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On the Impact of Response Time on Force Perception During Hand Movement

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Abstract. For the perception of haptic environmental properties such as stiffness, damping, or inertia, estimates of force and movement must be combined continuously over time. We investigate the relations between perceptual judgments about force, the time a perceptual response is given, and different types of hand movement conditions. Portions of response data are selected according to their response time and psychometric functions are fitted. In this way, we can estimate time-dependent JND and PSE functions. We show that response time and movement condition influence the JND and that there is a time window when force discrimination is most sensitive. These findings have the potential to influence the development of novel human-centered control algorithms, e.g. communication protocols in haptic telerobotics and haptic rendering.

Keywords: Psychophysics, Force Perception, Perceptual Dynamics

1 Introduction

Force is a fundamental haptic signal, crucial for the perception of object properties such as weight and stiffness. Most investigations of human force perception aim at obtaining a psychometric function, relating the proportion of responses to a change in the force characteristic under investigation, e.g., its magnitude [1]. Two measures are extracted from it: The just noticeable difference (JND) characterises the sensitivity of the perceptual judgment to the stimulus. The point of subjective equality (PSE) determines the most likely perceptual representation of a stimulus's value. In haptic telerobotics, force JND has received particular attention to determine perceptually "irrelevant" haptic data which does not have to be sent from the remote side to the human-robot interface so to ease the load on the communication channel [3]. The simple rule employed is to send only data packages containing forces that differ more than a threshold near the JND from the previously sent package.

Investigations of JND and PSE have so far neglected temporal aspects of perception. Most studies measured these using a single stimulus presentation time or several durations. Challenging this time-invariant view, it has been recognised that perception in general is a dynamical process [4, 8], suggesting that a percept builds up and can vary over time. As a result, a stationary threshold based on the

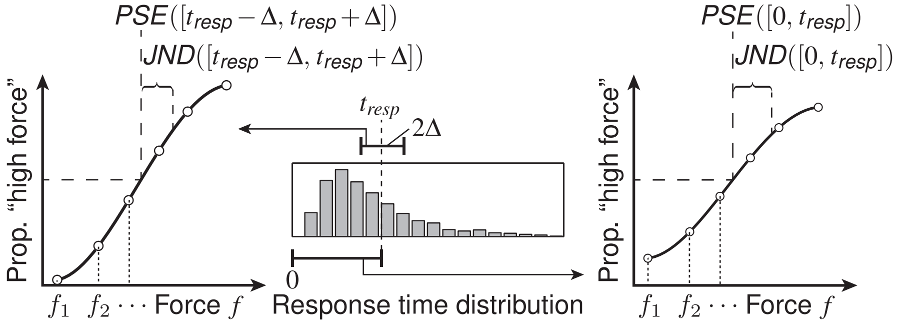

Fig. 1. Two types of response-time dependent JND and PSE measures are introduced: $JND([t_{resp} - \varDelta,\ t_{resp} + \varDelta])$ and $PSE([t_{resp} - \varDelta,\ t_{resp} + \varDelta])$ are calculated using responses that were given within a time interval around t_{resp} (left). To determine $JND([0,\ t_{resp}])$ and $PSE([0,\ t_{resp}])$, all responses given prior to t_{resp} are considered (right).

JND would not be ideal as a filter criterion for perception-based data transmission, given force perception sensitivity might actually change over time as well, so instead a representation of perceptual properties should explicitly exhibit a temporal component. In visual perception, computational dynamic models based on a diffusion process are well-established and correctly predict both the shape of the psychometric function and the response time distributions in a range of experimental paradigms [6, 7]. For the joint representation of response time and response proportions, so-called quantile-probability functions have been introduced [6, 7]. These graphs are, however, hard to interpret for non-experts and a comparison between different experimental conditions is renowned as difficult.

Here, we expand on the idea of characterising the perceptual system using JND and PSE but we want to be able to account for the fact that these measures may depend on the time the response is given. We present a psychophysical study on force magnitude perception during different hand movement conditions: No movement, active movement and non-active movement. These conditions have been chosen to test whether hand movement has an influence on the dynamics involved in force perception and because they are an integral part in most haptic perceptual processes. The results are interpreted using a novel way of analysing JND and PSE by calculating them over response time windows.

