Identifying Haptic Exploratory Procedures by Analyzing Hand Dynamics and Contact Force

Jansen, S.E.M., Bergmann Tiest, W.M., Kappers, A.M.L.

IEEE Transactions on Haptics, 6(4), 464-472

Published version: http://dx.doi.org/10.1109/ToH.2013.22

Identifying Haptic Exploratory Procedures by Analyzing Hand Dynamics and Contact Force

Sander E.M. Jansen, Wouter M. Bergmann Tiest, and Astrid M. L. Kappers

Abstract— Haptic exploratory procedures (EPs) are prototypical hand movements that are linked to the acquisition of specific object properties. In studies of haptic perception, hand movements are often classified into these EPs. Here, we aim to investigate several EPs in a quantitative manner to understand how hand dynamics and contact forces differ between them. These dissimilarities are then used to construct an EP identification model capable of discriminating between EPs based on index finger position and contact force. The extent to which the instructed EPs were distinct, repeatable and similar across subjects was confirmed by showing that more that 95% of the analyzed trials were classified correctly. Finally, the method is employed to investigate haptic exploratory behavior during similarity judgments based on several object properties. It seems that discrimination based on material properties (hardness, roughness, and temperature) yields more consistent classification results compared to discrimination based on the acquisition of shape information.

Index Terms— haptic perception, touch, exploratory movements, material properties

1 Introduction

THE human hand is used for perception as well as manipulation of the world around us. By interpreting signals from pressure-sensitive, thermal, and kinesthetic sensors it is possible to retrieve information from the environment and act accordingly. At the same time, active movement of the hand and fingers enables dynamic exploration of different aspects of the environment.

Studies investigating this perception-action relationship in the visual modality have proposed a strong link between the type of eye-movements made by observers and the information they intend to perceive [1, 2]. Furthermore, gaze supports hand movement planning by marking key positions to which the fingertips or grasped object are subsequently directed [3].

With respect to active haptic exploration, Lederman and Klatzky proposed a construct called an Exploratory Procedure (EP). They defined this as a “stereotyped movement pattern having certain characteristics that are invariant and others that are highly typical” [4]. Furthermore, these EPs appear to be linked to specific object dimensions. They propose the following EP – object property relations where each EP is optimal for investigation of that property: *contour following* for local shape; *pressure* for compliance; *lateral motion* for roughness; *static contact for temperature*; *unsupported holding* for weight; and *enclosure* for global shape. Even in very young infants rudimentary versions of these EPs have been found [5].

By combining these EPs, observers can perceive a multitude of object properties, which enable object recognition. It has been shown that blindfolded observers are capable of identifying common 3D objects with near perfect accuracy within a 2-second interval [6].

In addition to the type of requested object property (e.g., estimation of roughness or compliance), its magnitude influences hand dynamics and forces. Smith and colleagues [7] conclude that during active exploration with the fingertip, tangential finger speed, normal contact force, and tangential shear force, are optimally adjusted depending on the surface friction. In addition, Tanaka et al. [8] observed a distinction in the applied normal force between exploration of rough and smooth surfaces. The latter yielded larger mean contact forces as well as greater variation within a trial. Furthermore, Kaim and Drewing [9] showed that people vary the movement parameters of an EP to optimize performance. More specifically, they observed increased speed and decreased force for soft stimuli compared to hard ones.

A thorough understanding of human haptic perception in general and EPs in particular may benefit domains such as medicine [10], [11], teleoperations [12], touchscreens for mobile devices [13], and data presentation [14]. Moreover, the development of sophisticated anthropomorphic robotic hands requires knowledge from human haptic perception. Interestingly, the reverse is also true; robotic platforms can be used to develop and test theories of haptic perception because of their ability to reproduce movement and forces in a

• *The authors are currently affiliated with the MOVE Research Institute, Faculty of Human Movement Sciences, VU University Amsterdam, the Netherlands. However, a large portion of the work was carried out at Physics of Man, Helmholtz Institute, Utrecht University, the Netherlands.*
Email: (s.e.m.jansen, w.m.bergmanntiest, a.m.l.kappers)@vu.nl

Manuscript received (insert date of submission if desired).

xxxx-xxxx/0x/$xx.00 © 200x IEEE

Digital Object Indentifier 10.1109/ToH.2013.22

precise and repetitive manner [15, 16].

Following this reasoning, Fishel and Loeb [17] propose a Bayesian exploration approach for texture discrimination by an artificial finger. Properties of different textures were identified by performing different human-like sliding movements (combinations of normal force and velocity). The pattern of these properties for a specific texture was then used to identify it among others.

Our general goal is to better understand human behavior during active haptic exploration. What do people do in order to extract relevant information from the external world by touch? And subsequently, why do we behave in such a way? Moreover, we would like to study this behavior quantitatively.

The aim of the present study is twofold. First, we will empirically analyze several EPs to determine how they differ from one another. The second aim is to investigate if these differences can be used to construct a simple EP-identification model that is capable of classifying EPs that are performed in isolation. This method should be able to correctly identify a given EP for different stimuli and different people. For example, the hand movements for the contour following EP might differ between participants and stimulus shapes. Nevertheless, certain characteristics of this behavior remain invariant, which can allow for correct classification. By employing optical motion tracking and contact force registration, we will investigate behavioral patterns that can be used to identify possible EPs.

The remainder of this paper is organized in three parts. First we will investigate how hand dynamics and contact force differ between several EPs. In order to select variables that can be used to discriminate between EPs, it is necessary to first investigate how they are affected as a function of the EP that is performed. This analysis is based on data of the first half of the participant group.

