Haptic Identification of Stiffness and Force Magnitude

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Abstract

As haptics becomes an integral component of scientific data visualization systems, there is a growing need to study "haptic glyphs" (building blocks for displaying information through the sense of touch) and quantify their information transmission capability. The present study investigated the channel capacity for transmitting information through stiffness or force magnitude. Specifically, we measured the number of stiffness or force-magnitude levels that can be reliably identified in an absolute identification paradigm. The range of stiffness and force magnitude used in the present study, 0.2-3.0 N/mm and 0.1-5.0 N, respectively, was typical of the parameter values encountered in most virtual reality or data visualization applications. Ten individuals participated in a stiffness identification experiment, each completing 250 trials. Subsequently, four of these individuals and six additional participants completed 250 trials in a force-magnitude identification experiment. A custom-designed 3 degrees-of-freedom force-feedback device, the ministick, was used for stimulus delivery. The results showed an average information transfer of 1.46 *bits* for stiffness identification, or equivalently, 2.8 correctly-identifiable stiffness levels. The average information transfer for force magnitude was 1.54 *bits*, or equivalently, 2.9 correctly-identifiable force magnitudes. Therefore, on average, the participants could only reliably identify 2-3 stiffness levels in the range of 0.2-3.0 N/mm, and 2-3 force-magnitude levels in the range of 0.1-5.0 N. Individual performance varied from 1 to 4 correctly-identifiable stiffness levels and 2 to 4 correctly-identifiable force-magnitude levels. Our results are consistent with reported information transfers for haptic stimuli. Based on the present study, it is recommended that 2 stiffness or force-magnitude levels (i.e., high and low) be used with haptic glyphs in a data visualization system, with an additional third level (medium) for more experienced users.

Keywords: Identification, information transfer, haptic perception, stiffness, force, force magnitude, data visualization, perceptualization.

Index Terms: C.0 [Computer Systems Organization]: General - Hardware/software interfaces; J.4 [Computer Applications]: Social and Behavioral Sciences - Psychology

1 Introduction

The present study was motivated by the need for a better understanding of the use of "haptic glyphs" in a scientific data perceptualization system. The term *haptic glyph* refers to the basic unit for displaying information through the sense of touch. The term *perceptualization* is used to emphasize the use of haptic and auditory displays in a data visualization system. The goal of any perceptualization system is to convey a large amount of information to users in an efficient and intuitive manner with a minimum cognitive load.

The last decade has witnessed rapid advancements in incorporating haptic feedback into data visualization systems (e.g., [1-7]). Although there exist many guidelines on how information should be displayed visually (e.g., [8, 9]), the design of "haptic glyphs" is still in its infancy (although see [10] for the design of "haptic icons"; and [11] for a study of "tactons" – tactile icons). A variable in a data perceptualization system can be either continuous or discrete. To represent a continuous variable with a haptic signal, a knowledge of the Weber fraction – the percentage change in the signal that can be barely noticed – is useful. Past studies of haptic signals using a discrimination paradigm have established a Weber fraction of 3-10% for length by the finger-span method [12], 5-10% for force magnitude [13-15], 13% for torque [16, 17], 22% for stiffness [18-20] and 34% for viscosity [21]. The discrimination thresholds for some other haptic signals did not increase with the reference signal as predicted by Weber's Law. They instead remained constant; e.g., the discrimination threshold was 2.0-2.7° for joint-angle position [22] and 25-35° for force direction [23, 24].

To represent a discrete variable with a haptic signal, a knowledge of channel capacity – the maximum amount of information that can be transmitted through the signal – is required. From the information transfer measurement, we can estimate the number of signal levels that can be correctly identified, which translates into the number of categories a particular haptic signal can represent without confusion. In general, our ability to identify the value of a parameter in isolation is limited [25]. Past absolute identification studies have reported an information transfer of 2 *bits* (4 correctly-identifiable *items*) for length by the finger-span method [12], 1.7-1.9 *bits* (3-4 *items*) for joint-angle position [22] and 3-4 *items* for size [26, 27]. One recent study of tactons on mobile devices demonstrated that users could reliably identify 2-3 types of rhythms, 1 type of roughness and 2-3 locations of vibrotactile stimuli on the forearm when the three vibrotactile signal attributes were presented simultaneously [11].