2 Methods

JND and PSE are estimated from the distribution of perceptual decisions about physical stimuli presented in a psychophysical experiment, e.g. when force magnitude is classified to be low or high. It is important to acknowledge that a decision about the perceived stimulus is an integral part of the perceptual process [5] and there is no known way of measuring a percept before a decision has been made. As a consequence, we introduce two methods for explicitly considering temporal factors in haptic perception by including the time of the expressed decision – the response time: 1) We consider $\mathit{JND}([t_{resp} - \Delta,\ t_{resp} + \Delta])$ and $\mathit{PSE}([t_{resp} - \Delta,\ t_{resp} + \Delta])$, describing force sensitivity and magnitude perception within an interval around a specific response time t_{resp}. These functions characterise haptic perception temporally localised, meaning they are valid only for response given within the 2Δ band around t_{resp}. 2) For many practical applications, e.g., telerobotics, instead of knowing only about perceptual decisions made during a specific time window, it is more important to characterise all decisions which have been made up to a specific time t_{resp}. As a consequence, $\mathit{JND}([0,\ t_{resp}])$ and $\mathit{PSE}([0,\ t_{resp}])$ functions with increasing time window size are defined and discussed in addition.

Response data within the response time range of interest is extracted from all answers given. Psychometric functions are fitted to this portion of responses to estimate the corresponding JND and PSE values from the 50% and 75% thresholds. The method for obtaining both perceptual measures is illustrated in Fig. 1. Because the shape and range of the response time distributions depends on the stimulus condition itself [6, 7], only the responses associated to time windows overlapping between all stimulus conditions contribute to the psychometric function estimate. For a reliable estimate of a psychometric function, a minimum of 6 repetitions per stimulus condition is required, making a very large number of repetitions compulsory for this method. In order to make economic use of response data, we introduce an approximation to the above introduced functions using a moving average technique with a fixed window size N_w. We will refer to the fastest response time associated to a response in force stimulus level $f_i,\ i = 1 \dots N_f$ (N_f is the number of stimuli) as $t^{f_i}_{resp}[1]$, to the slowest one $t^{f_i}_{resp}[N_{resp}]$, where N_{resp} is the total number of responses for this condition. All response data associated to $t^{f_i}_{resp}[1 \dots N_w]$ is taken together to estimate a psychometric function over all stimulus conditions. An approximate response time $\tilde{t}_{resp}$ is obtained by computing the mean response time of all responses taken into consideration,

$$\tilde{t}_{resp} = \frac{1}{N_f} \frac{1}{N_w} \sum_{j=1}^{N_f} \sum_{i=n}^{n+N_w} t^{f_j}_{resp}[i].$$

In a similar way, $\mathit{JND}([0,\ t_{resp}])$ and $\mathit{PSE}([0,\ t_{resp}])$ functions are approximated by increasing the number of samples taken into consideration with a minimum of N_w, starting with the fastest response times in all stimulus conditions. The response times for $\mathit{JND}([0,\ \tilde{t}_{resp}])$ and $\mathit{PSE}([0,\ \tilde{t}_{resp}])$ are the mean response times of the slowest samples taken into consideration

$$\tilde{t}_{resp} = \frac{1}{N_f} \sum_{j=1}^{N_f} t^{f_j}_{resp}.$$

2.1 Experiment

We investigated the temporal properties of force perception using a 1-interval, 2-alternative forced choice task similar to the one reported in [6]. Participants were asked to classify a force applied to the palm of their dominant hand by means of a force.dimension Delta haptic interface into the two categories of either a "high force" or a "low force". The force was always directed towards the elbow which rested on a table in a fixed position.

Participants. Seven psychology students were recruited via the University of Birmingham research participation scheme (SONA) and paid 12 £ (age range 19-28, 4 female, 1 left-handed as assessed by a questionnaire). They all gave their written informed consent prior to participating in the study, which has been approved by the local ethics committee. None of them reported any history of sensorimotor disorders.

