Curvature affects haptic length perception

Abram F.J. Sanders *, Astrid M.L. Kappers

Human Perception, The Physics of Man, Helmholtz Institute, Utrecht University, P.O. Box 80000, 3508 TA Utrecht, The Netherlands

A R T I C L E   I N F O

A B S T R A C T

One possible way of haptically perceiving length is to trace a path with one's index finger and estimate the distance traversed. Here, we present an experiment in which observers judge the lengths of paths across cylindrically curved surfaces. We found that convex and concave surfaces had qualitatively different effects: convex lengths were overestimated, whereas concave lengths were underestimated. In addition, we observed that the index finger moved more slowly across the convex surface than across the concave one. As a result, movement times for convex lengths were longer. The considerable correlation between movement times and length estimates suggests that observers take the duration of movement as their primary measure of perceived length, but disregard movement speeds. Several mechanisms that could underlie observers' failure to account for speed differences are considered.

1. Introduction

When estimating distance or size by touch, observers apply a range of different exploration strategies. For example, one could estimate the size of an object by picking it up between thumb and index finger or between both hands and use kinaesthetic information about the postures of fingers and arms. Alternatively, small objects can be impressed on the skin of the fingertip to extract size information from cutaneous stimulation. On a different scale, proprioceptive information resulting from the act of walking can be used to infer the distance traveled. In this paper, we will focus on a different, very common strategy for haptic length perception: observers moving their finger or hand along an edge or across a surface to estimate the distance traversed.

Until now, researchers have only investigated linear pathways or curved pathways that were entirely contained in the horizontal plane (see below). No research has so far addressed the general case of length perception on arbitrary surfaces in 3D. This is an interesting research topic from the perspective of haptic shape perception, since the shape of a three-dimensional object is essentially defined by a surface bounding a certain portion of space, and since movement of the index finger or hand is a stereotyped pattern of action associated with assessment of that object's shape (Klatzky & Lederman, 2003).

Many geometrical descriptors of shape exist, curvature being one of the more advantageous ones from a psychophysical point of view, because it is independent of the position and orientation of the object. In mathematical terms, any smooth surface can be locally approximated by doubly curved surfaces, being either egg-like or saddle-like (e.g., Hilbert & Cohn-Vossen, 1932). Thus, any shape can be construed as a collection of such elementary surface patches. In this research, we investigated length perception on cylindrically curved surfaces. Participants moved their index finger across such a surface and estimated the distance traversed.

When using limb movement to perceive length, observers' length estimates are closely tied to the kinematic characteristics of the tracing movements. For example, it has been shown for both active and passive movements of the hand that observers judge linear extents traced at higher speeds to be shorter than the same extents traced at lower speeds (Hollins & Goble, 1988; Lederman, Klatzky, Collins, & Wardell, 1987; Von Skramlik, 1933; Wapner, Weinberg, Glick, & Rand, 1967). Movement speeds could differ by as much as a factor of one hundred (Hollins & Goble, 1988). However, it is not simply the duration of movement that determines perceived length. For a given duration, considerably longer pathways were still judged longer than the shorter ones. Similarly, when observers actively explore a curved pathway (a raised-line drawing for example) and estimate the straight-line distance between starting point and end point, they systematically overestimate it. These overestimations vary with the length of the detour taken as well as with the straight-line distance between the end

* Corresponding author. Tel.: +31 30 253 2831; fax: +31 30 252 2664.
E-mail address: a.f.j.sanders@uu.nl (A.F.J. Sanders).

points (Faineteau, Gentaz, & Viviani, 2003; Lederman, Klatzky, & Barber, 1985).

A related illusion that is important to our research is the so-called radial-tangential effect (RT effect) for whole-arm movements in the horizontal plane: linear extents oriented radially from the trunk are overestimated relative to tangentially oriented extents (for an overview of the literature on the RT effect, see McFarland & Soechting, 2007). In addition to this, researchers have observed that radial movements are executed slightly more slowly than tangential movements, and thus take more time (Armstrong & Marks, 1999; Wong, 1977).

According to one hypothesis that has been put forward to account for speed differences, these stem from the inertial anisotropy of arm movements (Wong, 1977). Moments of inertia are usually greater for radial arm movements, in which case they require more energy than movements in the tangential direction. Perhaps observers do not account for differences in moments of inertia when executing arm movements (cf. Gordon, Ghilardi, Cooper, & Ghez, 1994), causing them to move faster in the tangential direction. The basis for the RT effect would then be as follows (Marchetti & Lederman, 1983): to use movement time as an estimate of distance traversed, observers try to move at constant speeds, but they do not succeed; the small speed differences that arise are "undetected", p. 46 by the observer which causes overestimations of radial extents.

Marchetti and Lederman (1983) tested the inertial anisotropy hypothesis by attaching small weights to the moving hand, thus altering the moments of inertia, and investigating how this affects length estimates. They predicted that the effect of the weights would be that observers move their hands more slowly and that the corresponding increase in movement time would then cause observers to overestimate the length of the movement with weights compared to the length of the movement without weights. It is, of course, debatable whether one could prove that observers do not compensate for inertial anisotropies of arm movements by showing that they do not compensate for differences in external loads. Unfortunately, the results of the experiment by Marchetti and Lederman (1983) were inconclusive, but more importantly, the actual effect on movement speeds was not measured. Therefore, even clear results would have been hard to interpret concerning the origin of the illusion.