In the second part, we propose a method that is capable of identifying EPs performed in isolation (for different people and different objects) based on the results of the analysis in part I.

In the final part, applicability of the method is assessed during similarity judgment tasks of several object properties.

2 Part I: Analysis of Hand Dynamics and Forces

In this first part, we will investigate hand dynamics and forces during the execution of several EPs. The following EPs are investigated: *contour following* (CF), *pressure* (PR), *lateral motion* (LM), *static contact* (SC), and *enclosure* (EN). This task was always executed at the end of the session. The first two tasks of the session consisted of haptic discrimination tasks (which will be discussed in part III). This order of the tasks was chosen because it was not preferable that participants noticed the explicit link between an EP and its matched object property. Therefore, they were first given the discrimination tasks after which they conducted the instructed EP movements.

2.1 Methods

Participants

Eight participants (five male) took part in the experiment. Their mean age was 24 years (SD = 4). Seven of them were strongly right-handed, while one showed moderate right-handedness according to Coren's test [18]. All followed the same experimental procedure. Data from all participants was used for the model evaluation (discussed in section 3.3). However, only the data of the first four participants (three male) was used for the empirical analysis. This enabled classification of both 'old' and 'new' participants, which is required for testing generalizability of the method.

Experimental Materials

Stimuli - During each trial, participants were presented with a stimulus on which they had to perform an instructed EP. Each stimulus was attached to an MDF board (150 × 150 × 8 mm) that was placed on a digital weighing scale in front of the participant. Irrespective of the material and shape, all stimuli were produced to have a flat surface, raised approximately 15 mm from the MDF board. Moreover, four stimuli per EP where chosen such that they offered variation on the dimension assumed to be linked to that EP. For example, the stimuli presented during the LM trials, varied in roughness and CF stimuli varied in local shape. Table 1 describes the presented stimulus for each of the different trials and Figure 1 shows a top view photograph of each.

Table 1
Stimuli used during the different trials

	EP	Stimulus	
		Shape	Material
1	CF	square	hard PE foam
2	CF	circle	hard PE foam
3	CF	triangle	hard PE foam
4	CF	irregular	hard PE foam
5	PR	square	brass
6	PR	square	hard PE foam
7	PR	square	semi-hard PE foam
8	PR	square	soft PE foam
9	LM	square	coarse sandpaper
10	LM	square	semi-fine sandpaper
11	LM	square	fine sandpaper
12	LM	square	hard plastic
13	SC	square	brass
14	SC	square	hard plastic
15	SC	square	hard PE foam
16	SC	square	coarse sandpaper
17	EN	square	hard PE foam
18	EN	circle	hard PE foam
19	EN	triangle	hard PE foam
20	EN	irregular	hard PE foam

CF = contour following, PR = pressure, LM = lateral motion, SC = static contact, EN = enclosure.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication.

Fig 1. Stimuli used during the different trials. Each row shows the four stimuli used per EP. From top to bottom: CF, PR, LM, SC, and EN. See Table 1 for a description of each stimulus.

Apparatus - An NDI Optotrak Certus system was used to record 3D positional data of 6 infrared emitting diodes placed on the right hand and wrist. The position of these markers in a global coordinate system was recorded with a sample rate of 200 Hz. The marker locations are shown in Fig. 2f. In addition, a Mettler Toledo digital weighing scale (type SPI A6) was used to record the contact force applied to the stimulus surface. Force data were collected using LabVIEW 9.0 (update rate of 14 Hz).

Design and Procedures

Participants gave informed consent after which they were blindfolded and the optical markers were attached. Participants were instructed to perform the movement, as they felt best matched each of the following verbal descriptions:

"Contour following"(CF)
"Pressing" (PR)
"Rubbing" (LM)
"Static contact" (SC)
"Enclosing" (EN)

Every EP was tested with four different stimuli. This resulted in a total of 20 trials that were performed in random order. Prior to each trial, the right hand was positioned at a starting point to the right of the target stimulus. The experimenter verbally announced the EP that was to be performed. This was the cue for the participant to start the trial. Both the position of the markers and the applied force on the stimulus were recorded during the execution. At the end of each trial, the participant was instructed to move the hand back to the starting position. Fig. 2 shows video stills of the execution of different EPs.

