

Humans terminate their haptic explorations according to an interplay of task demands and motor effort

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Abstract. Haptic exploration is an inherently active process by which humans gather sensory information through physical contact with objects. It has been proposed that humans generally optimize their exploration behavior to improve perception. We hypothesized that the duration of haptic explorations is the result of an optimal interplay of sensory and predictive processes, also taking costs such as motor effort into account. We assessed exploration duration and task performance in a two-alternative forced-choice spatial frequency discrimination task under varying conditions of task demand and motor effort. We manipulated task demands by varying the discriminability of virtual grating stimuli and manipulated motor effort by implementing forces counteracting the participants' movements while switching between stimuli. Participants were instructed to switch between stimuli after each swipe movement. Results revealed that higher task demands lead to higher numbers of exploratory movements (i.e. longer exploration duration), likely reflecting a compensatory mechanism that enables participants to attain a certain level of task performance. However, this effect is reduced when motor effort is increased; while low and medium task demands yield similar numbers of movements regardless of related motor effort, higher demands are not associated with increased numbers of movements when the required motor effort is high. In conclusion, the extent to which increased task demands are compensated via the extension of an exploration seems to depend on the motor costs that the agent is confronted with.

Keywords: Haptic exploration, behavioral optimization, motor control.

1 Introduction

Humans gather sensory information about objects, materials, or textures via active touch, i.e. by haptic exploration. Previous research has illustrated the adaptive nature of such explorations with various examples: In texture perception for instance, humans systematically use different scanning velocity patterns depending on the perceptual task [1] or they gradually adjust their movement direction to the orientation of grating textures over the course of an exploration [2]; or in curvature perception, participants update their contact force according to the present surface curvature [3]. The adjustments

of those exploration parameters serve as optimization mechanisms, increasing task performance [2, 4, 5] and efficiency of explorations [6]. Another parameter that might be subject to optimization is the duration of haptic explorations, i.e. the time individuals dedicate to touching and perceiving objects. The amount of time spent on an exploration can drastically differ across situations and objectives: Humans might be rather quick when checking for keys in their pocket or lifting the milk package to check whether it is empty, though explorations might take longer when they do woodwork and investigate the smoothness of edges, or when surgeons inspect tissues and organs during procedures.

Humans typically conduct serial exploration with repetitive movements, i.e. multiple indentations for deformable objects or swiping and rubbing movements for rough surfaces [7]. The percept then results from the integration of the sensory information gained during each of these single movements [8]. Prolonged exploration, i.e. the extension of the exploration over space and time, was shown to increase perceptual reliability [9–13] (up to a saturation point). This is consistent with the Maximum Likelihood Estimation (MLE) model of optimal integration of information [14]. More recent (modified Kalman filter-) models also take memory limitations into account [10, 15], and hence are able to explain why the increase in the percept’s reliability in a prolonged exploration is overestimated by the MLE model [16].

Various factors have been previously shown to produce or affect optimization behavior (e.g., adjustment of contact forces and movement orientation) during haptic explorations, such as the (expected) task difficulty [5], the availability of prior information [17, 18], or motivational factors related to the individual relevance of the task and goal [19]. However, it is not yet clear how these factors interact in determining the time after which individuals decide to terminate their exploration. Given that the spatiotemporal extension of a haptic exploration increases the differential sensitivity of an agent, we could predict that the exploration would be extended in response to increased task demands to maintain a certain level of task performance. As the benefits of the extension of the exploration come at a cost of additional motor effort, we could also predict that it has a counteracting effect on the exploration length.