If undetected speed differences are the basis for the RT effect, then one might expect the illusion to disappear when speed profiles are made equal along both orientations. McFarland and Soechting (2007) tested this in a length discrimination experiment by having observers hold the handle of a robot arm and manipulating their arm movements. In the active conditions, force fields were generated such that the observer could actively explore a virtual contour. In the passive conditions, the observer's hand was guided along the contour by the robot arm, following a sinusoidal speed profile. Surprisingly, when the observer's hand was being moved with equal maximum speeds in the radial and tangential directions such that movement times were proportional to distances in the same way for both orientations, the RT effect persisted and replicated the illusion in the active control condition. Likewise, when movement times were made constant for all lengths so that the observer would have to rely entirely on speed and acceleration cues for discriminating lengths, the RT effect did not differ from the control condition. In a third passive condition, maximum speeds for the tangential orientation were 35% lower than for the radial orientation, leading to a corresponding increase in the movement times for the former direction. Although this was not reported, it seems reasonable to assume that observers noticed the substantial speed difference, but again the RT effect persisted. Thus, radial lengths were overestimated, whereas movement durations were longer

for the tangential direction. Finally, McFarland and Soechting (2007) tested an additional active condition in which an extra resistive force opposing tangential movements was produced. The added resistance made movement times longer in the tangential direction than in the radial orientation, whereas the opposite was the case in the control condition. Once more, however, the RT effect was present in this condition and did not differ from the control condition.

In particular the results for the passive condition that tested equal speed profiles argue against an explanation for the RT effect in terms of undetected speed differences, because in that case one would expect the RT effect to disappear. In our opinion, the experiments conducted by McFarland and Soechting (2007) suggest that an alternative and more likely explanation for the RT illusion is in terms of misperceived speeds or, possibly, misperceived durations. In other words, there is a systematic bias in perceiving speeds or durations between the radial and the tangential orientation, although the cause of this systematic misperception still remains unclear. This point will be further elaborated on in Discussion.

In this paper, we present a new experiment in which participants make arm movements to estimate distance traversed. Instead of being asked to judge linear extents they are now asked to judge lengths of paths across cylindrically curved surfaces. We set out to investigate whether observers make systematic errors in perceiving the length of cylindrically curved pathways. Because previous research had shown that length estimates are closely linked to the kinematic characteristics of arm movements, we decided to record movement profiles of the index finger while it traced the pathways.

Observers use the same exploration strategy in our experiment as in the RT effect. It is therefore reasonable to assume that the same mechanisms for length estimation underlie both experimental tasks. Thus, possible systematic misperceptions of curved lengths are expected to have causes similar to the causes of the misperceptions of linear extents in the RT effect. Questions concerning the basis of possible curvature effects therefore have theoretical implications that generalize to the RT effect, and vice versa. Consequently, the experiments reported in this paper are also of importance for unraveling the RT effect, since the basis for this effect is still poorly understood. In Discussion, we return to the question of the mechanisms that underlie misperceptions of traced lengths.

We tested for effects of both the magnitude and the sign of curvature, using circular pathways that had a frontoparallel orientation. Thus, we investigated perception of both convex and concave lengths of different radii. More in particular, in six discrimination experiments, observers compared convex with flat lengths, flat with concave lengths, and convex with concave lengths at two radii. We had no a priori expectations about the existence of curvature biases. However, if curvature biases do indeed exist, we expect their magnitude to increase with curvature: the larger the curvature of the cylindrical surface, the larger the possible curvature biases.

2. Method

2.1. Participants

Six right-handed participants in their 20s took part in this experiment (five males and one female). They were naïve as to the aims and designs of the experiment. Participants were paid for their efforts.

2.2. Apparatus

The setup consisted essentially of (a) a set of steel plates that were either flat or had been milled into cylindrically curved sur-

faces of fixed radius, (b) a framework in which the plates needed in a particular condition could be easily mounted, and (c) a set of flexible magnetic strips of varying lengths. Fig. 1 shows the setup together with its relevant dimensions. All the three possible combinations of the convex and the flat plates, the concave and the flat plates and the convex and the concave plates (Fig. 1a–c, respectively) were available at radii of 10 and 20 cm. Note that throughout this paper the terms convex and concave are always defined with respect to the finger touching the surface: in Fig. 1, all surfaces are being touched from above, the palm of the hand facing downwards. A simple rail system by which the plates could easily slide over each other allowed for efficient and rapid presentation of the strips. The framework was fixed onto a wooden board (not shown). The participant assumed a fixed position relative to the setup: the setup's midline (bold dashed line) lay in the sagittal plane passing through the right shoulder, as well as in the horizontal plane about 10 cm above the participant's navel. The spatial arrangement of the plates (Fig. 1d) was such that the midpoints of all the strips were at approximately the same location in space. The purpose of this particular arrangement was to make the posture of the participant's arm as similar as possible across the different surfaces. Magnetic strips had a thickness of 0.6 mm and were cut from a roll of commercially available magnetic foil. The strips lay entirely in the participant's frontoparallel plane. Their midpoints were either on the setup's midline or positioned 1.5 cm to the left or to the right of it, as indicated by numbers 1, 2, and 3 in Fig. 1d. The reason for this will be given below. The blindfolded participants were seated comfortably behind the setup. They moved their finger across the strip's edge that was furthest away. The distance between this edge and the frontal edge of the steel plate was 17 cm, which is roughly the distance between the tip of the outstretched finger and the wrist. The magnetic strips' corners were readily felt by the fingertip to indicate the edge's end

points. Otherwise participants could freely move their arm and, more particularly, they did not rest their elbow on any support while moving the index finger along the strip. Thus, participants' arm movements were entirely determined by the shape of the surfaces used.