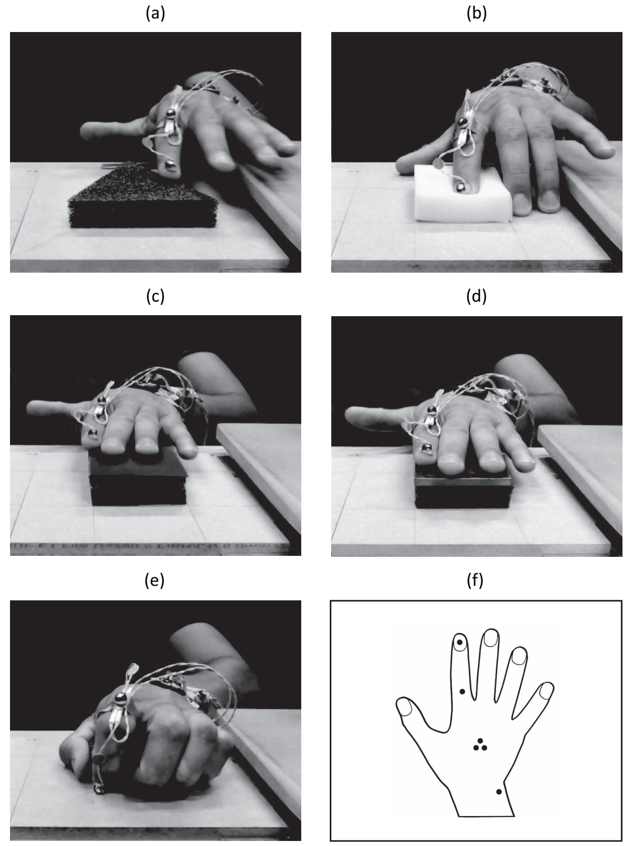

Fig 2. Video stills of a participant performing the different EPs: contour following (a), pressure (b), lateral motion (c), static contact (d), and enclosure (e). Panel f indicates the markers' locations.

Data Analysis

Using Matlab (version R2011b), raw marker positional data were processed as follows. First, missing data (due to temporary occlusion) were linearly interpolated. Second, all data were rotated such that the x and y-axes were aligned with the table and the z-axis pointed upward. Third, data were filtered by applying a low-pass second-order Butterworth filter with a cutoff frequency of 6 Hz.

Subsequently, for each trial, the positional and force data were synchronized. This was done by defining the starting moment in both data streams. For the positional data this moment was defined as the local minimum in the z-direction following the descent of the hand to the stimulus location. For the force data this was defined as the first moment at which the recorded force differed from zero. The end of a trial was determined by the local minimum in the z-direction directly preceding the repositioning to the starting location.

Following this general data processing, several measures were extracted for each trial. These were chosen based on their presumed ability to discriminate between EPs.

1) Mean **speed** (m/s) was calculated for the marker placed on the index finger nail. It is defined as the length of the traversed path in the *x-y* plane divided by the duration of the trial.
2) Maximum **force** (N) is defined as the largest force that was applied normal to the stimulus surface.
3) The size of the explored **area** (cm^2) is defined as the smallest 2-D convex hull that contains the path traversed by the index finger in the *x-y* plane over the duration of the trial.
4) Mean **distance** (cm) was calculated between the marker placed on the index finger nail and the center of the bounding box surrounding the stimulus.
5) Mean **pitch** rotation of the index finger was calculated as the mean angle (deg) made by the line connecting the markers placed on the index finger with the horizontal plane.

For each EP, the data of the four trials were averaged to construct a single data point for each EP. Next, for each of the measures, a separate one-way ANOVA was performed. Whenever the sphericity assumption was violated (as indicated by Mauchly's test), a Greenhouse-Geisser correction was applied. Pairwise comparisons were conducted using Bonferroni corrections. All statistical analyses were performed with STATISTICA 8.0 and significance levels for all analyses were set at 5%.

2.2 Results

Fig. 3 shows the magnitude of each variable as a function of EP. Table 2 represents the accompanying pairwise comparisons.

Mean speed of the index finger

Mean speed differed between EPs, $F(4, 12) = 15$; $p < 0.001$. Pairwise comparison revealed that both the contour following and lateral motion EPs yield higher mean speeds compared to the other EPs.

Maximum force applied to the stimulus

The maximum force applied to the stimulus surface differed between EPs, $F(4, 12) = 16$; $p < 0.001$. Pairwise comparisons revealed that the pressure EP yields a higher maximum force compared to the other EPs.

Size of the exploration area

The size of the exploration area differed between EPs, $F(1.2, 3.6) = 0.3$; $p < 0.01$. Pairwise comparison revealed that during execution of the contour following EP, the explored area was larger compared to the other EPs.

Mean distance from the center

Mean distance between the index fingernail and the center of the stimulus differed between EPs, $F(4, 12) = 31$; $p < 0.001$. Pairwise comparison revealed that both the contour following and enclosure EPs yield larger distances compared to the other EPs.

Mean pitch angle of the index finger

Mean pitch rotation differed between EPs, $F(4, 12) = 5.0$; $p = 0.013$. Pairwise comparison revealed that the enclosure EP yields a larger mean pitch angle compared to the static contact EP.

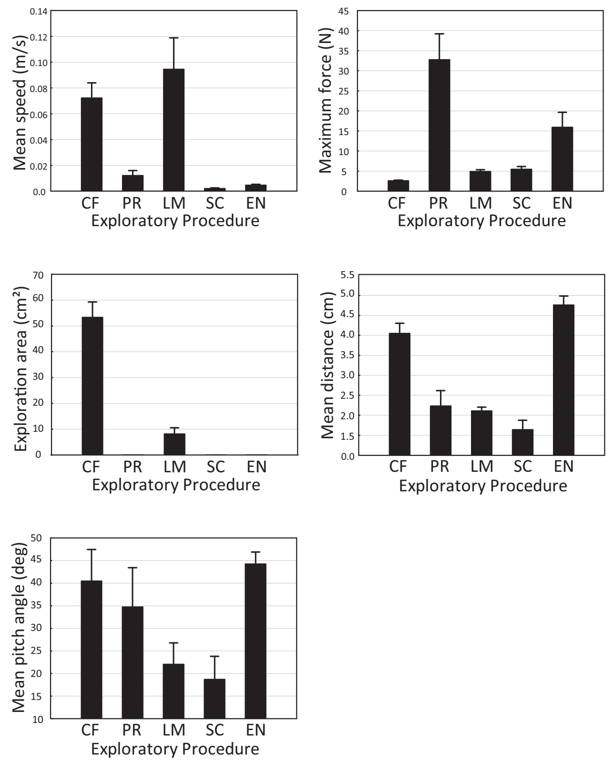

Fig 3. Variable magnitude as a function of EP: contour following (CF), pressure (PR), lateral motion (LM), static contact (SC), and enclosure (EN). Error bars represent standard error.

