Response Time-Dependent Force Perception During Hand Movement

Markus Rank and Massimiliano Di Luca

{m.rank,m.diluca}@bham.ac.uk
Research Centre for Computational Neuroscience and Cognitive Robotics
University of Birmingham, Edgbaston, UK

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 sensitivity of perceptual judgments about force and the time a perceptual response is given with different types of hand movements 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 the JND is different depending on which portion on the response time data it is based on. The JND follows the same pattern for responses given after 650ms. Furthermore, we find that forces are consistently overestimated during movement.

Keywords: Psychophysics, Force Perception, Perceptual Dynamics

1 Introduction

Two fundamental sources of haptic information are crucial for perceiving object properties such as inertia and stiffness: Force and movement. It is well-known that these two quantities depend on each other, physically linked by the impedance of one's moving limb and the environmental dynamics, but there is also an interdependency on the perceptual level. During the movement of a limb, detecting cutaneous stimuli is significantly more difficult [2, 4, 9]. This effect has been associated to a neural gating mechanism to cancel out forces resulting from limb movements and is well-captured by a control strategy using a forward model of limb and environment [12]. 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.

Investigations of JND and PSE have so far neglected temporal aspects of perception, in particular the time that is taken to express a decision about the perceived haptic stimulus. However, it has been recognised that perception in general is a dynamical process [5, 10], suggesting that a percept builds up and can vary during the exposure to sensory stimulation. As a result, a stationary and constant JND would not be an ideal characterisation of the perceptual system, but a temporal component must be added. 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 [7, 8]. For the joint representation of response time and response proportions, so-called quantile-probability functions have been introduced [7, 8]. 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 change with 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 the two hypotheses "Movement has an influence on the sensitivity and accuracy of force perception." and "Response time and perceptual sensitivity/accuracy are linked to each other." These hypotheses are tested using a novel way of computing JND and PSE by calculating them over different portions of response time data.

2 Methods

We investigated the temporal properties of force perception using a 1-interval, 2-alternative forced choice task similar to the one reported in [7]. Participants were asked to classify a force applied to the palm of their dominant hand by means of a force.dimension delta.3 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. Responses were collected through the left and right arrow keys on a customised computer keyboard labeled "low force" and "high force", respectively. Key press events were detected by a National Instruments PCI-6229 DAQ card at a rate of 1000Hz.

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 commanded to the haptic interface, 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

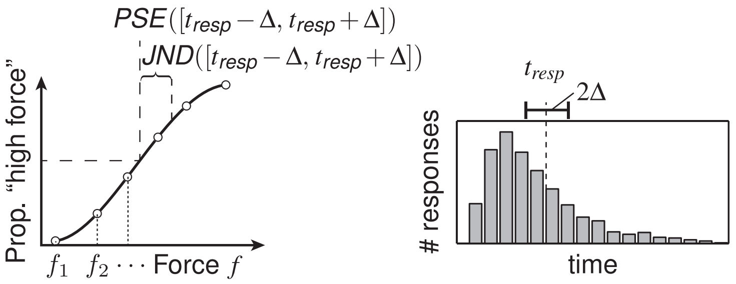

Fig. 1. $JND([t_{resp} - \Delta,\ t_{resp} + \Delta])$ and $PSE([t_{resp} - \Delta,\ t_{resp} + \Delta])$ are calculated using responses that were given within a time interval of 2Δ around a specific response time t_{resp}.

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. The order of block presentations was also randomised. 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. For the computation of the time-dependent JND and PSE functions introduced next, the number of repetitions taken into consideration was limited to 24, although several subjects performed more than that.