2.3. Procedure

2.3.1. Measuring psychometric functions

To determine the strip lengths that are perceived as equal, we measured psychometric functions according to the 2AFC method (constant stimuli). The experimental procedure is outlined in Fig. 1a for the convex-flat condition. Participants traced the strips with the tip of the index finger of their preferred hand. A trial proceeded as follows. Participants always started at the strip's left end point. After a signal from the experimenter, they traced the first strip four times, going back and forth along the strip's edge twice. They lifted their hands and the experimenter quickly put the second strip in place. The participants then positioned their index finger at the second strip's left end point and, after a signal from the experimenter, started feeling the second strip. This strip was traced for a maximum of four sweeps. The participant then decided which of the two strips felt longer. Averaged over all observers and all conditions, 6.5% of the strips were traced less than four times. The overall average number of sweeps per strip was 3.9. The time interval between the moment at which the hand was lifted from the first strip and at which it started to move along the second one was estimated to be around two seconds. The strips' positions were varied by small amounts by randomly assigning their midpoints to three possible locations (Fig. 1d). If the midpoints of the strips had always been positioned at exactly the same position in space, participants could have developed a strategy for performing the task based on a comparison of the relative locations in
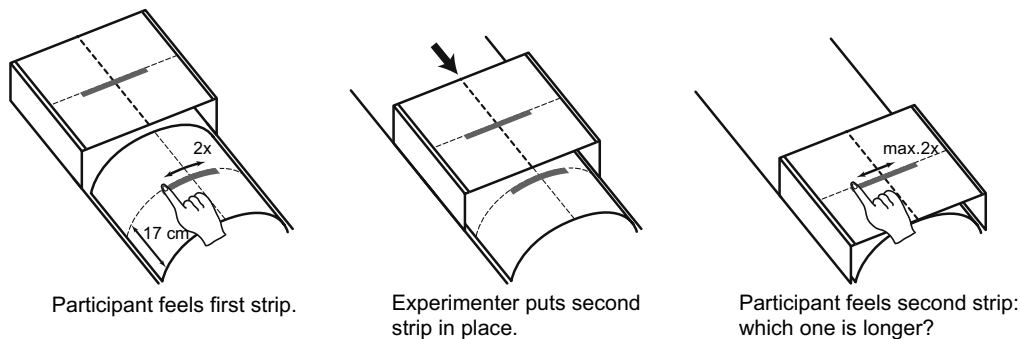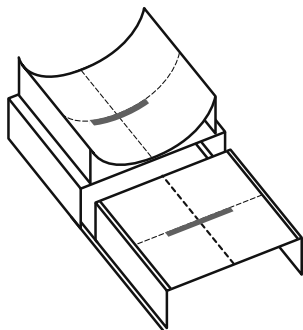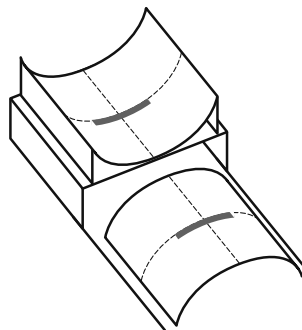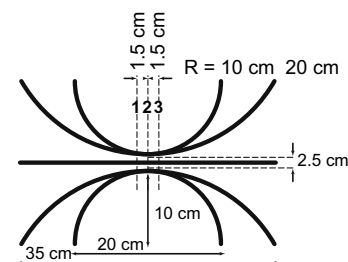

Fig. 1. Experimental setup. The strip depicted has reference length (18 cm). All the three possible combinations of convex (Cx), concave (Cv), and flat (F) surfaces are shown (Panel a, b, and c, respectively). Not shown: the setup is placed on a table, behind which the observer is seated. Convex and concave are defined with respect to the finger touching the surface. Panel a illustrates the experimental procedure. Panel d shows the relative locations in space of all the surfaces used.

space of either the left or the right end points. However, we wanted participants to make true distance estimates. We chose a distance of 1.5 cm between locations, because we had observed in pilot experiments that this was generally just enough for participants to notice whether the strips were positioned symmetrically on the curved surfaces. We also informed the participants about this procedure. Thus, the participants were fully aware of the fact that information about the locations of the left or the right end points alone was not sufficient to perform this task.

The length difference between the strips on the two surfaces used in a particular condition was taken as the independent variable. It was defined as convex-flat, concave-flat, or convex-concave. The reference strip was 18 cm and test lengths available were 14, 16, 17, 18, 19, 20, and 22 cm. We had observed in pilot experiments that this range of test lengths was broad enough to sample the entire psychometric function from its lower tail to its upper tail and produce reliable results. A length difference convex-flat of, for example, +4 cm corresponded to the following four possible combinations: Cx-22, F-18; F-18, Cx-22; Cx-18, F-14; or F-14, Cx-18. Thus, the two surfaces were presented in both the time orders: this was to avoid response biases. Furthermore, the reference strip was presented on both surfaces: this was to prevent learning effects, for otherwise the participants might have associated the reference length with one type of surface and might have used information from previous trials in making their judgment. For each of the seven length differences, the four possible strip combinations were repeated three times, amounting to a total of 84 2AFC trials per psychometric curve. All trials were randomized. A psychometric curve was measured in a single session, which lasted approximately between 1.5 h and 2 h. If needed, participants could take a small break halfway through the experiment. Every session started with a few practice trials (between 5 and 10). In addition, participants received a small training session of about 0.5 h prior to the experiment, in which they were instructed about the experimental procedure and did practice trials as well. Before the participants were seated and blindfolded, the setup was covered with a piece of cloth to prevent them from getting any visual impressions of the magnitude of the surfaces' curvatures.