To the best of our knowledge, no data exist on the human ability to identify surface stiffness or force magnitude. Therefore, the goal of the present study was to establish the information-transmission capabilities of stiffness and force-magnitude through the haptic channel. The rest of this article is organized as follows. Section 2 describes the methods common to the stiffness and force-magnitude identification experiments. Sections 3 and 4 present more details and the results of the two experiments, respectively. Section 5 concludes the article.

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2 General Methods

This section describes the elements that are common to both experiments. Details that are specific to each experiment are presented in Sections 3 and 4 where the respective experiments are discussed.

2.1 Participants

A total of sixteen participants (S1-S16; 10 males and 6 females, age range 18-61 years old, average age 27 years old) took part in the two experiments. While most participants took part in one of the experiments, four (S5, S7, S10, S12) participated in both experiments. Of the sixteen participants, four (S1, S2, S7, S12) had used the ministick force-feedback device before as participants of earlier studies. All were right-handed by self-report except for S5, who was left-handed. The participants gave their written consent to the experimental protocol that had been approved by the Institutional Review Board at Purdue University. They were compensated for their participation.

2.2 Apparatus

A custom-designed, high position-resolution, 3 degrees-of-freedom force-feedback device (the "ministick", see Figure 1) was used in both experiments [28]. The ministick has a typical position resolution of 1 µm. Its force commands are updated at 2 kHz. A user interacts with the virtual objects rendered by the ministick using a stylus. The stylus tip was modeled as a point; i.e., an infinitesimally small point.

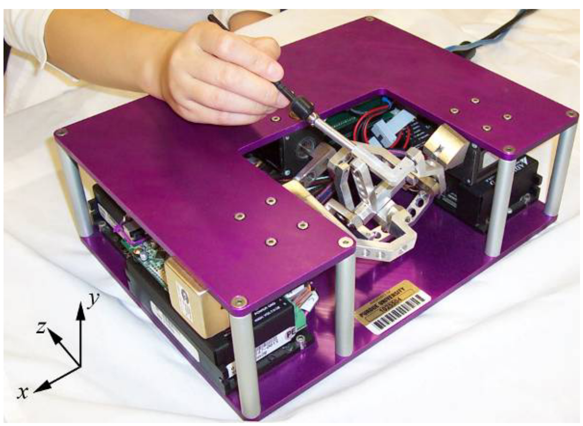

Figure 1. The "ministick" force-feedback device

2.3 Procedures

Both the stiffness and force-magnitude experiments employed a one-interval five-alternative forced-choice absolute identification procedure. On each trial, the participant received one stimulus randomly selected from the five stimulus alternatives with equal *a priori* probabilities. The participant's task was to identify the stimulus which could either be the stiffness of a surface in the *x-z* plane (in the case of stiffness identification) or the magnitude of a force along the *+y* direction (in the case of force identification). The participant was instructed to use an integer between 1 and 5 as a response, with 1 representing the lowest stiffness or force level, and 5 the highest stiffness or force level.

In a preliminary study, one participant (S7) who was experienced with force-feedback devices and who had taken part in several absolute identification experiments prior to the present study was tested with 8 stiffness alternatives and 8 force-magnitude alternatives within the same stiffness and force-magnitude ranges used in the main experiments, respectively. The results indicated that S7 could identify at most 4 levels correctly in either stiffness or force magnitude. Therefore, the main experiments used 5 stimulus alternatives to ensure that (1) the number of stimulus alternatives exceeded the expected number of items that could be correctly identified, and (2) the number of stimulus alternatives were kept low so as to minimize the number of trials needed for a reliable estimate of information transfer (see [26] for a discussion on the selection of stimulus parameters in an absolute identification experiment).

The participant was comfortably seated before a computer screen and keyboard with the elbow and wrist of the dominant arm rested on a comfortable support. The ministick probe was grasped by the dominant hand and held vertically in the same way that the participant would hold a pencil. Training was provided initially so the participant could feel the stimulus alternatives and associate them with the 1-5 response labels. The participant was allowed to train for as long as s/he desired, which typically lasted a few minutes. Data collection began when the participant indicated that s/he was ready.