2.1 Response-time dependent JND and PSE

JND and PSE are generally 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. The PSE is defined as the point of maximum uncertainty of the judgement to be performed, in the current case of a two-alternative forced choice task, it is the stimulus level that would provoke half of all responses to be “high force”. The JND is defined as the difference between the PSE and the stimulus level that causes 75% of “high force” responses. It is important to acknowledge that a decision about the perceived stimulus is an integral part of the perceptual process [6] and there is no known way of measuring a percept before a decision has been made. As a consequence, we introduce a method for explicitly considering temporal factors in haptic perception by including the time of the expressed decision – the response time: $JND([t_{resp} - \Delta,\ t_{resp} + \Delta])$ and $PSE([t_{resp} - \Delta,\ t_{resp} + \Delta])$ describe force sensitivity and magnitude perception within an interval of size 2Δ around a specific response time t_{resp}: 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 PSE and JND values. The method for obtaining $JND([t_{resp} - \Delta,\ t_{resp} + \Delta])$ and $PSE([t_{resp} - \Delta,\ t_{resp} + \Delta])$ is illustrated in Fig. 1. Because the shape and range of the response time distributions depends on the stimulus condition itself [7, 8], 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, using a minimum of ~5-10 repetitions per stimulus condition is advisable [11], 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 calculating JND and PSE over response portions with a fixed bin size N_w. The result are $JND([n - \frac{N_w}{2},\ n + \frac{N_w}{2}])$ and $PSE([n - \frac{N_w}{2},\ n + \frac{N_w}{2}])$ functions with $n = 1 \ldots N_{resp} - N_w$ being the participant's nth fastest response and N_{resp} is the total number of responses for this condition. The fastest response time associated to a response in force stimulus level $f_j,\ j = 1 \ldots N_f$ (N_f is the number of stimuli) is denoted $t^{f_j}_{resp}(1)$, the slowest one $t^{f_j}_{resp}(N_{resp})$. An approximate response time equivalent $\tilde{t}_{resp}$ is obtained by computing the mean response time of all responses taken into consideration to compute the JND and PSE functions,

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

3 Results

All seven participants together gave a total of 5400 responses. 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 of the individual participant's mean (43 answers) are discarded. Post-hoc force measurements using an ATI Mini 145 force/torque sensor against a rigid contact are collected. As a result, the truly rendered forces were measured to be lower by a constant offset of 0.2N. Thus, the point of objective equality (POE), denoting the force level separating "low" and "high" forces which is in our case the mean across the force range is corrected to 3.3 N.

Values for overall JND and PSE are reported in Fig. 2, next to the time-varying JND and PSE functions on the right. The movement condition has a

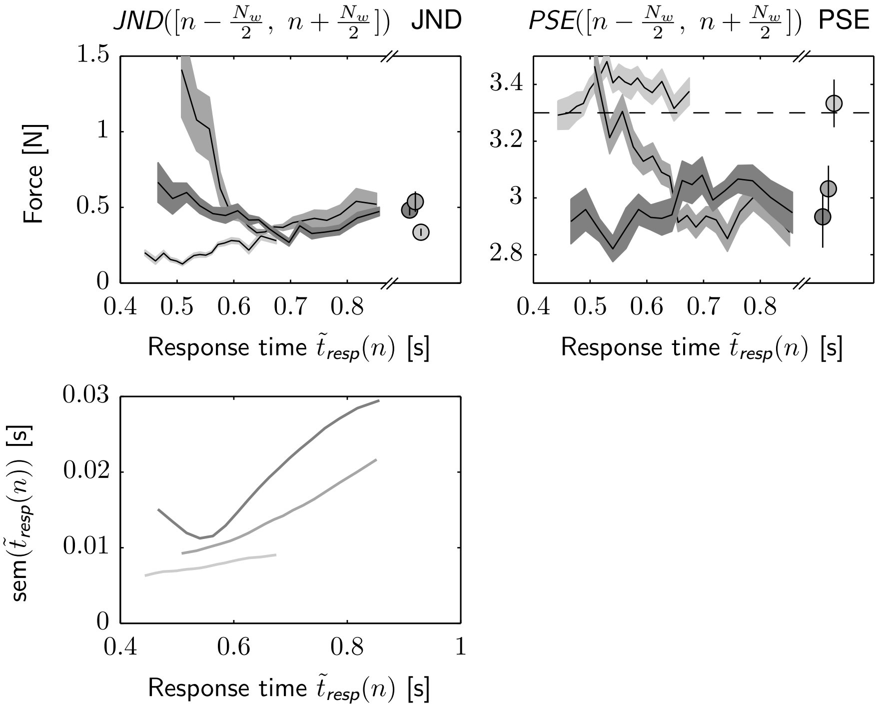

Fig. 2. (upper) The response-time dependent $JND([n-\frac{N_w}{2},\ n+\frac{N_w}{2}])$ functions are U-shaped. Depicted is the mean ± s.e.m across participants. Overall JND and PSE values estimated from the whole dataset are given on the right for comparison. (lower) The standard error of the estimate for the response time $\tilde{t}_{resp}(n)$.