2.3.2. Recording movement profiles

Movement profiles of the index finger were recorded by an Optotrak Certus system (Northern Digital Inc., Canada). One position marker (infrared LED) was stuck to the dorsal surface of the distal phalanx of the moving index finger. In addition, position markers were fixed to the steel plates such that we could retrieve coordinates of the magnetic strip's edge that was felt by the participant: three sensors for every curved surface, two for the flat surface. Three-dimensional spatial coordinates of the position markers were read out at a frequency of 100 Hz. Since the location of the position marker on the index finger did not correspond to the skin area touching the strip's edge, we inserted small breaks at one-third and two-thirds of a psychometric session, in which we asked the participants to place their index finger on the strips' end points and we gauged the finger marker's coordinates. In a single psychometric session, both end points for each of the seven test strips (midpoint location 2) and each type of surface were measured twice. By projecting the finger marker on the space curve passing through the strip's edge, we condensed three-dimensional coordinates into a single spatial parameter specifying the position of the index finger along the strip relative to the strip's midpoint.
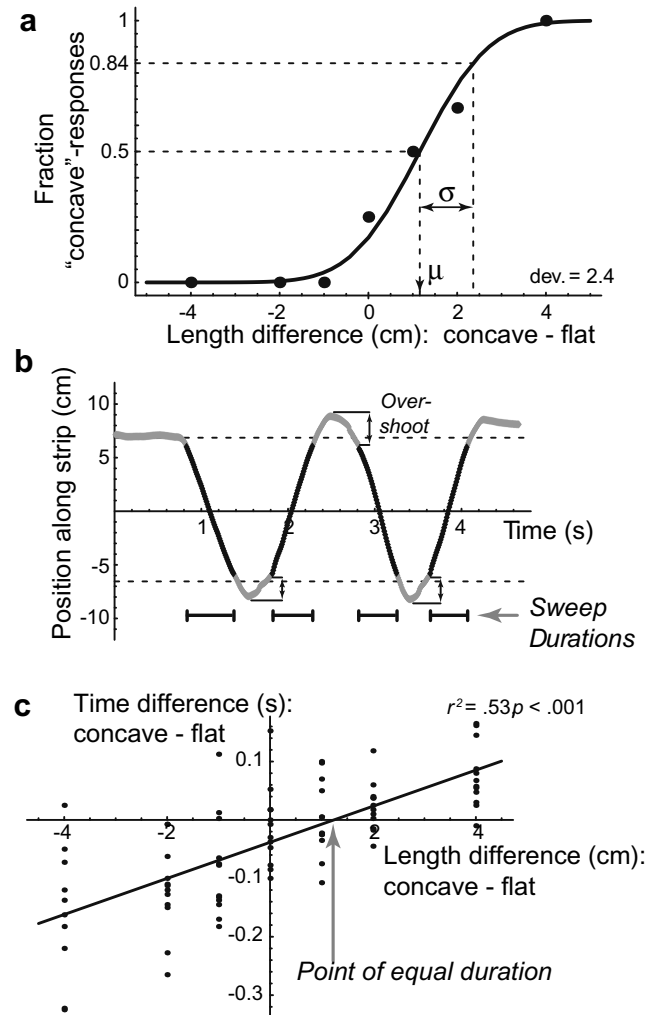
2.4. Data analysis

2.4.1. Points of subjective equality

We used cumulative Gaussian distributions as psychometric functions:

$$PF(x) = \frac{1}{2} + \frac{1}{2} \mathrm{erf}\left(\frac{x - \mu}{\sqrt{2}\sigma}\right) \tag{1}$$

where erf is the error function. The shape of this psychometric function is determined by two parameters: μ, which represents the location of the curve, and σ, which indicates its shallowness (Fig. 2a). They are interpreted as follows: μ is the point at which the response score is 50% and it is assumed to represent the observer's point of subjective equality (PSE), and σ is the difference between the 50% point and the 84% point and it is taken as a measure of the discrimination threshold. Psychometric curves were fitted to the data by

Fig. 2. Data analysis. Panel a shows a typical psychometric curve obtained in this study. Parameter μ represents the point of subjective equality. The deviance for this particular curve was 2.4. The average threshold (σ) was 1.68 cm or 9% of reference length ($SD = 0.48$ cm). Panel b shows the movement profile of the finger marker relative to the strip's midpoint for a concave strip of 14 cm. Dashed lines indicate the marker's positions corresponding to the strip's end points as recorded in the calibration measurement. One can see clearly that for the right end point the spatial coordinate of the finger marker (lower dashed line) slightly deviated from the end point's coordinate (-7 cm). We extracted the times needed to traverse the inner 90% of the range between the dashed lines (black parts of the movement profile). Movement times were taken to be the mean of those sweep durations (horizontal line segments). Furthermore, note that observers generally overshot their movements along the strip (vertical arrows). Panel c shows the relation between length differences and time differences for one of the observers in condition CvF10. Time differences were defined in the same way as length differences (convex-flat, concave-flat, convex-concave). They were computed by subtracting the mean sweep durations as derived from the movement profiles. The x-intercept of the regression line signifies the pair of strips that were traced in equal times. (All graphs are from a representative data set taken from condition CvF10, observer 6.)

maximizing a likelihood function, assuming that responses were generated by Bernoulli processes. Goodness-of-fit was assessed by computing log-likelihood ratios, or deviances, and comparing these against bootstrap-simulated distributions (parametric bootstrap: $N = 10{,}000$). If the experimentally obtained deviance fell between the 2.5th and the 97.5th percentile of the deviance distribution, the fit was accepted. Since this was the case for all psychometric fits, from now on we will refer to parameter μ as the Point of Subjective Equality. The same bootstrap simulations were also used to estimate the variability in the PSE. Bootstrap errors are the intervals between the 16th and the 84th percentile for the respective distributions and they were taken as the standard error for the PSE. For computational details we refer the reader to Wichmann and Hill (2001a, 2001b).