For stiffness identification, the participant was instructed to tap a horizontal virtual surface actively to gauge its stiffness (see [20] for discussion of tapping versus pressing for stiffness identification). Multiple taps were allowed. This allowed the participants full access to tactile, kinesthetic and central efferent command information to achieve the best performance possible [20, 29, 30]. For force-magnitude identification, the participant was instructed to hold the probe as steadily as possible while judging the magnitude of a vertical force pushing the probe upward. The force was presented only once per trial (see Section 4.1 for further details). The participant responded by pressing the number key 1, 2, 3, 4, or 5 on a keyboard. Trial-by-trial correct-answer feedback was provided during both the stiffness and the force-magnitude identification experiments.

Each participant completed a total of 250 trials per experiment, split across two runs of 125 trials each. A break of at least 15 minutes was enforced between runs to avoid muscle fatigue. According to several studies, a total of $5 \times k^2$ trials are required in an identification experiment in order to obtained an unbiased estimate of information transfer, where k represents the number of stimulus alternatives (k=5 in the present study) [26, 31, 32]. Our experimental design allowed for a total of $10 \times k^2$ trials per experimental condition, which was more than sufficient for an unbiased estimate of information transfer. The total experimental time for each participant to complete one experiment, including the training trials, breaks, and post-experiment debriefing, was approximately 1 hour.

2.4 Data Analysis

For each participant in each experiment, the 250 trials were summarized in a 5×5 stimulus-response confusion matrix. The information transfer (*IT*) was calculated according to Equation 1, where n is the total number of trials (n=250), n_{ij} is the number of times the i^{th} stimulus was presented and the integer j was the response, and $n_i = \sum_{j=1}^{k} n_{ij}$ and $n_j = \sum_{i=1}^{k} n_{ij}$ are the row and column sums, respectively. The *IT* values from the 10 participants in each experiment was then used to obtain an estimate of the population mean and standard deviation.

$$IT = \sum_{j=1}^{k} \sum_{i=1}^{k} \frac{n_{ij}}{n} \log_2 \left(\frac{n_{ij} \cdot n}{n_i \cdot n_j} \right) \tag{1}$$

A related quantity, 2^{IT}, is interpreted as the number of stimulus categories that can be correctly identified. It is an abstract concept since 2^{IT} is not necessarily an integer.

3 STIFFNESS IDENTIFICATION

This section describes the stiffness identification experiment and presents the results.

3.1 Stimuli

A virtual surface with variable stiffness was rendered according to Equation 2, where F_y denotes the force component along the vertical y-axis, y_0 denotes the y-position of the horizontal surface, and K the stiffness constant. It follows that the restoring force was always along the positive direction of the y-axis of the ministick coordinate system (i.e., pointing upward). Five values of K were used in the stiffness identification experiment: 0.2, 0.3936, 0.7746, 1.524, and 3 N/mm. Preliminary testing conducted with S10 resulted in slightly higher IT for K values that were equally spaced on a logarithmic scale than those on a linear scale over the same range of 0.2–3 N/mm. Therefore, the above five K values were chosen for the experiment. The minimum stiffness value of 0.2 N/mm was chosen so that the surface felt soft but was still reasonably well defined (as opposed to a cotton ball that is so soft that its outer surface would be hard to define). The maximum stiffness was chosen to be larger than the stiffness that can be rendered by most commercially-available desktop force-feedback devices without inducing instability when no damping is used. We believe that the stiffness range used in the present study represents what would be expected in a typical virtual-reality application. The quality of the stimuli was perceived to be "clean" and free of artifacts by the experimenters in the sense that no discernable "ringing" or "buzzing" was detected at even the highest stiffness level.

$$F_y = \begin{cases} K \times (y_0 - y), & \text{if } y < y_0 \\ 0, & \text{if } y \geq y_0 \end{cases} \tag{2}$$