It is widely established in fields such as ecology and economics that costs and benefits are central determinants of behavior, combined to form a utility function that can guide choices (e.g., [20]). This principle has been demonstrated to apply to motor control as well, with motor effort being represented as costs which humans seek to minimize and weigh up against potential positive outcomes [21]: Motor control has been shown to be an optimal process derived from the maximization of the weighted differences between anticipated rewards and motor efforts, i.e. energetic expenditure, with examples such as walking, flying, or reaching [22]. Extending this concept to the gathering of haptic information, we speculate that haptic explorations are similarly governed by closed-loop and open-loop optimization processes following the principles of established utility frameworks for decision and motor control with regards to cost-benefit discounting. More concretely, when being confronted with higher motor costs, humans should terminate their exploratory behavior earlier than when being confronted with lower motor costs. In line with this, humans typically stop their exploration before reaching the abovementioned saturation point of task performance [11, 12, 15]: Motor

costs appear to be a plausible reason why humans would display this premature termination behavior. Here we assessed the exploration duration as a function of task demands and the motor effort required to explore an object.

In our experiment, participants in each trial explored two virtual gratings (rendered by a force-feedback device) and decided which one had higher spatial frequency. Exploration duration can be operationalized in multiple ways, e.g. as the overall time spent on the exploration, the length of movement trajectories, or as the number of (repetitive) movement segments that are being executed. Here, we operationalized duration as the number of individual swiping movements over the stimuli (= swipes). Participants were instructed to switch after every swipe, which yields maximum perceptual performance by minimizing “memory loss” [16] and allows for thorough control of motor effort. Motor effort was manipulated by implementing forces that counteract the participants’ movements when switching between the virtual stimuli. Task demand was manipulated by varying the discriminability of the stimuli. We hypothesized that with increasing task demands, the exploration duration would increase, resembling a compensatory mechanism. Further, we expected increased motor efforts to reduce the expected utility of an exploration extension, leading to earlier termination of the exploration when compared to lower motor efforts.

2 Methods

2.1 Participants

Previous studies that investigated optimization processes in exploratory movement control oftentimes reported large effect sizes (e.g., [2, 17]). A sample size calculation for a large effect ($f = .40$), a power of 80% and an alpha of 5% yields a sample of 12 for a three-level within-participant factor of a repeated measures ANOVA (G*Power, [23]). In the present study, 12 right-handed students from Justus-Liebig University Giessen participated (8 female, 4 male, age 19-35 years, mean: 24.89 years). None of them reported motor or sensory impairments. All participants were naïve to the purpose of the experiment, provided written informed consent, and received financial compensation (8€/hour). The experiment was approved by the local ethics committee LEK FB06 and conducted in accordance with 2013 Declaration of Helsinki, except for preregistration.

2.2 Setup and Stimuli

The setup (Fig. 1a) consisted of a Geomagic Touch™ haptic force feedback device (spatial resolution: ~ 0.055 mm, temporal resolution: 1000 Hz). This was embedded in a virtual-reality environment to guide the participants through the experiment while preventing them from seeing their actual interaction with the haptic device. For this, we used the HTC Vive Pro Eye virtual head-mounted-display (HMD; 1440 x 1600 pixels per eye, 90 Hz; HTC Corp., Xindian, New Taipei, Taiwan). The experiment was implemented and programmed using Unity (Version 2021.2.7f1; Unity Technologies, Inc., San Francisco, CA, USA), SteamVR (Version 2.1.9), the Unity Experiment Framework package (Version 2.2.1, [24]) and the Haptics Direct Unity Plugin (Version

1.0; 3D Systems). It was run on a custom-built desktop PC (Intel Core i9-12900KF CPU at 3.2 GHz, 64 GB RAM, Dual NVidia GeForce RTX3080 GPU).