2.4.2. Points of equal duration

First, we extracted those portions from the movement profiles (Fig. 2b) where the finger was actually sweeping along the strip's edge (black parts). We did this by taking the inner 90% of the range between the two marker positions corresponding to the strip's end points as recorded in the calibration measurements (dashed lines). The reason for excluding 5% on either side of this range was twofold: first, due to trial-to-trial variability in finger posture a sweep reversal could occasionally fall just within the range defined by the dashed lines, and second, the first part of each movement profile consisted of the index finger resting on the strip's end point awaiting the start of the trial, as can be seen in Fig. 2b (the upper dashed line coincides with position marker recordings). A percentage of 90% was found to be about the maximum percentage that produced reliable sweep extractions. Mean sweep durations were used to calculate time differences between the two strips forming a psychometric trial. Time differences were defined in the same way as length differences (convex-flat, concave-flat, convex-concave). Next, we did a linear regression on length differences and movement time differences for every psychometric curve (Fig. 2c). If the length difference is a significant predictor for the difference in sweep duration, then the x-intercept of the regression line indicates the length difference between the two strips for which the times needed to trace each of them were equal. Since all regressions were highly significant ($ps < .001$), the x-intercepts will hereafter be called points of equal duration (PED). Error propagation was used to calculate standard errors in PEDs from errors in regression parameters.

We mention that we also did a full analysis by first doing a linear regression on position and time for each sweep (Fig. 2b), and then computing sweep duration as the time needed for traversing the 90% position range according to the regression equation for that particular sweep. In addition, we did both analyses (no regression vs. regression on sweeps) based on a percentage of 80% for sweep extraction. All analyses yielded the same pattern of results.
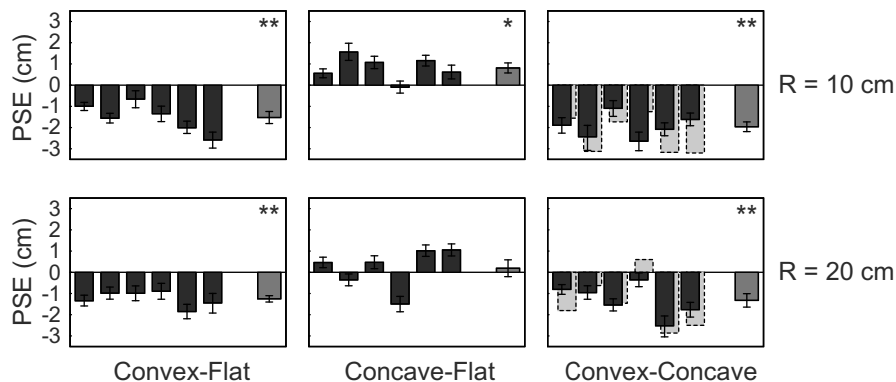
2.5. Experimental conditions

We measured points of subjective equality and points of equal duration in six conditions: CxF10, CxF20, CvF10, CvF20, CxCv10, and CxCv20, representing the combinations of the convex and the flat, the concave and the flat, and the convex and the concave plates at radii of 10 and 20 cm, respectively. We used a single reference length of 18 cm in all conditions. Experimental conditions were presented in random order.

3. Results

3.1. PSEs and PEDs

Fig. 3 shows points of subjective equality for all the six participants in all six experimental conditions, and Table 1 gives averages along with significance levels. All biases were negative in the convex-flat and convex-concave conditions, and they were generally positive in the Concave-Flat conditions. Condition CvF20 had a negative outlier. Consequently, average PSEs were significant in all conditions, except in condition CvF20. A negative bias in the Convex-Flat conditions indicates an overestimation of the length of the convex strip relative to the flat one. For instance, a PSE of −2 cm in this condition would mean that a convex strip of 17 cm was perceived as having the same length as a flat strip of 19 cm. Similarly, positive PSEs in the concave-flat conditions signify underestimations of concave lengths with respect to flat lengths, and negative PSEs in the convex-concave conditions indicate overestimations of convex lengths relative to concave lengths.

Dashed bars in Fig. 3 denote convex-concave PSEs computed by subtracting concave-flat PSEs from their convex-flat counterparts (convex-concave = convex-flat − concave-flat). For condition CxCv20, a paired-samples t test showed that the difference between computed and measured PSEs was nonsignificant, $t(5) = 0.40$, $p = .706$, whereas the correlation coefficient between computed and measured PSEs was significant, $N = 6$, $r = .86$, $p = .027$. Therefore, for individual observers computed and measured biases were the same. For condition CxCv10, a paired-samples t test showed that the difference was also nonsignificant, $t(5) = 0.86$, $p = .429$, but the correlation was nonsignificant as well, $N = 6$, $r = .01$, $p = .989$. Note in Fig. 3 that the variability in PSEs was

Fig. 3. Points of subjective equality for all observers in each of the six experimental conditions. Wide gray bars depict average PSEs for the respective conditions. These were significant in all conditions, except for CvF20. Dashed gray bars denote convex-concave PSEs computed from the first two conditions: convex-flat − concave-flat. Error bars for individual PSEs are bootstrap errors; error bars for mean PSEs are standard errors of the mean. $^{*}p < .05$. $^{**}p < .01$.

