First, sinusoidal torque profiles were used in the three experiments conducted in the present study. The sinusoidal waveforms were viewed as building blocks for any torque waveform because the latter could be expressed mathematically as the sum of sinusoidal waveforms through its Fourier series in either spatial or temporal domain. Our approach did not make any assumption about how the percepts for sinusoidal torque profiles might be combined in the perceptual space. The results obtained in the present study should therefore be interpreted as valid for raised sinusoidal torque waveforms only. Its validity for arbitrary torque profiles awaits further investigation.

The second issue concerns the validity of the torque stimuli given the chosen hardware components. Specifically, it was important to ascertain that the inertia of the motor assembly was sufficiently small as compared to that of the fingers grasping the rotary switch. Unlike classical studies of thresholds where a vibrating probe was applied directly to the skin (e.g., [23] and [24]), the participants in the present study grasped the center ridge of the rotary switch *firmly* between the fingerpad of the thumb and one side of the middle phalange of the index finger (see Fig. 2). As a result, the impedance of the system being measured (the fingers grasping the switch) was much larger than that of the measuring apparatus (including the motor, encoder, and rotary switch). The latter was therefore not expected to have a "corrupting" effect on the threshold measurements. To verify that the thresholds measured in the present study were independent of the motor inertia, an additional experiment was conducted using motors of varying inertia. One participant (S2) repeated Experiment I using the system shown in Fig. 2 with $\mathrm{J}_0 = 46.3\ \mathrm{g \cdot cm^2}$ (motor: 10.3 $\mathrm{g \cdot cm^2}$, moving shaft of the encoder: 29.0 $\mathrm{g \cdot cm^2}$, and rotary switch: 7 $\mathrm{g \cdot cm^2}$). Cylindrical weights centered on the motor shaft were added to increase the total inertia of the apparatus to $\mathrm{J}_1 = 77.3\ \mathrm{g \cdot cm^2}$, $\mathrm{J}_2 = 106.3\ \mathrm{g \cdot cm^2}$, and $\mathrm{J}_3 = 280.3\ \mathrm{g \cdot cm^2}$. The data shown in Fig. 11 confirmed that the detection thresholds were not affected by the inertia of the apparatus until it was more than twice the original inertia ($\mathrm{J}_2/\mathrm{J}_0 = 2.3$). Significant deviations in thresholds were obtained when the system inertia was increased to six times its original value ($\mathrm{J}_3/\mathrm{J}_0 = 6.1$). These results can be taken as empirical verification that the detection thresholds obtained in the present study were not affected by the inertia of the experimental apparatus.

The third issue concerning the methodology is the use of both active (Experiments I and III) and passive

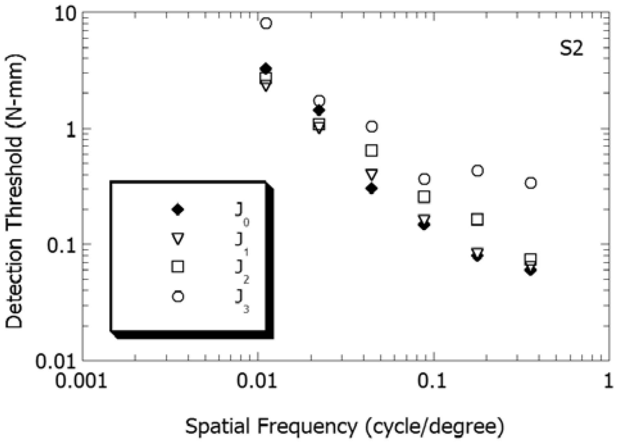

Fig. 11. Detection thresholds for raised sinusoidal torque variations measured at four levels of motor assembly inertia. See texts for details.

(Experiment II) conditions in estimating the detection thresholds for torque variations. One might argue that the main reason for the mismatch between the thresholds obtained in Experiments II and III (see Fig. 9) were the passive versus active conditions used in the two experiments, respectively. Although this might have indeed been the case (see, for example, [32]), we hasten to point out that the data obtained in Experiment III alone were sufficient to demonstrate that the detection thresholds were determined by the spatial frequency of the torque stimuli (as demonstrated by the overlap of the open circles and squares in Fig. 8 when the data were plotted against *spatial* frequency) and not by the temporal frequency of the stimuli (as demonstrated by the mismatch of the open circles and squares in Fig. 9 when the data were plotted against *temporal* frequency). The close match of the data obtained in Experiments I and III (Fig. 8) further support this main conclusion of our present study.