The visual scene (Fig. 1b) consisted of the two virtual stimuli, two response buttons above the stimuli (grey cubes), and the bright green stylus that participants used to interact with the objects. The stimuli bases were rendered in white while the ridges were invisible. As soon as participants moved the pen over the ridge area, the stylus became invisible as well. Thus, no information on movement velocity or the spatial frequency of the stimuli was visually revealed to them via movement characteristics of the stylus. A semi-transparent pink ellipsoid object was permanently placed between the two stimuli to remind participants of the prescribed switching movement trajectory (arc-like motion over the ellipsoid) and prevent them from carelessly moving too close to the stimuli during the transportation phase. The virtual stimuli were simulated by the force feedback device by applying reaction forces (\vec{F}_p) as a function of the 3D-position of the end effector. The force magnitude is directly proportional to the indentation depth (i_p) of the virtual stimulus and its' spring constant (K), i.e. its' stiffness. The direction of the indentation is computed by Unity's built-in 3d physics engine (Nvidia PhysX 3.4). The force direction is normal to the texture's surface at the contact point (\vec{n}_p):

$$\vec{F}_p = \vec{n}_p \times |\vec{F}_p|, \quad |\vec{F}_p| = K \times i_p \quad (1)$$

The virtual grating stimuli all consisted of a $10 \times 4 \times 0.5$ cm rectangular cuboid and $0.1 \times 40 \times 0.05$ mm cylindrical segments (= ridges) on their top side (Fig. 1c). The distance between the centers of adjacent ridges (= period) defined the spatial frequency and differed between stimuli. Amplitude and ridge width was constant. With constant stimulus sizes, higher spatial frequencies would always be characterized by higher absolute number of ridges. To partly decouple the spatial frequency from the absolute number of ridges, we varied the length of the ridged stimulus area between trials. The length of the ridge area could comprise ca. 7 cm, 5.5 cm, and 4.5 cm (slightly varying depending on the respective period), with each size appearing equally often in randomized order. At the front and back ends of each stimulus, there were areas without ridges: 2.5×4 cm at the front end, being the starting area, and 0.5, 2, or 3×4 cm at the back end, depending on the length of the ridged area. The stimulus set comprised two reference stimuli with periods of 10.84 mm and 13.38 mm. For each demand-level, reference stimuli were paired with comparison stimuli of either +/- 2.54 mm period (high demand), +/- 3.81 mm (medium demand), or +/- 4.45 mm (low demand), resulting in 4 stimulus pairs for each demand level. The stimulus pairs were selected after examination of psychometric functions derived from a pilot-study ($N = 5$): their differences corresponded to discrimination performances of about 65%, 75%, and 85%. Throughout the experiment, brown noise was presented via the headset's headphones additional white noise was played from a speaker directly above the force feedback device.

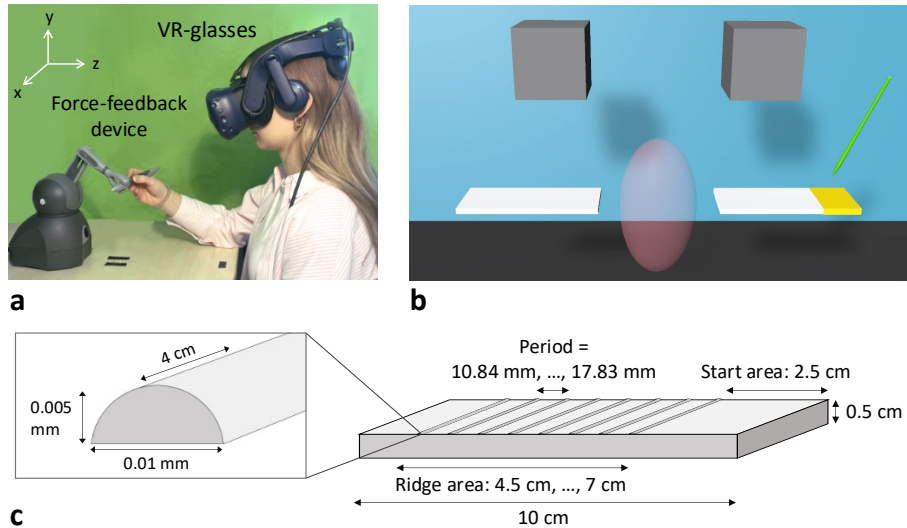


Fig. 1. a, setup. b, visual scene (before participant touches the stimulus for the first time in a trial), yellow area indicates start stimulus. c, Schematic depiction of virtual stimulus.