2.3 Discussion

In this first part, we investigated how hand dynamics and forces differ between the following EPs: *contour following* (CF), *pressure* (PR), *lateral motion* (LM), *static contact* (SC), and *enclosure* (EN). Based on their qualitative descriptions [4], we expected differences in hand dynamics and forces between these EPs. These will be discussed here individually.

First, it was expected that the mean speed of movement is higher during CF and LM compared to the other EPs. Indeed, the results support this hypothesis. Both CF and LM require movement of the hand (and subsequently, the index finger). Alternatively, during the execution of the other EPs (i.e., PR, SC, and EN), movement in the *x-y* plane was minimal.

Second, it was expected that during execution of PR, a large force would be applied. The results indicate that this was indeed the case. Also, a substantial force was registered during execution of EN. However, this did not differ significantly from the other EPs.

Table 2

p-values for pairwise comparisons for each variable (CF = contour following, PR = pressure, LM = lateral motion, SC = static contact, EN = enclosure)

Mean speed

	PR	LM	SC	EN
CF	*	n.s	*	*
PR		**	n.s	n.s
LM			**	**
SC				n.s

Maximum force

	PR	LM	SC	EN
CF	**	n.s	n.s	n.s
PR		**	**	*
LM			n.s	n.s
SC				n.s

Exploration area

	PR	LM	SC	EN
CF	**	**	**	**
PR		n.s	n.s	n.s
LM			n.s	n.s
SC				n.s

Mean distance

	PR	LM	SC	EN
CF	**	**	**	n.s
PR		n.s	n.s	**
LM			n.s	**
SC				**

Mean pitch

	PR	LM	SC	EN
CF	n.s	n.s	n.s	n.s
PR		n.s	n.s	n.s
LM			n.s	n.s
SC				*

* = $p < 0.05$; ** = $p < 0.01$; n.s = $p > 0.05$

Thirdly, the explored area was expected to be larger during CF than each of the other EPs because this required the index finger to move over the outer edge of the stimulus. As a result, the explored area approximated the size of the stimulus. The analysis confirmed this.

Next, it was expected that the mean distance between the index finger and the center of the stimulus was larger during CF and EN compared to the other EPs. This was confirmed by the analysis. During CF and EN the index finger is required to be positioned on top or over the edge of the object. For the other EPs, this is not a necessity.

Finally, the mean pitch angle of the index finger with the object surface was expected to be larger during EN than during the other EPs. The results indicate that indeed, EN yields the largest pitch angle. However, this was found to be significantly different only from SC.

The five EPs yield different combinations of hand dynamics and forces. Interestingly, the observed behavior differed somewhat from the original descriptions of the EPs. The most prominent example is LM. In the original description [4] this was characterized as follows: 'the fingers quickly rub back and forth across a small homogeneous area of the surface; interior surfaces are explored rather than edges'. However, we observed that there are many ways to 'rub' a surface. In addition to quickly moving back and forth, the following movements were displayed when instructed to rub the surface:

1) Moving the index finger in circles.
2) Moving in one direction while in contact with the surface and in the opposite during finger lift.
3) Rubbing slowly while applying a substantial force.

Observing these different types of lateral motion is in accordance with a recent study by Nagano and colleagues [19] who differentiate between "stroking" and "scrubbing" based on the force applied to the material (small vs. large force). However, all of these movements share invariant aspects of LM.

The challenge in constructing an EP identification model is to recognize all these behaviors as belonging to the same EP class despite of variance in execution. For the other EPs, participants also varied in their behavior, but this was less prominent than during LM.

Overall, the current analysis indicates that the five variables proposed here are very well suited for inclusion in a model that is capable of recognizing EPs based on index finger position and force data. In the next part of this paper, we will propose such a model.

3 Part II: Construction of an EP Identification Model

3.1 Behavioral profiles

The results obtained in part I will be used to construct an model that is capable of classifying unknown exploratory behavior into one of the EPs.

When combining the variable scores for hand dynamics and forces, it is possible to formulate behavioral profiles capable of discriminating between EPs. For instance, LM and EN can be differentiated as follows:

1) Mean speed – very high (LM) vs. very low (EN).
2) Maximum force – small (LM) vs. medium (EN).
3) Exploration area – small (LM) vs. very small (EN).
4) Distance from the center – medium (LM) vs. very large (EN).
5) Pitch angle – medium (LM) vs. very large (EN).

3.2 Model proposal

Normalized variable scores are the means for each EP (see Fig. 3) divided by the mean value for that variable. The model we propose simply compares the observed profile for a given trial to each of the prototypical EP profiles. Whichever yields the least deviation (as calculated by the sum of squares) is assumed to be the EP that was actually performed by the participant.

In order to calculate the deviation, each observed variable is quantified to a normalized score similar to the ones for the EP profiles. They are the original values (i.e., mean speed, max force, etc.) for a given trial divided by that person's mean value for that variable (see Table 3). Finally, for each single trial, a deviation score is calculated for each EP by summing the squared deviations of each observed variable score from the predicted score for that EP. Fig. 4 shows a graphical representation of this procedure. In the top left panel, data from a given trial is represented as a combination of normalized variable scores. The remaining panels show comparisons between this observed behavior and the prototypical profiles based on the data shown in Table 3. In this example, the observed behavior is classified as contour following.