The fourth issue concerns the estimation of the temporal frequency associated with the stimuli presented in Experiment III. An average duration was used in converting torque variations defined in the spatial domain to those defined by an average temporal frequency. It is well known that the velocity versus travel relation typically follows a bell-shaped curve in linear stroking or turning motions. Therefore, the horizontal positions (along the frequency axis) of the open circles and squares shown in Fig. 9 can be viewed as the average as well. One might therefore argue that the apparent mismatch of the open symbols and the filled symbols in Fig. 9 may have been due to the possible horizontal shift of the open symbols. A closer examination of Fig. 9, however, discounts such an explanation. The concave-up shape formed by the open symbols are not likely to change due to lateral shifts of the individual data points. Therefore, the convex-up shape exhibited by the thresholds collected with stimuli specified in the temporal domain (Experiment II) remains different from the concave-up shape exhibited by the thresholds obtained in Experiment III.

The last issue has to do with the number of participants tested in Experiment III. At a first glance, three participants may seem to be too small a sample size from which to draw any conclusions. It is well established, by now, that properties of sensory systems are innate and, as a result, individual variability in thresholds (visual, auditory, and tactual) are small, provided that reliable thresholds from motivated and well-trained participants are obtained [33], [34], [35]. Large individual variability is expected only in cases where the observer's task involves preferences, rather than perception alone (e.g., a study in which the participants are asked to choose the most pleasing switch design). In the present study, we have used a within-participant design so that data for the same participant could be compared across the three experiments. Each of the three participants (S1, S3, and S6) who participated in all the experiments was tested for about 2,000 trials that lasted 10-12 hours. It is unlikely that we could find a dozen of volunteers for this kind of experiment.

The question of whether the spatial or the temporal characteristics of a rotary switch determined its percepts (or detection thresholds specifically) has both theoretical and practical implications. From a theoretical point of view, our study confirmed that the human somatosensory system is capable of discounting sensory information due to our own motor actions and is able to extract object information independent of our actions. That this is achievable has been cleverly demonstrated in a study of self-induced tickle. It was hypothesized that the somatosensory system is able to suppress sensory inputs predictable from an efference copy of the motor outputs [36]. The exact mechanism for such perceptual constancy remains a topic for future studies.

From a practical point of view, our conclusion that the spatial characteristics of a switch determine its torque-variation detection thresholds is an important (and a lucky) one for designers and suppliers of rotary switches. It is much more practical to work with switches in the spatial domain than in the temporal domain since the temporal characteristics of switches are largely determined by user actions. It is worth noting that our results are not consistent with other studies that have examined the effect of speed on haptic perception such as roughness judgment of textures [37], [38]. It was shown that lateral scanning speed influenced perceived roughness using either bare fingers in [37, Fig. 3] or rigid probes in [38, Figs. 2 and 3] under both passive and active conditions. Note, however, that the Lederman et al. study [38] used a 10-fold and a 4-fold change in speed, whereas the present study employed a 2-fold change in speed. It is possible that we could have observed some effect of turning speed on switch perception had we employed a much wider range of speeds. However, the parameters used in Experiment III of the present study were designed to replicate "natural" to "sped-up" turning speeds, and therefore our conclusion should still hold for typical usage of rotary switches.

7 Concluding Remarks

The present study was our first step toward understanding the physical attributes that determine the percept of rotary switches. We started by measuring the detection thresholds for torque variations in the spatial domain $\tau(\alpha)$, and in the temporal domain $\tau(t)$. We then studied whether the thresholds were invariant with respect to $\tau(\alpha)$ or $\tau(t)$. This was accomplished by requiring the participants to turn switches with the same $\tau(\alpha)$ profile using different speeds, thereby producing different $\tau(t)$ profiles. The data gathered from three participants using a within-participant design suggest that the spatial specification of the switch $\tau(\alpha)$ was a better predictor of detection thresholds. Our future work will use the methodology developed in the present study to continue our investigation of the perceptual attributes of switches and the engineering specifications of physical parameters for achieving target switch perception.

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REFERENCES

[1] Y. Adachi, T. Kumano, and K. Ogino, "Sensory Evaluation of Virtual Haptic Push-Buttons," *Proc. Third Int'l Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS '94),* vol. 55-1, pp. 361-368, 1994.