Stimuli. Six force levels spanning equally between 2.0 N and 5.0 N were presented, the lower three associated to the "low force" group. After each stimulus presentation, feedback about the correctness of the judgment was given via coloured LEDs. The perceptual task was repeated under three movement conditions: No hand movement ("still"), "active" movement and, "non-active" movement. In the active case, participants were required to move their forearm towards their sagittal plane in a circular movement around their elbow with a constant angular velocity of approximately 0.26 rad/s. For the trials with non-active movement, the haptic interface itself moved the forearm with 0.26 rad/s by applying a force perpendicular to the arm. Each trial started with a beep, triggering the participant to initiate the forearm movement ("active" condition), expect the device to move in the "non-active" case, or expect the stimulus onset in the "still" condition. The stimulus force was applied at the beep or the movement onset (whichever was later) plus a uniformly random distributed waiting time between 0.1 and 0.3 s. A third-order polynomial was used to ramp up the force stimulus over 0.1 s. Afterwards it stayed constant until either a response was given or 1.5 s was passed, whichever was earlier. The next trial was initiated after the participant moved her/his arm into the vertical configuration again and remained there. Trials of the same movement condition were presented blocked and all conditions were presented with 10 repetitions and in a random order. Four repetitions of each block were targeted to be completed by each participant within 2 hours; conditions that could not be done in this period were discarded. The order of block presentations was random.

3 Results

In total, 5400 responses are obtained from all seven participants. Responses given after 1.5 s (88 answers) are removed from the dataset. In addition, response times are normalised by means of a logarithmic transformation and outliers beyond 3σ (43 answers) are discarded. Post-hoc force measurements using an ATI Mini 145 force/torque sensor against a rigid contact are collected so that the results reported are based on the recorded force levels. Furthermore, the point of objective equality (POE), indicating the force level separating "low" and "high" forces is corrected to 3.3 N.

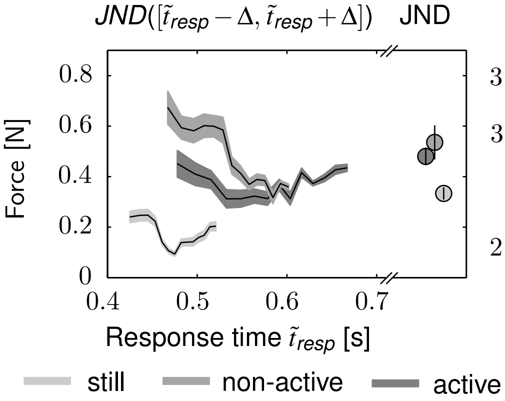

Fig. 2. The response-time dependent $JND([\tilde{t}_{resp} - \Delta,\ \tilde{t}_{resp} + \Delta])$ functions are U-shaped. Depicted is the mean ± s.e.m across participants. Response time does not have a significant effect on the $PSE([\tilde{t}_{resp} - \Delta,\ \tilde{t}_{resp} + \Delta])$ functions. Overall JND and PSE values estimated from the whole dataset are given for comparison.

Values for overall JND and PSE are reported in Fig. 2. The movement condition has a significant influence on JND (1-way r.m. ANOVA $F(2, 12) = 6.10$, $p < 0.05$) and PSE ($F(2, 12) = 5.02$, $p < 0.05$). Post-hoc tests suggest that the JND in the "still" condition is significantly lower compared to the "active" (paired t-test, $t(6) = 3.27$, $p < 0.05$) and the "non-active" condition ($t(6) = 2.80$, $p < 0.05$), but the two moving conditions do not differ significantly ($t(6) = -0.94$, $p = 0.38$). The PSE values for the "active" and "non-active" conditions differ significantly from the POE ($t(6) = -3.36$, $p < 0.05$ and $t(6) = -3.28$, $p < 0.05$, respectively) but not in the "still" condition ($t(6) = 0.39$, $p = 0.71$). Significantly lower PSE values suggest that forces applied to the hand are overestimated when the arm moves during the perceptual task.