2.3 Design and Procedure

The experimental design was a 3 (Demand) \times 3 (Motor Effort) - design, with $3 \times 3 \times 4$ (stimulus pairs) \times 6 (repetitions) = 216 trials in total. The experiment was split in two blocks. Each block contained 3 repetitions of the trial types and the trial order was randomized within each block. There was a break of 15 minutes between the blocks and a break of 5 minutes in the middle of each block. All in all, the session took about 2 hours. In each trial, participants had to complete a two-alternative forced choice (2AFC) discrimination task, in which they had to successively explore two grating stimuli and decide which one had a higher spatial frequency. To ensure a reasonable level of effort in the completion of the task, we provided participants with a monetary incentive (i.e. they received points for correct responses, which could amount to max. total 8.64 €). After every 10 trials, the number of accumulated reward points was displayed (3 s), to not give immediate performance feedback after each trial. The starting area of the respective stimulus on which participants were supposed to begin the exploration was highlighted in bright yellow before each trial until they first touched it (Fig. 1b). Exploration began equally often on the left and right stimulus, in randomized order. This was also the case for the position of the reference stimulus. As indicated via the starting area, exploration always began at the “outer” area of a stimulus towards the “inner” area (with regards to the visual scene). Participants were instructed to switch to the other stimulus after one swipe. Here again, exploration started at the outer area and ended in the inner area. Thus, the switching movement was sufficiently long to allow for proper manipulation of motor effort. Participants were free to switch as often as desired. To log their decision, they had to touch the virtual button (cube) above the

respective stimulus that they perceived to have the higher spatial frequency, triggering the next trial to begin. We manipulated „motor effort” by implementing forces counteracting the participants’ movement when switching from one stimulus to the other. Thus, when a participant finished one swipe, lifted the stylus up, and moved to the other stimulus, the device exerted a constant force F_x of either 1.7 Newton (high effort), 0.85 N, (medium) or 0 N (baseline) along the x-axis of the device in the opposite direction of the movement vector. Thus, participants had to put a constant additional effort into moving from one stimulus end area to the other stimulus start area. The force was only active > 1.5 cm above and next to the stimuli, to ensure that the sensory perception during exploration was not directly affected by e.g. increased muscular effort. The onsets and offsets of the counterforce were not abrupt; the force linearly increased/decreased from zero to the respective value and vice versa by 3.6N/s. Participants were instructed that they should never touch the stimuli while switching. To standardize the switching movement, they were additionally instructed to make an arc-like motion and avoid the semitransparent pink capsule object between the two stimuli. This way, the switching movement comprised a minimum distance of ~ 22 cm.

Before each session, participants had a familiarization phase for the HMD and the force-feedback device and a subsequent training phase of about 10 minutes (10 practice trials) to practice the movement coordination. During training and experimental trials, we aimed to keep scanning velocities relatively constant between and especially within participants at around 100-120 mm/s to avoid any potential confounds [11, 25–27]. This target velocity has been observed to occur naturally and was proven feasible during piloting. While moving over the stimulus, the velocity was continuously tracked and averaged over the last previous 250 ms for smoothing. Whenever the average value exceeded or fell below the threshold of 180 mm/s or 60 mm/s respectively, an acoustic warning signal was played (low pitch tone or high-pitched beep tone, duration 300 ms). We kept the criterion relatively liberal, enabling participants to mainly focus on the task rather than on the movement execution. Consequently, the training phase also helped with automatizing the prescribed velocity. It additionally gave a rough orientation on how much force participants should exert during stimulus contact. This was verbally instructed by the experimenter, who received visual feedback on the current reaction forces of the device (desired range: approx. 0.4-1 N). After the experiment, participants filled out a brief questionnaire to check whether they noticed any behavioral changes in reaction to the motor effort manipulations.