Table 1
Mean points of subjective equality

Condition	Mean PSE (cm)	$t(5)$	p
CxF10	-1.53^{**}	-5.37	.003
CxF20	-1.25^{**}	-8.36	<.001
CvF10	0.81^{*}	3.43	.019
CvF20	0.19	0.48	.650
CxCv10	-1.96^{**}	-8.56	<.001
CxCv20	-1.32^{**}	-4.18	.009

* $p < .05$.
** $p < .01$.

much smaller in condition CxCv10. Thus, PSEs cluster in a narrow region, causing the correlation to be nonsignificant. Also for this condition we conclude that computed and measured biases agreed.

As we anticipated, magnitudes of average PSEs were larger for the smaller radius for all three combinations of surface types (Table 1). We tested whether this was a significant effect by comparing absolute values in a one-tailed paired-samples t test for each of the three surface combinations. However, the effect was not found to be significant, $t(5) = 1.18$, $p = .147$; $t(5) = 0.10$, $p = .464$; and $t(5) = 1.36$, $p = .116$, for CxF, CvF, and CxCv, respectively.

Fig. 4 shows points of equal duration together with points of subjective equality, each of the six experimental conditions being represented by a different symbol. PEDs are to be interpreted in the same way as PSEs. A PED in the convex-flat conditions of, say, -2 cm indicates that a convex strip of 17 cm was traced in the same time as a flat strip of 19 cm. In other words, the observer needed more time to trace convex strips than flat ones of the same length. In the same manner, a positive PED in the concave-flat conditions signifies that the observer needed shorter times for concave strips than for flat strips, and a negative PED in the convex-concave conditions indicates longer times for convex strips than for concave ones. In short, PSEs and PEDs represent length differences that are subjectively equal or are traced in equal times, respectively.
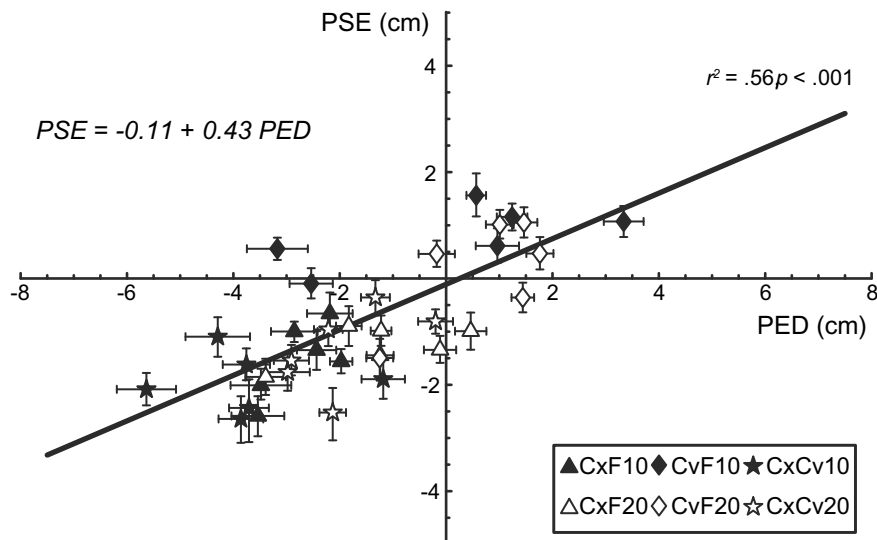
We did a linear regression on PSEs and PEDs, weighting data points according to their errors in both x and y (York, Evensen, López Martínez, & De Basabe Delgado, 2004). PSEs correlated significantly with PEDs, $N = 36$, $r = .75$, $p < .001$: The best straight line corresponded to the equation PSE $= (-0.11 \pm 0.12) + (0.43 \pm 0.05)$ PED (standard errors indicated). Note that the participant who had a strongly negative PSE in condition CvF20 (-1.50 cm) had a

similar PED (-1.25 cm). Thus, although the bias in this participant's distance estimates was opposite to the biases of the other participants, the bias closely followed his PED.
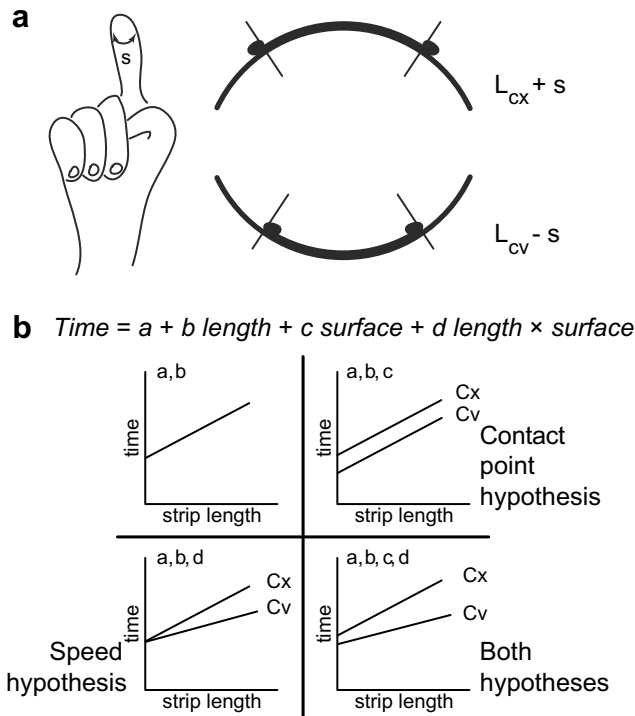
3.2. Analysis of movement duration differences