$JND([\tilde{t}_{resp} - \Delta,\ \tilde{t}_{resp} + \Delta])$ and $PSE([\tilde{t}_{resp} - \Delta,\ \tilde{t}_{resp} + \Delta])$ obtained with a window size of $N_w = 10$ are depicted in Fig. 2. Presentation has been limited to 14 samples because one participant completed only 23 repetitions of all force stimuli in one movement condition within the time limit of 2 hours. $JND([\tilde{t}_{resp} - \Delta,\ \tilde{t}_{resp} + \Delta])$ functions for the "still" and "active" condition show a pronounced U-shape with minima at $\tilde{t}_{resp} \approx 0.48$ s and $\tilde{t}_{resp} \approx 0.55$ s, respectively. In the "non-active" condition, the $JND([\tilde{t}_{resp} - \Delta,\ \tilde{t}_{resp} + \Delta])$ function is decreasing with response time. A 2-way r.m. ANOVA with factors response time and movement condition reveals significant main effects ($F(13, 78) = 2.21$, $p < 0.05$ and $F(2, 12) = 5.81$, $p < 0.05$). The interaction term is also significant ($F(26, 156) = 2.35$, $p < 0.001$). A similar statistical analysis for $PSE([\tilde{t}_{resp} - \Delta,\ \tilde{t}_{resp} + \Delta])$ reveals a significant main effect for the movement condition factor ($F(2, 12) = 4.61$, $p < 0.05$), but no significant effect for response time ($F(13, 78) = 0.25$, $p = 0.996$) and no significant interaction term ($F(26, 156) = 0.87$, $p = 0.65$).

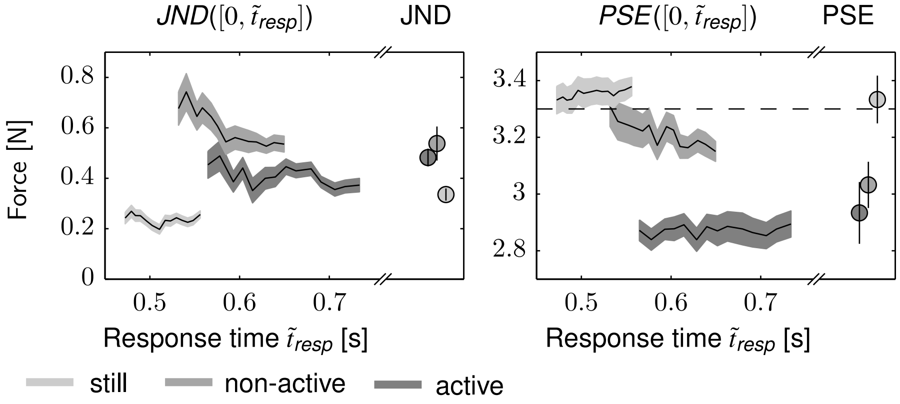

Fig. 3. The shape of the $JND([0,\ \tilde{t}_{resp}])$ functions are similar to $JND([\tilde{t}_{resp} - \Delta,\ \tilde{t}_{resp} + \Delta])$. The U-shape is less pronounced. $JND([0,\ \tilde{t}_{resp}])$ and $PSE([0,\ \tilde{t}_{resp}])$ functions are bound to end in the static estimates of JND and PSE.

Analogous statistical analyses for the $JND([0,\ \tilde{t}_{resp}])$ function which is plotted together with $PSE([0,\ \tilde{t}_{resp}])$ in Fig. 3 reveal a significant main effect of response time ($F(13, 78) = 2.55$, $p < 0.01$), no significant influence of the movement condition ($F(2, 12) = 3.17$, $p = 0.06$) and no significant interaction ($F(26, 156) = 1.02$, $p = 0.45$). The main effect of response time is not significant in the $PSE([0,\ \tilde{t}_{resp}])$ function ($F(13, 78) = 0.40$, $p = 0.97$). The movement condition is a significant factor $F(2, 12) = 4.08$, $p < 0.05$) and no significant interaction is found ($F(26, 156) = 0.97$, $p = 0.52$).

4 Discussion

The perceptual sensitivity for force perception depends on the time it takes to respond to the physical stimulus and the movement situation under which the perceptual task is performed. We can confirm the previously reported finding that arm movements can impair force discrimination [2] which may well be influenced by the interaction forces caused by the movement and not the stimulus. With our novel analysis technique using time-dependent functions, we could furthermore show that perceptual sensitivity to force is not constant over time. The $JND([\tilde{t}_{resp} - \Delta,\ \tilde{t}_{resp} + \Delta])$ functions indicate the existence of a time window where force discrimination is most sensitive in conditions where the hand is held still or actively moved, resulting in a minimum JND that is drastically lower compared to the classical JND estimated over the whole dataset. We can speculate that quick, impulsive responses could have a high proportion of random errors, leading to an increased JND for early responses. For late responses, participants could have felt a time pressure due to our experimental design which limits stimulus presentation to 1.5 s. This time pressure could have led to responses given prematurely, that means without the required confidence to make the best possible judgment. Following this argumentation, the lowest possible JND would be observed with infinite stimulus presentation time and without imposing time pressure.