Table 3

Variable scores for each of the following EPs: contour following (CF), pressure (PR), lateral motion (LM), static contact (SC), and enclosure (EN). Values are normalized to the mean for each variable.

	speed	force	area	distance	pitch
CF	1.95	0.21	4.30	1.37	1.26
PR	0.33	2.65	0.04	0.75	1.08
LM	2.54	0.40	0.66	0.71	0.69
SC	0.06	0.44	0.00	0.56	0.58
EN	0.13	1.29	0.00	1.61	1.38

3.3 Model evaluation

This section describes the evaluation of the proposed EP identification model. The typical EP profiles are based on data gathered from the first half of the participants (group A), but not the second (group B). Therefore, the evaluation of the predictive quality of the model will be tested for both groups separately.

Each participant performed all 20 trials (see Table 1). Index finger position and force data were collected as described in section 2.1. Table 4 shows confusion matrices indicating the response frequency for each combination of instructed and predicted EP.

The results indicate that the proposed EP identification model correctly identified > 95% of all trials, which is well above chance level (i.e., 20%). There were seven errors in total, six of which consisted of PR and SC trials erroneously classified as EN procedures. During three PR trials, it seems that participants applied a medium force near the edge of the stimulus instead of the expected large force near the center. The three SC trials classified as EN were the result of using the palm instead of the fingers to establish contact with the stimulus. The large distance to center and low mean speed caused the model to pick EN as the best classification in that case. In addition, there appears to be no difference between groups A and B with respect to the amount of errors (3 vs. 4).

Furthermore, for six out of seven errors, the model did identify the instructed EP as the second best. As a consequence, the success rate of the classification might be improved by adding a second stage in which the two best scoring (least deviating) EPs are compared in more detail. However, this is beyond the scope of this paper.

Overall, we find the predictability of the model to be sufficient for an investigation of the relation between object properties and EPs. In the next part, we will investigate hand dynamics and forces during an object property discrimination task. Application of the EP identification model could lead to a more thorough understanding of the haptic perception of object properties.

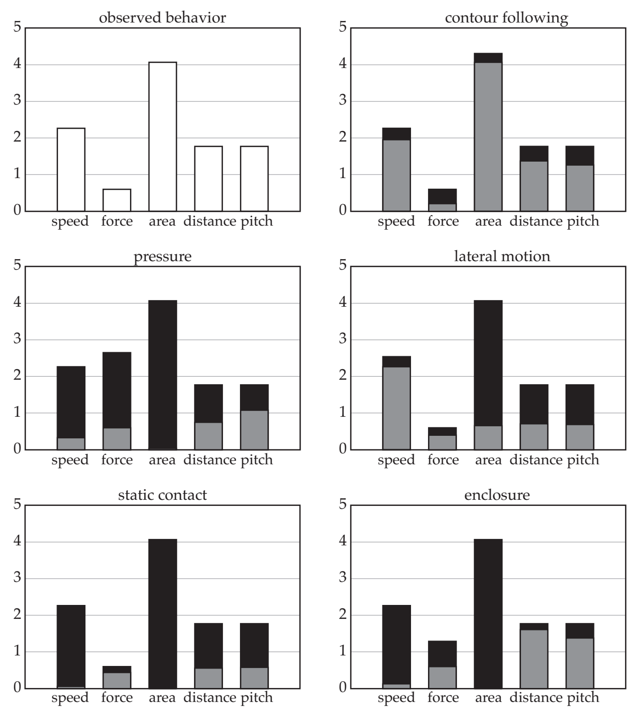

Fig 4. An example of the classification procedure. The top left panel shows the profile of the observed variable scores for a given trial. The other five graphs represent comparisons between that observed profile and the expected profile for each EP. Black areas indicate the deviations between both profiles. Whichever EP yields the least total deviation (by sum of squares) is assumed to be the one that was performed by the participant (i.e., contour following in this case).

4 PART III: HAPTIC DISCRIMINATION OF OBJECT PROPERTIES

In this last part, we aim to apply the classification method to a haptic discrimination task where stimuli are compared based on certain object dimensions. The goal here is to evaluate the use of the proposed EP identification model during a haptic discrimination task. This can be done by analyzing the consistency of the classification over different stimuli pairs and people.

Table 4
Confusion matrices for EP classification

Group A

instructed EP	predicted EP CF	PR	LM	SC	EN	total
CF	16	0	0	0	0	16
PR	0	14	0	0	2	16
LM	0	0	16	0	0	16
SC	0	0	0	16	0	16
EN	0	1	0	0	15	16
total	16	15	16	16	17	80

Group B

instructed EP	predicted EP CF	PR	LM	SC	EN	total
CF	16	0	0	0	0	16
PR	0	15	0	0	1	16
LM	0	0	16	0	0	16
SC	0	0	0	13	3	16
EN	0	0	0	0	16	16
total	16	15	16	13	20	80

Group A consists of four participants whose data was used for the analysis in part I. Group B consists of four new participants. Values within the diagonal outline indicate correct classification.

4.1 Methods

Participants

All eight participants took part in the experiment. However, due to a technical failure, data of one participant were only partly recorded. Therefore, this participant was excluded from the analysis.