To constrain the probe movements in the x-z plane, additional forces along the x and z directions were rendered according to Equation 3, where F_x *and* F_z denote the force component along the x and z axes, and x_0 and y_0 denote the corresponding origin coordinates. The constraint stiffness K_c was fixed at 2.0 N/mm. With the help of these "virtual fixture" forces, the participant was able to concentrate on tapping the virtual surface vertically and judging its stiffness.

$$\begin{cases} F_x = K_c \times [x_0 - x] \\ F_z = K_c \times [z_0 - z] \end{cases} \tag{3}$$

3.2 Results

The results of stiffness identification are shown in Table 1 for the ten participants. The IT results for the first and second 125-trial runs were also calculated for the participants, but a one-way analysis of variance (ANOVA) did not reveal any statistically significant difference. The information transfer averaged across the ten participants was 1.46 *bits*, corresponding to 2.8 correctly-identifiable stiffness levels. This means that, on average, the participants could only reliably identify 2-3 levels (i.e., high and low, possibly a middle level too) of the stiffness values in the range 0.2–3 N/mm. Some variability was observed among the participants tested: the more experienced S7 was able to identify

Table 1. Information transfer for stiffness identification

Participant	IT in *bits*	Summary
S1	1.65	Average IT: 1.46 ± 0.35 *bits* $2^{IT} = 2.8$ *items*
S2	1.47	
S4	1.77	
S5	1.27	
S7	2.06	
S8	1.50	
S9	0.83	
S10	1.06	
S11	1.41	
S12	1.53	

4 stiffness levels ($2^{2.06 bits} = 4.2$ *items*), but the less experienced S9 could not even identify 2 levels correctly ($2^{0.83 bits} = 1.8$ *items*). Although prior experience with the ministick haptic device might have helped the participant in its use, it did not consistently lead to higher information transfer in the participants tested (e.g., the second highest IT of 1.77 *bits* was achieved by S4 who was not experienced with the ministick or other force-feedback devices).

4 FORCE-MAGNITUDE IDENTIFICATION

This section describes the force-magnitude identification experiments and presents the results.

4.1 Stimuli

No virtual object was rendered in the force-magnitude identification experiment. On each trial, a force was exerted in the $+y$ (upward) direction for 2 s. The force magnitude ramped up from 0 N to a target value at either 5 or 10 N/s (randomly selected), remained at the target magnitude for 2 s, and then ramped down to 0 N at the same rate. The participant was instructed to relax the grip on the probe at the beginning of a trial, and then gradually tighten the grip as needed to oppose the upward force while keeping the probe stationary in space. The ministick probe was again constrained in its motion in the x-z plane.

Five force magnitudes, again equally-spaced on a logarithmic scale, were used: 0.1, 0.2659, 0.7071, 1.8803, and 5 N. Preliminary testing conducted with S10 resulted in a slightly higher IT for force magnitudes that were equally spaced on a logarithmic scale than those on a linear scale (i.e., 0.1, 1.325, 2.55, 3.775, and 5 N). Therefore, the above 5 force magnitudes were chosen for the experiment. The minimum force magnitude was near the detection threshold, and the maximum force value was limited to 5 N to avoid user fatigue during the course of the experiment. The force range exceeds the force magnitudes typically encountered in a virtual-reality application (e.g., [7, 33]). The quality of the stimuli was perceived to be "solid" and free of artifacts by the experimenters. The "ministick" can stably deliver forces of at least 8-10 N, and therefore the force values employed in the present study were well within the capability of the experimental apparatus.

4.2 Results

The results of force-magnitude identification are shown in Table 2 for the ten participants. The IT results for the first and second 125-trial runs were also calculated for the participants, but a one-way analysis of variance (ANOVA) did not reveal any statistically significant difference. The information transfer averaged across the ten participants was 1.54 *bits*, corresponding to 2.9 correctly-