[2] K.E. MacLean, "The "Haptic Camera": A Technique for Characterizing and Playing Back Haptic Properties of Real Environments," *Proc. Fifth Int'l Symp. Haptic Interfaces for Virtual Environments and Teleoperator Systems (HAPTICS '96),* vol. 58, pp. 459-467, 1996.

[3] K.E. MacLean and J.B. Roderick, "Aladdin: Exploring Language with a Haptic Door Knob," Technical Report 1999-058, Interval Research Corp., 1999.

[4] S.S. Snibble, K.E. MacLean, R. Shaw, J.B. Roderick, W. Verplank, and M. Scheeff, "Haptic Metaphors for Digital Medial," *Proc. ACM Symp. User Interface Software and Technology (UIST '01)*, p. 10, 2001.

[5] C. Swindells and K.E. MacLean, "Capturing the Dynamics of Mechanical Knobs," *Proc. World Haptics Conf. (WHC '07),* pp. 194-199, 2007.

[6] B. Allotta, V. Colla, and G. Bioli, "A Mechatronic Device for Simulating Push-Buttons and Knobs," *Proc. IEEE Int'l Conf. Multimedia Computing and Systems (ICMCS '99),* pp. 636-642, 1999.

[7] M. Angerilli, A. Frisoli, F. Salsedo, S. Marcheschi, and M. Bergamasco, "Haptic Simulation of an Automotive Manual Gearshift," *Proc. 10th IEEE Int'l Workshop Robot and Human Interactive Comm. (ROMAN '01),* pp. 170-175, 2001.

[8] M.L. Nagurka and R. Marklin, "Measurement of Stiffness and Damping Characteristics of Computer Keyboard Keys," *J. Dynamic Systems, Measurement, and Control (Trans. ASME),* vol. 127, pp. 283-288, 2005.

[9] M.B. Colton and J.M. Hollerbach, "Identification of Nonlinear Passive Devices for Haptic Simulations," *Proc. World Haptics Conf. (WHC '05),* pp. 363-368, 2005.

[10] M.B. Colton and J.M. Hollerbach, "Reality-Based Haptic Force Models of Buttons and Switches," *Proc. IEEE Int'l Conf. Robotics and Automation (ICRA '07),* pp. 497-502, 2007.

[11] M.B. Colton and J.M. Hollerbach, "Haptic Models of an Automotive Turn-Signal Switch: Identification and Playback Results," *Proc. World Haptics Conf. (WHC '07),* pp. 243-248, 2007.

[12] C.J. Hasser and M.R. Cutkosky, "System Identification of the Human Hand Grasping a Haptic Knob," *Proc. 10th Int'l Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS '02)*, pp. 180-189, 2002.

[13] G. Mauter and S. Katzki, "The Application of Operational Haptics in Automotive Engineering," *Business Briefing: Global Automotive Manufacturing and Technology,* pp. 78-80, 2003.

[14] M. Badescu, C. Wampler, and C. Mavroidis, "Rotary Haptic Knob for Vehicular Instrument Controls," *Proc. 10th Int'l Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS '02),* pp. 342-343, 2002.

[15] D. Grant, "Two New Commercial Haptic Rotary Controllers," *Proc. EuroHaptics '04,* pp. 451-455, 2004.

[16] G. Michelitsch, M. Osen, J. Williams, B. Jimenez, and S. Rapp, "Haptic Chameleon," *Proc. EuroHaptics '04,* pp. 430-433, 2004.

[17] D.W. Weir, M. Peshkin, J.E. Colgate, P. Buttolo, J. Rankin, and M. Johnston, "The Haptic Profile: Capturing the Feel of Switches," *Proc. 12th Int'l Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS '04),* pp. 186-193, 2004.

[18] J. Reisinger, J. Wild, G. Mauter, and H. Bubb, "Mechatronic Tools in Haptic Research for Automotive Applications," *Proc. Sixth Int'l Workshop Research and Education in Mechatronics*, pp. 293-298, 2005.

[19] J. Reisinger, J. Wild, G. Mauter, and H. Bubb, "Haptical Feeling of Rotary Switches," *Proc. EuroHaptics '06*, pp. 49-55, 2006.