From a system theoretic point of view, the current experiment could be seen as the observation of the perceptual system's response to a step-like force stimulus input. The system output is the force percept at response time t_{resp} which is observable over multiple perceptual decisions and whose statistical properties are described by the here-proposed response time-dependent JND and PSE functions. On the example of the $\mathit{JND}([t_{resp}-\mathit{\Delta},\ t_{resp}+\mathit{\Delta}])$ function, the statistical model prediction can be expressed as a conditional probability

$$\begin{aligned} p(\text{“different”}\,|\,\mathit{\Delta} f = \mathit{JND}([t_{resp}-\mathit{\Delta},\ t_{resp}+\mathit{\Delta}]),\\ t^*_{resp} \in [t_{resp}-\mathit{\Delta},\ t_{resp}+\mathit{\Delta}]) = 0.75 \end{aligned} \tag{1}$$

with t^*_{resp} being a specific response time in one experimental trial and $\mathit{\Delta} f$ being the difference in force which is to be perceived. Two hypotheses about the structure and nature of the underlying system model can be based on the data presented here: Firstly, there may be a time delay between the physical input and the perceptual output, because no responses are given before ≈ 430 ms. Secondly, the significant influence of response time on the $\mathit{JND}([t_{resp}-\mathit{\Delta},\ t_{resp}+\mathit{\Delta}])$ and $\mathit{JND}([0,\ t_{resp}])$ functions can be taken as evidence that the system model should be dynamic, thus based on differential equations instead of algebraic mappings.

For the purpose of building a computational perception model, the $\mathit{JND}([t_{resp}-\mathit{\Delta},\ t_{resp}+\mathit{\Delta}])$ and $\mathit{PSE}([t_{resp}-\mathit{\Delta},\ t_{resp}+\mathit{\Delta}])$ functions are most valuable because the underlying force percept is characterised with a high temporal resolution. On the other hand, they are less suited to guide a human-centered design of technical systems and algorithms, e.g., the initially mentioned perception-based control of network traffic [3] or haptic rendering algorithms. In these applications, the communication or rendering process is not stopped after a perceptual decision is made, thus the time instance t^*_{resp} in equation (1) is unknown. To decide in real-time whether or not a force difference at time $t = 0$ is or has been perceived, the $\mathit{JND}([0,\ t_{resp}])$ and $\mathit{PSE}([0,\ t_{resp}])$ functions account for all decisions made so far.

5 Conclusion

In a force magnitude perception task, the time when a response is given has a significant influence on perceptual sensitivity. Overall JND and PSE measures estimated from all responses in a psychophysical experiment are time-invariant and can not capture this effect. In this paper, we introduced response time-dependent JND and PSE functions, enabling us to draw conclusions about the structure of a computational model for force perception over time and allow the development of novel haptic real-time control algorithms.

There are multiple open questions that deserve particular attention in the future: The role that $JND([t_{resp} - \Delta,\ t_{resp} + \Delta])$ and $PSE([t_{resp} - \Delta,\ t_{resp} + \Delta])$ functions can play in the development of dynamic perception models is to be further investigated. Especially the relation to the diffusion process utilised in modelling visual perception phenomena [6, 7] remains open at this point. The PSE for force has been found to be significantly lower than the POE in conditions when the hand was in movement. Reasons for force overestimation during movements and implications for the perception of haptic environments as well as for technical applications require a dedicated discussion. Lastly, the force stimuli in the current case have been unrelated to the hand movement. During the perception of environmental stiffness, damping, or inertia these information sources are highly correlated. Understanding temporal characteristics of movement and force in this latter case is an important step to develop a dynamic, computational model for the perception of generic haptic environments.

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