Experimental setup and design

As mentioned earlier, this investigation was always executed before the instructed EP session (described in part I). The setup was very similar to that described in part I. However, instead of performing the EP instructed by the experimenter, participants were now required to make similarity judgments for stimulus pairs based on a given object dimension. The five possible dimensions were: *hardness*, *roughness*, *temperature*, *global shape*, and *local shape*. It should be noted here that for both the global and local shape conditions, the instruction was to discriminate the stimuli based on "shape".

Each trial started with the participant's right hand on the starting position. After the experimenter announced the object dimension that was to be examined, the hand moved to the first stimulus to explore it. Whenever the participants felt that they established a good percept of the required dimension, they moved their hand to the second stimulus to investigate if it was equal or different regarding that particular dimension. Participants were not allowed to move back and forth between stimuli. As soon as (in)equality was assessed, a verbal response was given stating either "equal" or "different" while the hand moved back to the starting position.

Each of the object dimensions was tested with four different stimulus pairs, resulting in 20 conditions. Table 5 shows the required dimension and both stimuli per trial. All trials were randomized within a session and each participant was tested during two sessions.

Data analysis

Data of the exploration of the first stimulus were analyzed, but not of the second. Initially, it was unknown to the participants what to compare the first stimulus to. Consequently, they were required to extract the dimension information as detailed as possible. The fast response made after brief exploration of the second stimulus constitutes a discrimination task where salient object properties can evoke a rapid response, even when this feature is encountered accidently. For example, perceiving a corner at initial finger placement immediately results in the conclusion that the stimulus is not circular in shape, even though that movement was not made to establish shape information. This makes the exploration of the second stimulus less suitable for our analysis. The end of the exploration of the first stimulus was defined as the moment of a local minimum in elevation of the marker on the index finger nail preceding its ascent and subsequent movement to the second stimulus. For each trial, analysis of index finger position and force data was performed as described in section 2.1 and EP classification was accomplished via the method explained in section 3.2.

Table 5
Stimulus pairs used during each trial

Trial		Stimulus #1 Shape	Stimulus #1 Material	Stimulus #2 Shape	Stimulus #2 Material
1	hardness	square	soft PE foam	square	medium PE foam
2	hardness	square	medium PE foam	square	hard PE foam
3	hardness	square	hard PE foam	square	soft PE foam
4	hardness	square	hard PE foam	square	hard PE foam
5	roughness	square	fine sandpaper	square	medium sandpaper
6	roughness	square	medium sandpaper	square	coarse sandpaper
7	roughness	square	coarse sandpaper	square	medium sandpaper
8	roughness	square	coarse sandpaper	square	fine sandpaper
9	temperature	square	brass	square	hard plastic
10	temperature	square	hard plastic	square	semi-hard plastic
11	temperature	square	semi-hard plastic	square	brass
12	temperature	square	hard plastic	square	hard plastic
13	shape	square	hard PE foam	circle	hard PE foam
14	shape	circle	hard PE foam	triangle	hard PE foam
15	shape	triangle	hard PE foam	square	hard PE foam
16	shape	square	hard PE foam	square	hard PE foam
17	shape	irregular 1	hard PE foam	irregular 2	hard PE foam
18	shape	irregular 2	hard PE foam	irregular 3	hard PE foam
19	shape	irregular 3	hard PE foam	irregular 1	hard PE foam
20	shape	irregular 1	hard PE foam	irregular 1	hard PE foam

4.2 Classification evaluation

Results of the classification procedure are presented in Table 6. For each dimension 56 classifications (7 participants × 8 trials) were performed.

It seems that the EP classification for the three material properties is quite consistent. In accordance with previous studies using observer classifications, we find the following dimension–EP relations: hardness–pressure, roughness–lateral motion, and temperature–static contact. For these, the model predicted the expected EP at least twice as often as the second most frequent EP. Furthermore, in 30 out of the 46 non-expected outcomes made for these three dimensions, the model selected the expected EP as second best. For the shape dimension, the results are much less in agreement. During local and global shape exploration, behavior is most often classified as either lateral motion or contour following. However, there is much less consistency in the classification.

It should be noted that it is not possible to evaluate the accuracy of classification, only the consistency. We cannot conclude if an unexpected classification of a certain trial is caused by a failure to recognize the performed EP or that the participant actually performed an EP different from what was expected.

Table 6
The frequency of a predicted EP (by the identification model) as a function of the explored object dimension

dimension	predicted EP					
	PR	LM	SC	EN	CF	total
hardness	50	1	0	5	0	56
roughness	0	36	17	3	0	56
temperature	4	0	36	16	0	56
global shape	0	25	5	12	14	56
local shape	0	18	7	6	25	56
total	54	80	65	42	39	280

GENERAL DISCUSSION

Previous studies have proposed certain stereotyped movement patterns called exploratory procedures (EPs) that appear to be linked to the haptic acquisition of knowledge concerning specific object dimensions [4]. Currently, classification of human exploratory behavior into these EPs is performed manually by human observers [20], [21]. This is a laborious and time-consuming task.

The main purpose of this study was to quantitatively investigate several EPs. To that end, an empirical analysis was performed to examine hand dynamics and contact force for each. The results of this analysis were then used to construct an EP identification model capable of recognizing EPs when they are performed in isolation. Finally, we tested the applicability of this method for investigation of human haptic exploratory behavior during a haptic discrimination task.