A convex strip took longer to trace than a flat one, which in turn took longer than a concave one. The question then is what caused these differences in sweep duration. At least two hypotheses can explain our results. Firstly, duration differences could simply be brought about by differences in the movement speed of the index finger. Secondly, time differences could have been caused by differences in what we will call contact points for the left and the right corner of the strip. We define the contact point as the skin area where the observer feels the strip's end point. If the contact points for the left and the right end point of the strip are located on different parts of the finger (Fig. 5a, left part), then the traced length will be shortened or lengthened by the distance between the contact points (Fig. 5a, right part). Note that this hypothesis does not explain the cause of directional shifts in contact points. It tells us only that there is a shift in contact point which is opposite for convex and concave surfaces, and we assume that this shift is symmetric. Shifts as indicated in Fig. 5a would agree with the differences in movement durations as found in this experiment.

At this point, it is important to realize that we cannot find evidence in favor of or against the contact point hypothesis by observing raw movement profiles, as for example in Fig. 2b. For this particular movement profile, the spatial coordinate of the right end point (-7 cm) deviated slightly from the corresponding coordinate of the position marker as recorded in the calibration experiment (lower dashed line). However, remember that we recorded the movement of the index finger by reading out coordinates of a position marker that was stuck to an arbitrary location on the dorsal surface of the distal phalanx. So, the location of this position marker did not correspond to the skin area that was actually touching the strip's edge. Thus, unfortunately the data do not allow us to deduce from the coordinates of this position marker whether contact points were indeed different, since differences in the location of the position marker relative to the left and the right strip's end point could have been provoked not only by differences in contact point, but also by rotations of the index finger relative to the strip which keep the contact point the same. From the raw move-

Fig. 4. Points of subjective equality vs. points of equal duration.

Condition	Regression model					Speed difference %
	a (10^{-2} s)	b (10^{-2} s/cm)	c (10^{-2} s)	d (10^{-2} s/cm)	R	
CxF10	11.31	6.94	–	−1.02	.45	−14.6
CxF20	0.19	6.61	–	−0.39	.29	−5.9
CvF10	10.05	5.63	–	–	.27	–
CvF20	19.31	4.71	–	0.20	.32	0.7
CxCv10	2.51	7.30	–	−1.40	.37	−29.4
CxCv20	10.01	5.66	–	−0.66	.41	−11.7

Note: Surface type term: convex = 0 and flat = 1 for convex – flat conditions, concave = 0 and flat = 1 for concave – flat conditions, convex = 0 and concave = 1 for convex – concave conditions. Dashes indicate that the predictor's contribution to the model was nonsignificant or the relative speed difference could not be computed. All models: $p < .001$. Relative speed differences between surface types are computed from regression parameters b and d. Speed differences are defined as (Cx−F)/F, (Cv−F)/F and (Cx−Cv)/Cv for the convex–flat, concave–flat and convex–concave conditions, respectively.

Fig. 5. Analysis of movement duration differences. Panel a illustrates the contact points hypothesis. According to this hypothesis differences in sweep durations are caused by a shift in the contact points for the left and right end points of the strip. The traced distance gets lengthened or shortened by the amount of the shift for convex or concave surfaces, respectively. Panel b explains the multiple regression model for sweep durations. The contact point hypothesis predicts that parameter c is significant, and the speed hypothesis predicts that parameter d makes a significant contribution to the model.

ment profiles we can only extract the times that the participants associated with the movement along the strip.

However, the two hypotheses can be tested against each other by considering the relationship between movement times and actual strip length they predict. For instance, in the case of the Convex-Concave conditions, the speed hypothesis predicts

$$T_{Cx} = \frac{L_{Cx}}{v_{Cx}} \qquad \text{vs.} \qquad T_{Cv} = \frac{L_{Cv}}{v_{Cv}} \qquad (2)$$

where T, L, and v denote movement time, actual strip length and average speed for the respective surface types. The contact point hypothesis, on the other hand, predicts

$$T_{Cx} = \frac{L_{Cx} + s}{v} \qquad \text{vs.} \qquad T_{Cv} = \frac{L_{Cv} - s}{v} \qquad (3)$$

in which s signifies the shift in contact point (Fig. 5a) and v the average speed, which in this case is the same for both surfaces. Thus, the speed hypothesis predicts a difference in slope, whereas the contact point hypothesis predicts different constant terms.

Therefore, we did a multiple regression on each of the six experimental conditions, combining the data for all participants (N = 6 observers × 2 surface types × 84 trials). As a measure of movement time, we took the mean sweep duration (Fig. 2b). The predictors we considered were length, surface type, and their interaction length × surface type (Fig. 5b). The regression equation is time = a + b length + c surface type + d length × surface type. The predictor length was always included in the model. We did a forward regression for surface type and length × surface type: after length had been included, the predictor that accounted for the largest portion of the remaining unexplained variance in movement times (largest semipartial correlation) was added and retained, if it made

a significant improvement to the model. The predictor that remained was considered likewise. If only the surface term is added to the model, this would mean that there is a significant difference in the constant terms for the two surface types, which supports the contact point hypothesis. If the interaction term is included in the model, there is a significant slope difference, which shows that the movement speeds across the surfaces were different. Finally, if the surface term as well as the interaction term is included, then differences in sweep durations are due to both speed differences and different contact points.

Table 2 gives the results of the multiple regression analysis. Apart from the length term, the regression model included the interaction term but not the surface term in five of six conditions, showing that in these conditions different movement speeds provide the best prediction of the differences in movement times for the various surface combinations. In one condition, only the length term constituted the regression model. Thus, the contact point hypothesis is rejected in favor of the speed hypothesis. Table 2 also gives relative speed differences as computed from the regression parameters.