2.4 Data analysis

Raw data of individual observers is available at [10.5281/zenodo.10370635](https://zenodo.org/record/10370635). Data analysis was performed using MATLAB (Version R2020b). Raw data comprised the positions of the end effector represented as Cartesian coordinates in three-dimensional space, the movement velocities, and the participants’ responses. The number of swipes was derived from the position of the end effector, i.e. the number of times that the effector changed from one stimulus area to the other stimulus area + 1. We compared the number of swipes using a two-way repeated measures analysis of variance

(ANOVA) with the within-participant factors Task Demand and Motor Effort. Likewise, we analyzed the average response accuracy. As a manipulation check, we also assessed whether there were systematic differences in the average movement velocities between the different conditions, conducting a similar ANOVA as the previous ones. Whenever the assumption of sphericity was violated, the p-values of the respective ANOVA were Greenhouse-Geisser adjusted [28]. The assumption of normality (tested with the Shapiro-Wilk test) was not violated (all $p > .07$).

3 Results

The average numbers of exploratory movements can be seen in Fig. 2a. A two-way repeated measures ANOVA with the within-participants factors Task Demand (low, medium, high) and Motor Effort (baseline, medium, high) showed that a higher number of movements was executed when task demands were increased, $F(2,22) = 4.65$, $p = .021$, $\eta^2_p = 0.30$, confirmed by a linear trend, $t(22) = 2.9$, $p = .008$. There was no significant main effect of Motor Effort, $F(2,22) = 1.79$, $p = .19$, $\eta^2_p = 0.14$, but an interaction between the two factors, $F(4,44) = 3.76$, $p = .01$, $\eta^2_p = 0.26$. Bonferroni-corrected post-hoc tests (36 pairwise comparisons) revealed that for Baseline Motor Effort, more movements were executed in the High Demand condition than in the Low Demand condition, $t(11) = 4.54$, $p = .001$, $d = 0.83$. For High Motor Effort, this was not the case ($p > .99$). For High Demand, in line with that, more movements were executed in the Baseline Effort condition than in the High Effort condition, $t(11) = 3.65$, $p = .022$, $d = 0.65$. Trivially, more movements were executed for Baseline Effort/High Demand than for High Effort/Low Demand, $t(11) = 3.47$, $p = .035$, $d = 0.73$. For Low Demand, the amount of movements did not differ regardless of the Effort level, all $p > .99$ (same for all other 33 comparisons). In summary, participants extended their explorations in reaction to higher task demands, but only when motor effort was low. Average accuracies entered a similar repeated measures ANOVA (Fig. 2b), which revealed a main effect of Task Demand, $F(2,22) = 13.01$, $p < .001$, $\eta^2_p = 0.54$, with accuracies decreasing with increasing task demand, confirmed by a linear trend, $t(22) = 5.08$, $p < .001$. No main effect of Motor Effort, $F(2,22) = 0.34$, $p = .072$, $\eta^2_p = .03$, and no interaction effect, $F(4,44) = 0.78$, $p = 0.55$, $\eta^2_p = 0.07$, was found. As intended, participants kept their movement velocities rather constant across conditions, resulting in no significant main effect of Task Demand on the average velocities, $F(2,22) = 0.12$, $p = 0.89$, $\eta^2_p = 0.01$, no main effect of Motor Effort, $F(2,22) = 2.58$, $p = .1$, $\eta^2_p = 0.19$, and no interaction effect, $F(4,44) = 0.57$, $p = .69$, $\eta^2_p = .05$.