In part I hand dynamics and forces are compared between the following EPs: *contour following* (CF), *pressure* (PR), *lateral motion* (LM), *static contact* (SC), and *enclosure* (EN). The setup chosen for this study (i.e., raised surfaces) did not allow for the unsupported holding EP to be investigated. The results indicate that these five EPs differ from one another on the tested variables, which are: mean speed of the index finger, maximum force applied to the object surface, size of the explored surface area, mean distance from the object center, and mean pitch angle of the index finger.

In part II, the results obtained from the empirical analysis are used to construct an EP identification model. The combination of normalized variable scores results in a distinct behavioral profile for each EP that can be used to classify EPs that are performed in isolation. A simple comparison between unknown observed behavior and each profile determines which EP was likely performed. In order to evaluate the predictive quality of this classification method, it is applied to data extracted during EP execution of different participants with several stimuli. Over 95% of the 160 trials were classified correctly (the model predicted the EP that participants were instructed to perform).

Finally, in part III we tested the applicability of this method by investigating haptic exploratory behavior during an object discrimination experiment. Participants made similarity judgments for stimulus pairs based on one of the following object dimensions: hardness, roughness, temperature, and shape. Hand dynamics and contact force were gathered and used to classify the trials into EPs. The results indicate a fair consistency for the material properties: hardness, roughness, and temperature. These were associated with: pressure, lateral motion, and static contact, respectively. In contrast, for the shape discrimination trials the classification was much less consistent. This observation appears to be in line with the original classification evaluation by Lederman and Klatzky [4]. They report higher interobserver agreement during object matching based on material properties (80-90%) compared to shape matching (60-62%). It should be noted here that there is a difference between executing a movement when asked to perform that movement (e.g., pressing) as was the case in part I and II and the situation where such a movement is needed to gather information concerning a certain object property (e.g., hardness). The inconsistencies found in the classification of the discrimination task may reflect this discrepancy. However, it is also possible that participants simply employed a different EP from the expected one.

Concluding from the present results, it seems that the identification of EPs in isolation can be done using only a few variables extracted from index finger position and contact force. Furthermore, it seems that the EPs investigated here are distinct, repeatable and similar across participants. In contrast, evaluation of EP classification during a discrimination task is less straightforward. In order to assess the accuracy of classification, it is required to establish which EP (if any) was actually performed. Therefore, we can only comment on the consistency of certain EP-property classification pairs.

With this study we propose a novel quantitative approach to the challenge of classifying exploratory behavior. However, it is not yet a widely applicable solution. Several features could be implemented to improve its generalizability. During real life object handling, it does not seem plausible that typical EPs are executed in an isolated and serial fashion. Rather, it seems that different dimensions are (in part) assessed simultaneously. In addition, periods of information acquisition are often preceded by intervals of inactivity. Therefore, it would be preferable to divide a manual exploration episode into different phases. After initial contact between the hand and the object, the fingers are positioned such that the planned EP can be optimally performed. Whenever the required dimension is sufficiently estimated, repositioning occurs or the hand moves away. Ideally, we would like a system to recognize these different phases and extract relevant information only during the EP execution phases.

Furthermore, future work should investigate haptic exploratory behavior with 3D objects that can be picked up and explored bimanually. Consequently, this requires a different set of parameters that can be used to classify behavior independent of stimulus type and orientation.

In summary, we have proposed a quantitative classification approach capable of identifying haptic exploratory procedures (EPs) performed in isolation. This method is based on an empirical analysis of several hand position and force variables, a combination of which can be used to discriminate between EPs. When applied to data of isolated EP execution, prediction accuracy exceeds 95% (for different participants and different stimulus types).

In addition, we evaluated the applicability of the method to investigate exploratory behavior during haptic discrimination of several object properties. The results show that it often predicts the expected EP (based on previous research) during exploration of material properties. However, for shape perception the classification seems much less consistent. In order to be useful as an automatic classifier during haptic perceptual tasks, the method needs to be improved and subsequently validated by comparing it with manual classification.

ACKNOWLEDGEMENTS

This work has been supported by the European Commission with the Collaborative Project no. 248587, “THE Hand Embodied,” within the FP7-ICT-2009-4-2-1 program “Cognitive Systems and Robotics.”

REFERENCES

[1] K. Rayner, “Eye movements and attention in reading, scene perception, and visual search,” *Quarterly Journal of Experimental Psychology*, vol. 62, no. 8, pp. 1457–506, Aug. 2009.

[2] G. T. Buswell, *How people look at pictures: A study of the psychology of perception in art*. Chicago, USA: the university of Chicago press. 1935

[3] R. S. Johansson, G. Westling, A. Bäckström, J. R. Flanagan,”Eye-Hand Coordination in Object Manipulation,” *The Journal of Neuroscience,* vol. 21,no. 17, pp. 6917-32, 2001.

[4] S. J. Lederman and R. L. Klatzky, “Hand movements: a window into haptic object recognition,” *Cognitive Psychology*, vol. 19, no. 3, pp. 342–368, 1987.

[5] E. Bushnell and J. Boudreau, “Motor development and the mind: The potential role of motor abilities as a determinant of aspects of perceptual development,” *Child Development*, vol. 64, no. 4, pp. 1005–1021, 1993.

[6] R. L. Klatzky, S. J. Lederman, and V. Metzger, “Identifying objects by touch,” *Perception & Psychophysics*, vol. 37, no. 4, pp. 299–302, 1985.

[7] A. M. Smith, G. Gosselin, and B. Houde, “Deployment of fingertip forces in tactile exploration,” *Experimental Brain Research*, vol. 147, no. 2, pp. 209–18, 2002.