Table 2. Information transfer for force-magnitude identification

Participant	*IT* in *bits*	Summary
S3	1.22	Average *IT*: 1.54 ± 0.28 *bits* $2^{IT} = 2.9$ *items*
S5	1.51	
S6	1.59	
S7	2.03	
S10	1.20	
S12	1.65	
S13	1.21	
S14	1.78	
S15	1.80	
S16	1.43	

identifiable force-magnitude levels. This means that, on average, the participants could only reliably identify 2-3 levels of the force magnitudes in the range 0.1–5 N. Some variability was also observed among the participants tested: the more experienced S7 was able to identify 4 force levels ($2^{2.03bits} = 4.1$ *items*), but the less experienced S10 could only identify 2 levels correctly ($2^{1.20bits} = 2.3$ *items*). As in the case of stiffness identification, prior experience with the ministick device did not consistently lead to higher information transfer for force-magnitude identification in the participants tested. Among the four individuals who had participated in the stiffness identification experiment earlier, S7 and S12's *IT* scores were above the group average while those of S5 and S10 were at or below the average, indicating that prior experience in an absolute identification experiment did not necessarily result in a better performance in a subsequent experiment.

During the experiment, it was noticed that the participants were unable to keep the ministick probe stationary except at the lowest force levels, despite explicit instructions to do so. Therefore, the displacement data along the *y*-axis (i.e., $y_{max} - y_{min}$) were analyzed. The average displacement per participant and per force magnitude ranged from 0.14 mm (S5 at 0.1 N) to 26.03 mm (S3 at 5 N). The displacement per participant averaged across all five force magnitudes ranged from 1.86 mm (S12) to 7.99 mm (S3). Figure 2 shows the *y*-displacement averaged over the ten participants for each of the five force magnitudes. The average displacement and its standard deviation increased monotonically with force magnitude. For the three higher force magnitudes, the average displacements were close to or above the 2.2 mm human detection threshold as estimated in [22], and therefore could have served as an additional cue for force-magnitude identification. Further analysis confirmed that the correlation of the probe displacements (mean = 3.94 mm, s.d. = 5.44 mm, N = 2500) and the participants' responses (mean = 2.82, s.d. = 1.42, N = 2500) was highly significant [$r(2498) = 0.707$, $p < 0.001$], indicating that the participants' responses were related to the displacements. The higher the force magnitude, the larger the probe displacement, and the more likely the force was perceived to be higher in its magnitude. Therefore, the participants may have attended to probe displacement as well as force magnitude cues in the identification of force-magnitude levels. Although this can be viewed as a potential flaw in the experimental design, we hasten to point out that displacement is likely to co-vary with force levels in any virtual-reality applications. In that light, our results can still be viewed as the best possible force-magnitude identification performance that can be expected of typical users.

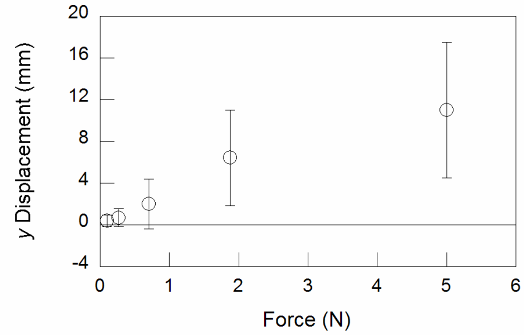

Figure 2. Displacement along the *y*-axis as a function of force magnitude, averaged over the ten participants. Also shown are the standard deviations

5 Concluding Remarks

The present study measured the information transfer associated with two haptic parameters: stiffness and force magnitude. It was found that the participants could reliably identify 2 to 3 levels of each parameter. Performance varied across participants: one participant who was experienced with many types of force-feedback devices could consistently identify 4 stiffness levels and 4 force-magnitude levels while other participants demonstrated an ability to identify 1 to 3 levels. Our results are consistent with the information transfers reported by earlier studies, which varied from 2-4 correctly-identifiable levels for haptic parameters [11, 12, 22, 26, 27]. Based on the results of the present study, we recommend that designers of data perceptualization systems assign two stiffness or force-magnitude levels (i.e., high and low) to represent categorical variables, with an additional third level (medium) for more experienced users.

In the future, we will investigate the channel capacities of other haptic parameters such as viscosity and mass. We will also conduct experiments on the identification of multiple haptic parameters, as it is well known that multidimensional channel capacity is typically less than the sum of unidimensional channel capacities [34]. The results will contribute to the knowledge base for designing haptic glyphs in a scientific data perceptualization system.

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