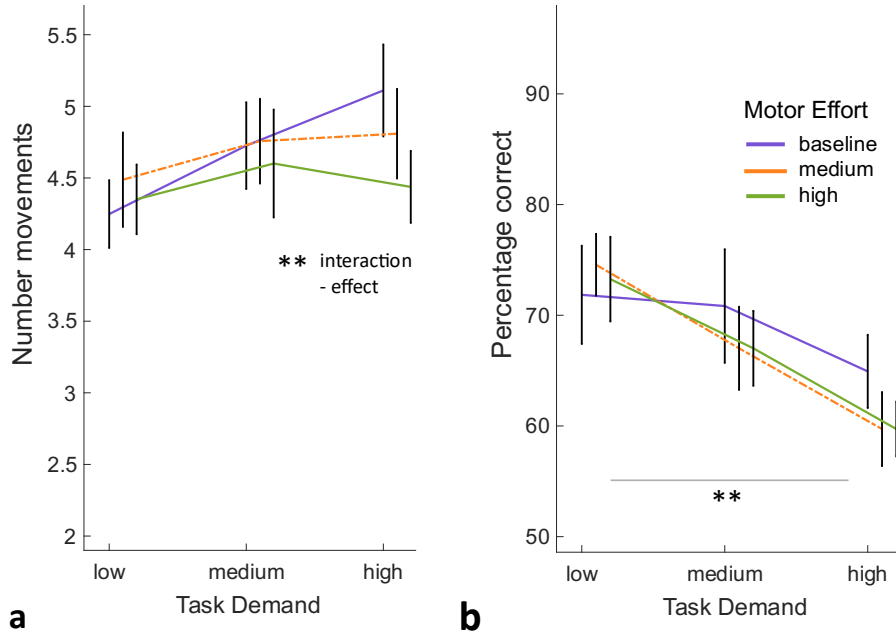


Fig. 2. a, Exploration duration (number of swiping movements) as a function of task demands separately for all motor effort conditions. b, Task performance (average percentage of correct responses) as a function of task demands separately for all motor effort conditions. Error bars represent the standard error of the mean.

4 Discussion

The current study provides evidence that humans adjust the duration of their haptic exploration as a function of both task demands and the motor efforts that are associated with the execution of the exploration. When being confronted with higher task demands, participants extended their exploration by executing more exploratory movements. This likely constitutes an adaptation mechanism serving perception/task performance—given that previous literature showed that extension of exploration generally leads to an increased sensitivity of the agent [9–12]. The effect though seems to strongly depend on the motor effort participants must exert during the execution of their exploration, as it disappears when the associated motor effort is high. While participants devoted the same number of movements to less demanding trials, they did not extend their exploration during the more demanding trials anymore.

Furthermore, higher task demands were associated with reduced accuracies, demonstrating successful manipulation of task demands. However, one could expect an interaction effect with motor effort here as well, with stronger effects of task demands when motor effort is increased, resulting from the lack of the observed adaptation behavior. This was not the case though, possibly due to other, e.g. attentional compensatory mechanisms.

With this study, we hope to provide a first cornerstone for a comprehensive understanding of how humans adapt their haptic exploration strategy with respect to the extension of the exploration. In light of our findings, we theorize that humans adjust the duration of their exploration according to the principles of an expectancy \times value framework (see e.g. [29]). Herein, the utility of the extension of an exploration would be derived from the expected task performance, which in turn consists of the agent's perceptual ability and the task demands at hand, combined with the value that is associated with a correct task performance (e.g. monetary reward, positive consequences). Thus, higher task demands would be compensated with extended explorations due to expected task performance differences. Additionally, aligning with motor control literature [22], motor costs would be discounted with the expected utility. The accumulated costs increased with increasing motor efforts, while the (intrinsic) reward stayed constant. Consequently, the expected utility of an exploration extension would be reduced due to the changed ratio of (expected) motor costs and reward, leading to earlier termination of exploration behavior.