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.

$JND([n-\frac{N_w}{2},\ n+\frac{N_w}{2}])$ and $PSE([n-\frac{N_w}{2},\ n+\frac{N_w}{2}])$ obtained with a window size of $N_w = 6$ are depicted in Fig. 2. The $JND([n-\frac{N_w}{2},\ n+\frac{N_w}{2}])$ function for the "non-active" condition starts at a JND estimate of 1.4 N, decreases to a minimum of approximately 0.35 N at $\tilde{t}_{resp} \approx 0.65$ s and rises afterwards. In the "active" condition, the $JND([n-\frac{N_w}{2},\ n+\frac{N_w}{2}])$ function is shallower than in the “non-active” case, yet a slight U-shape is noticeable as well. The $JND([n-\frac{N_w}{2},\ n+\frac{N_w}{2}])$ in the still condition starts from the lowest JND value of approximately 0.2 N and increases afterwards. Remarkably, the $JND([n-\frac{N_w}{2},\ n+\frac{N_w}{2}])$ functions of all three movement conditions overlap to the same shape after $\tilde{t}_{resp} \approx 0.65$ s. A 2-way r.m. ANOVA on $JND([n-\frac{N_w}{2},\ n+\frac{N_w}{2}])$ with factors n (bin index) and movement condition reveals a significant main effect of bin index ($F(17,102) = 2.35$, $p < 0.01$) but not for movement condition $F(2,12) = 2.1$, $p = 0.17$). The interaction term is not significant ($F(34,204) = 0.97$, $p = 0.52$). A similar statistical analysis for $PSE([n-\frac{N_w}{2},\ n+\frac{N_w}{2}])$ reveals a significant main effect for the movement condition factor ($F(2,12) = 6.2$, $p < 0.05$), but no significant effect for bin index n ($F(17,102) = 0.48$, $p = 0.95$) and a significant interaction term ($F(34,204) = 1.5$, $p < 0.05$).

4 Discussion

The perceptual sensitivity for force perception as represented by $JND([n-\frac{N_w}{2},\ n+\frac{N_w}{2}])$ is influenced by the portion of response time data taken to make the fit and thus on the response time, thus we can accept our second hypothesis for JND. The movement condition was found to be not significant in the 2-way ANOVA, but the shape of the JND function in Figure 2 is interesting: While the JND functions start from different initial values, the differences between the movement conditions vanish for responses given after approximately 650 ms. This behaviour could point to the existence of two mechanisms contributing to the perception of force magnitude – one predominantly influential for early responses, one for late responses. The early response mechanism is influenced by the type of movement performed by the arm, the late response mechanism is not. We can speculate that the early responses are based on the tactile sensation of the force onset, being in line with the result from Vitello et al. [9] that the JND for tactile skin stretch is higher when the arm is moved actively or passively. With more time between the occurrence of the onset event and the response, more information about the static pressure distribution and the proprioceptive response from the stimulus could be taken into consideration for making the perceptual judgment. Interestingly, movement-independent tactile sensitivity is as well known to exist [4]. However, response times are not reported for neither [9] nor [4], making a definite conclusion difficult.

The second major finding is that force is overestimated when the arm is moving, confirming our first hypothesis in this point. This result is at odds with the conclusion of [4] that movement has a “masking effect” manifesting in a higher absolute detection threshold for cutaneous electrical stimulation. Instead, the internal compensation for the arm and haptic device dynamics which should in principle cancel out all forces related to one’s movement state may be imperfect, e.g. due to noise in the estimation of the body state [3]. Movement-induced forces could thus lead to a perceived force stimulus which is higher than the actual physical magnitude. There are two considerations making this explanation debatable: In order to influence force magnitude perception in the suggested way, participants would have to maintain a constant internal criterion separating low forces from high forces between conditions. However, the movement conditions were separated in blocks and participants were informed about the correctness of their answer after every trial, easing it for them to adapt their internal criterion to the movement condition. Secondly, the significant interaction between the type of movement and the index suggests that there is a difference in the pattern across the movement conditions.