[20] B. Woodruff and H. Helson, "Torque Sensitivity as a Function of Knob Radius and Load," *Am. J. Psychology,* vol. 80, pp. 558-571, 1967.

[21] L. Jandura and M.A. Srinivasan, "Experiments on Human Performance in Torque Discrimination and Control," *Proc. Third Int'l Symp. Haptic Interfaces for Virtual Environment and Teleoperator Systems (HAPTICS '94),* vol. 55-1, pp. 369-375, 1994.

[22] S. Yang, H.Z. Tan, P. Buttolo, M.R. Johnston, and Z. Pizlo, "Thresholds for Dynamic Changes in a Rotary Switch," *Proc. EuroHaptics '03,* pp. 343-350, 2003.

[23] S.J. Bolanowski Jr., G.A. Gescheider, R.T. Verrillo, and C.M. Checkosky, "Four Channels Mediate the Mechanical Aspects of Touch," *J. Acoustical Soc. of Am.*, vol. 84, pp. 1680-1694, 1988.

[24] A.J. Brisben, S.S. Hsiao, and K.O. Johnson, "Detection of Vibration Transmitted through an Object Grasped in the Hand," *J. Neurophysiology,* vol. 81, pp. 1548-1558, 1999.

[25] H. Levitt, "Transformed Up-Down Methods in Psychoacoustics," *J. Acoustical Soc. of Am.*, vol. 49, pp. 467-477, 1971.

[26] M.R. Leek, "Adaptive Procedures in Psychophysical Research," *Perception & Psychophysics,* vol. 63, pp. 1279-1292, 2001.

[27] A. Israr, S. Choi, and H.Z. Tan, "Detection Threshold and Mechanical Impedance of the Hand in a Pen-Hold Posture," *Proc. 2006 IEEE/RSJ Int'l Conf. Intelligent Robots and Systems (IROS '06),* pp. 472-477, 2006.

[28] A. Israr, S. Choi, and H.Z. Tan, "Mechanical Impedance of the Hand Holding a Spherical Tool at Threshold and Suprathreshold Stimulation Levels," *Proc. World Haptics Conf. (WHC '07),* pp. 56-60, 2007.

[29] H.E. Wheat, L.M. Salo, and A.W. Goodwin, "Human Ability to Scale and Discriminate Forces Typical of Those Occurring during Grasp and Manipulation," *J. Neuroscience,* vol. 24, pp. 3394-3401, 2004.

[30] L.A. Jones, "Matching Forces: Constant Errors and Differential Thresholds," *Perception,* vol. 18, pp. 681-687, 1989.

[31] X.-D. Pang, H.Z. Tan, and N.I. Durlach, "Manual Discrimination of Force Using Active Finger Motion," *Perception & Psychophysics,* vol. 49, pp. 531-540, 1991.

[32] S.J. Lederman, "Perception of Surface Roughness by Active and Passive Touch," *Bull. Psychonomic Soc.,* vol. 18, pp. 253-255, 1981.

[33] G.T. Fechner, *Elements of Psychophysics,* vol. 1. Holt, Rinehart and Winston, Inc., 1860/1966.

[34] G.A. Gescheider, *Psychophysics: The Fundamentals,* third ed. Lawrence Erlbaum Assoc., 1997.

[35] N.A. Macmillan and C.D. Creelman, *Detection Theory: A User's Guide,* second ed. Lawrence Erlbaum Assoc., 2004.

[36] S.-J. Blakemore, D. Wolpert, and C. Frith, "Why Can't You Tickle Yourself?" *NeuroReport,* vol. 11, pp. 11-16, 2000.

[37] S.J. Lederman, "Tactual Roughness Perception: Spatial and Temporal Determinants," *Canadian J. Psychology,* vol. 37, pp. 498-511, 1983.

[38] S.J. Lederman, R.L. Klatzky, C.L. Hamilton, and G.I. Ramsay, "Perceiving Roughness via a Rigid Probe: Psychophysical Effects of Exploration Speed and Mode of Touch," *Haptics-e: The Electronic J. for Haptics Research,* vol. 1, http://www.haptics-e.org, 1999.

[39] S. Yang, H.Z. Tan, P. Buttolo, and M.R. Johnston, "Detection of Torque Vibrations Transmitted through a Passively-Held Rotary Switch," *Proc. EuroHaptics '04,* pp. 217-222, 2004.

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