Even though it seems plausible that the observed effect of the effort manipulation is a result of cost-benefit-weighting, there are more banal alternative explanations. One would be the mere exhaustion of the participant, i.e. a ceiling effect due to physical restrictions of their bodies. This might produce an absolute limit of exploration duration, only manifesting itself in higher task demand trials due to the necessary exploration durations being longer. More extensive assessments could rule this out, but while the progressing fatigue over time might have some moderating effect, it does not seem likely that it is the main driving force for the observed behavior. Participants did not report that they noticed immense exhaustion of their arm or changes in their behavior. One might still wonder why the motor effort manipulation affects the behavior when task demands are high but does not affect it when demands are low. A possible explanation could involve the expected utility of the exploration segments/swipes. As task demands increase, the exploration duration needed for a consistent task performance also increases. Hence, when exploring a very demanding stimulus pair, each swipe yields a lower repetition gain, i.e. benefit regarding expected task performance, than when exploring a less demanding pair. Thus, the expected utility of each swipe would be lower for high task demands than for low demands. As a consequence, with the reward (value) staying constant and the utility of each swipe being lower, the increased motor efforts (= increased accumulated costs) would carry higher weights for high demand trials than for low demand trials, thus reducing the expected utility of an exploration extension more. In other words: For high demand trials, one can renounce one or two swipes as a measure for cost reduction without affecting the task performance too drastically. This might possibly not be the case for the low demand swipes, as the impact of e.g. just one swipe less might be immense. Obtaining the individual perceptual performances of each participant as a function of instructed exploration duration would help elucidating on that matter.

Please note that the artificial manipulation of motor effort did not only have unspecific binary effects; it could have been possible that the manipulation is perceived as unnatural and disruptive, so that participants virtually cease to explore as soon as any additional effort is introduced. However, when motor effort was only increased by one

level (= medium effort), the participants' behavior only slightly deviated from the baseline level. That is, the impact of the effort-manipulation is likely not dichotomous; we can rather expect a gradual progression of the effect's magnitude, just as we would expect it for the real life. This underlines the feasibility of the experimental procedure. Further, one might speculate that sensory consequences of the counterforce in medium- and high motor effort conditions could have tampered with perceptual performance due to masking effects or conflicts with proper sensory input. However, as the average accuracy for low demand trials does not substantially differ between the baseline and high effort condition, this seems improbable. Finally, an evident peculiarity of the present study is the restricted exploration scheme. Investigating unrestricted explorations could offer valuable insights: One might expect less switching as a reaction to increased efforts and possibly more swipes as a consequence [4]. Still, the driving mechanisms would be the same, i.e. cost reduction and cost-benefit weighting; but could be assessed from a different viewpoint.

For future studies, a more thorough examination of the influence of task demands on the duration of haptic explorations might provide interesting insights. Data of the baseline effort condition in the current study suggests a linear relationship between exploration duration and the three implemented levels of task demands. However, it can be expected that exploration duration would at some demand level reach a saturation point, in line with the observed saturation point of task performance as a function of instructed exploration duration [10], and because trivially, humans would not explore infinitely long. It is likely as well that the relationship is not linear when task demands are closer to saturation: Task demands might become so high that people terminate earlier again, as the expected utility-gain from an extension could be perceived as insufficient. As every additional movement is associated with costs but would yield only extremely limited information gain due to the very high task demand, the marginal increase in expected task performance might not provide sufficient "incentive", resulting in premature termination of exploration. Additionally, it would be necessary to confirm the derived conclusions in a more naturalistic setting. In this context, one could also tackle the question whether the artificial motor effort manipulation introduces additional cognitive load; although participants did not report notable disturbances in the questionnaire, the perceived unnaturalness of the effort manipulation might yield subtle effects.

Ultimately, we plan to model the trade-off between motor effort and task performance and aim to be able to predict natural exploration duration by also taking motivational influences into account, as these were proven to be crucial in the motor control literature [21]. We expect this to provide valuable insights: Dissecting the prediction and valuation processes that take place during haptic explorations is worthwhile for both practical and theoretical reasons, as the derived conclusions can inform the development of more efficient and ergonomic human-computer interfaces, improve design choices for haptic experiences, and enhance our understanding of the intricacies of human perception and action.

Acknowledgments. We would like to thank Marai Söhngen, Kimberly Glas and Lars Hagenmeier for their help with data collection. This research was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – project number 222641018 – SFB/TRR 135, A5.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.

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