From a system theoretic point of view, the results could be interpreted as 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 $JND([t_{resp} - \Delta,\ t_{resp} + \Delta])$ function, the statistical model prediction can be expressed as a conditional probability

$$p(\text{“different”}|\Delta f = JND([n - \frac{N_w}{2},\ n + \frac{N_w}{2}]),\ \tilde{t}^*_{resp}(n)) = 0.75$$

with t^*_{resp} being a specific response time in one experimental trial and Δf 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 the bin index n on the $JND([n - \frac{N_w}{2},\ n + \frac{N_w}{2}])$ function can be taken as evidence that the system model should be dynamic, thus based on differential equations instead of algebraic mappings. One possibility to approach this problem is to model the haptic system as a noisy information accumulating process [7, 8].

5 Conclusion and Outlook

Limb movement and the response time are important factors to take into account for describing force perception. While traditional JND and PSE measures are estimated from all responses in a psychophysical experiment and can not capture these effects per se, we introduced response time-dependent JND and PSE functions in this paper. We find that the JND estimates significantly depend on the portion of responses taken into consideration, and that differences in JND between no limb movement, non-active and active movement vanish in responses given after ~650 ms. Secondly we show that forces are consistently overestimated when the arm is moved.

There are multiple open questions that deserve attention in the future: The role that $JND([t_{resp} - \Delta,\ t_{resp} + \Delta])$ and $PSE([t_{resp} - \Delta,\ t_{resp} + \Delta])$ functions (or the here-utilised $JND([n - \frac{N_w}{2},\ n + \frac{N_w}{2}])$ and $PSE([n - \frac{N_w}{2},\ n + \frac{N_w}{2}])$ functions) could 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 [7, 8] remains open at this point. 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.

Acknowledgments

This work was supported by a fellowship within the Postdoc-Programme of the German Academic Exchange Service (DAAD), the FP7 ICT grant no. 287888 `http://www.coglaboration.eu` and the Royal Society research grant RG110521. The authors thank Stephanie Mason for her help with the data collection.

References

1. Abbink, D., van der Helm, F.: Force perception measurements at the foot. In: Proceedings of the 2004 IEEE International Conference on System, Man and Cybernetics. vol. 3, pp. 2525–2529. Ieee (2004)
2. Angel, R.W., Malenka, R.C.: Velocity-dependent Suppression of Cutaneous Sensitivity During Movement. Experimental Neurology 77, 266–274 (1982)
3. Bays, P.M., Wolpert, D.M.: Computational principles of sensorimotor control that minimize uncertainty and variability. The Journal of Physiology 578(Pt 2), 387–396 (2007)
4. Chapman, C., Bushnell, M., Miron, D., Duncan, G., Lund, J.: Sensory Perception During Movement in Man. Experimantel Brain Research 68(3), 516–524 (1987)
5. Kelso, J.: Dynamic patterns: The self-organization of brain and behavior. The MIT Press (1995)
6. Macmillan, N.A., Creelman, C.D.: Detection Theory: A User's Guide. Lawrence Erlbaum (2005)
7. Ratcliff, R., Thapar, A., McKoon, G.: The effects of aging on reaction time in a signal detection task. Psychology and Aging 16(2), 323–341 (2001)
8. Smith, P.L., Ratcliff, R.: Psychology and neurobiology of simple decisions. Trends in Neurosciences 27(3), 161–8 (2004)
9. Vitello, M., Ernst, M., Fritschi, M.: An instance of tactile suppression: Active exploration impairs tactile sensitivity for the direction of lateral movement. In: Proceedings of the 2006 EuroHaptics Conference. pp. 351–355 (2006)
10. Warren, W.H.: The dynamics of perception and action. Psychological Review 113(2), 358–89 (2006)
11. Wichmann, F.a., Hill, N.J.: The psychometric function: II. Bootstrap-based confidence intervals and sampling. Perception & Psychophysics 63(8), 1314–29 (2001)
12. Wolpert, D.M., Miall, R.C.: Forward Models for Physiological Motor Control. Neural Networks 9(8), 1265–1279 (1996)