[8] Y. Tanaka, W. M. Bergmann Tiest, A. M. L. Kappers, and A. Sano, “Contact force during active roughness perception,” in *Haptics: Perception, Devices, Mobility, and communication; Lecture Notes in Computer Science*, vol. 7283, pp. 163–168, 2012.

[9] L. R. Kaim and K. Drewing, “Finger force of exploratory movements is adapted to the compliance of deformable objects,” *World Haptics 2009 - Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 565–569, 2009.

[10] I. Nisky, A. Pressman, C. M. Pugh, F. A. Mussa-Ivaldi, and A. Karniel, “Perception and action in teleoperated needle insertion,” *IEEE Transactions on Haptics*, vol. 4, no. 3, pp. 155–166, 2011.

[11] T. R. Coles, N. W. John, D. A. Gould, and D. G. Caldwell, “Integrating Haptics with Augmented Reality in a Femoral Palpation and Needle Insertion Training Simulation,” *IEEE Transactions on Haptics*, vol. 4, no. 3, pp. 199–209, 2011.

[12] P. Kammermeier, A. Kron, J. Hoogen, and G. Schmidt, “Display of Holistic Haptic Sensations by Combined Tactile and Kinesthetic Feedback,” *Presence: Teleoperators and Virtual Environments*, vol. 13, no. 1, pp. 1–15, 2004.

[13] E. Hoggan, S. A. Brewster, and J. Johnston, “Investigating the effectiveness of tactile feedback for mobile touchscreens,” in *Proceeding of the twenty-sixth annual CHI conference on Human factors in computing systems*, pp. 1573–1582, 2008.

[14] S. Paneels and J. C. Roberts, “Review of Designs for Haptic Data Visualization,” *IEEE Transactions on Haptics*, vol. 3, no. 2, pp. 119–137, 2010.

[15] G. E. Loeb, G. A. Tsianos, J. A. Fishel, N. Wettels, and S. Schaal, “Understanding haptics by evolving mechatronic systems,” in *Progress in brain research*, vol. 192, A. M. Green, C. E. Chapman, J. F. Kalaska, and F. Lepore, Eds., pp. 129–144, 2011.

[16] L. Pape, C. M. Oddo, M. Controzzi, C. Cipriani, A. Förster, M. C. Carrozza, and J. Schmidhuber, “Learning tactile skills through curious exploration,” *Frontiers in Neurorobotics*, vol. 6, pp. 1–16, Jul. 2012.

[17] J. A. Fishel and G. E. Loeb, “Bayesian Exploration for Intelligent Identification of Textures,” *Frontiers in Neurorobotics*, vol. 6, pp. 1–20, Jun. 2012.

[18] S. Coren, “Measurement of Handedness via Self-Report: The Relationship between Brief and Extended Inventories,” Perceptual and Motor Skills, vol. 76, no. 3, pp. 1035-1042, 1993.

[19] H. Nagano, S. Okamoto, and Y. Yamada, “Haptic Invitation of Textures: An Estimation of Human Touch Motions,” in *Haptics:*

Perception, Devices, Mobility, and communication; Lecture Notes in Computer Science, 2012, pp. 338–348.

[20] A. Withagen, A. M. L. Kappers, M. P. J. Vervloed, H. Knoors, and L. Verhoeven, "Haptic object matching by blind and sighted adults and children," *Acta Psychologica*, vol. 139, no. 2, pp. 261–271, 2012.

[21] A. Theurel, S. Frileux, Y. Hatwell, and E. Gentaz, "The haptic recognition of geometrical shapes in congenitally blind and blindfolded adolescents: is there a haptic prototype effect?" *PloS One*, vol. 7, no. 6, p. e40251, 2012.

Sander E.M. Jansen received the MSc degree in cognitive psychology from Utrecht University, The Netherlands in 2006. From 2007 until 2011 he worked at the Netherlands Organization for Applied Scientific Research (TNO) and the Department of Information and Computing Sciences of Utrecht University, from which he received the PhD degree in January 2012. He currently works as a postdoctoral researcher at the Faculty of Human Movement Sciences of the VU University Amsterdam. His research interests include haptic exploration and human obstacle avoidance behavior.

Wouter M. Bergmann Tiest received the MSc degree in experimental physics from Utrecht University, The Netherlands in 1999. Until 2004, he was employed by the Netherlands Institute for Space Research, while getting the PhD degree from Utrecht University. After working as a postdoc at the department of Physics and Astronomy of Utrecht University, in the Human Perception group of the Helmholtz Institute, he is currently a researcher at the Faculty of Human Movement Sciences of the VU University Amsterdam. His research interests include haptic perception of volume, mass, force, velocity, and material properties. He is an associate editor of IEEE Transactions on Haptics.

Astrid M.L. Kappers studied experimental physics at Utrecht University, the Netherlands. She received the PhD degree from Eindhoven University of Technology. From 1989 till Sept. 2012, she has been with the Department of Physics and Astronomy, Utrecht University. From 2008-2012 she was head of the Human Perception group of the Helmholtz Institute. In Sept. 2012 she moved with her whole group to the MOVE Research Institute, Faculty of Human Movement Sciences, VU University Amsterdam, the Netherlands. She was promoted to full professor in 2005. Her research interests include haptic and visual perception. In 2003, she won the prestigious VICI grant. She is/was member of the editorial boards of Acta Psychologica (2006-present) and Current Psychology Letters (2000-2011) and associate editor of the IEEE Transactions on Haptics (2007-2011).