3.3. Other variables

We investigated whether the magnitude of the PSE depended on the overall average movement speed of the index finger. First, we computed the average speed per condition for each participant (i.e., the average speed applied in a single psychometric session) from the slope of the straight line fitted to mean sweep durations versus strip lengths for the aggregated data of the two surface types. Note that this is an average of movement speeds across the two surfaces tested in that particular condition. Movement speeds could differ by as much as a factor of three (Min = 9.8 cm/s, Max = 29.3 cm/s, Mdn = 15.7 cm/s, IQR = 5.0 cm/s). There was no significant correlation between PSE magnitudes and movement speeds, $N = 36$, $r = -.19$, $p = .270$.

Further more, we tested whether there were systematic differences in the overshooting movements between the various surface types. To exclude any effect of strip length, we only analyzed trials in which both strips were 18 cm (N = 6 observers × 12 trials). First, we computed the mean extent of the overshooting movement for each movement profile (Fig. 2b). In the case of four sweeps, there were three overshooting movements, etc. Occasionally, a trial had to be excluded from the analysis, because only a single sweep was made and consequently no overshooting movement could reliably be defined. The overall average extent of the overshooting

movement at reference length was 17 mm. Next, we performed a paired-samples *t* test for each of the six experimental conditions. The difference in the overshooting extent for the two surfaces used in a particular condition was defined in the same way as the length difference for that condition (convex-flat, concave-flat, or convex-concave). For three conditions, the difference in the overshooting extent was significant and in agreement with the direction of the corresponding PSE: $M = -2.9$ mm, $t(71) = -7.34$, $p < .001$; $M = -0.9$ mm, $t(70) = -2.88$, $p = .005$; and $M = 0.9$ mm, $t(71) = 2.35$, $p = .022$, for CvF10, CvF20, and CxCv20, respectively. For example, in the case of condition CvF10, overshooting was smaller for the concave strip by about 3 mm, while at the same time concave lengths were underestimated. However, for two conditions, the difference in the overshooting extent was significant but opposite to the direction of the PSE for that condition, $M = -1.4$ mm, $t(69) = -3.39$, $p = .001$, for CxF10, and $M = -1.4$ mm, $t(69) = -2.77$, $p = .007$, for CxCv10. For condition CxF20, the difference was nonsignificant, $M = -0.03$ mm, $t(68) = -0.09$, $p = .927$.

For reasons that will be explained Discussion, we also computed instantaneous movement speeds at the very start and end of a sweep by taking the three-point derivative (Press, Teukolsky, Vetterling, & Flannery, 2002). We assume that the starting and ending speeds of a sweep are indicative of the speeds at which the index finger passes the first and last end points of a strip. Again, we only analyzed trials in which both strips had reference length. We then averaged the starting and ending speeds over all sweeps for each movement profile. The starting speed for the first sweep was excluded from the analysis. We were interested in the difference between the mean starting and ending speed and whether this difference varied systematically between the various surface types. Paired-samples *t* tests showed that the effect was significant only in condition CxF10, $M = -0.95$ cm/s, $t(69) = 2.57$, $p = .012$. For both the convex and flat surfaces in this condition, starting speeds were on average higher than ending speeds, the difference between starting and ending speed being in turn 0.95 cm/s larger on the flat surface compared to the convex one. For all other conditions, differences were nonsignificant, all $ps > .183$.

4. Discussion

We found that convex and concave surfaces had qualitatively different effects on observers' length percepts: convex lengths were overestimated, whereas concave lengths were underestimated compared to flat strips. Thus, not only whether a surface was curved or flat, but also the sign of curvature affected observers' length estimates and any explanation for curvature biases would have to account for this qualitative difference.

If a convex length is overestimated relative to a flat one, and a concave length is underestimated relative to a flat length, then in turn, one would expect convex lengths to be overestimated relative to concave lengths. The results did indeed indicate that measured convex – concave PSEs and convex – concave PSEs computed from the first two conditions agreed very well. Not only does this finding demonstrate that the experiment is highly reproducible, but it also shows that the experimental conditions are consistent in the sense that observers appear to use the same mechanism in each condition to draw inferences about the length of the traced edge.

If curvature influences an observer's perception of length, then one would also expect to find smaller PSEs for smaller curvatures, or larger radii, since in the limit case the observer would essentially be comparing the lengths of flat strips and, given the experimental design, we do not anticipate any biases in that case. Although there was a trend in the data for PSEs to be smaller for the larger radius, this trend was not significant. Apparently, the dif-

ference between the 10 cm radius and the 20 cm radius was too small for any effect on PSEs to be detected.

As a next step in our analysis, we showed that there was a positive and significant correlation between points of subjective equality and points of equal duration. We were surprised by the considerable correlation between subjective estimates and movement characteristics, given that we are investigating conditions of relatively unconstrained exploration. Thus, observers' length estimates followed durations of movement and, taken together with previous research on haptic length perception, this suggests that observers indeed took movement time as a measure of perceived length. We also demonstrated that the differences in movement duration derived from differences in movement speeds. The index finger moved slowest along the convex surface and fastest along the concave one, which led to longer movement times for convex lengths.

4.1. Cause of speed differences

How can we explain these speed differences? Why did the observers move their index finger at different speeds across the different surface types? Several hypotheses can be put forward to account for this effect. Our first hypothesis is that gravity modulates movement speeds along the different surface types. Observers try to move at equal speed across all surfaces, but they do not succeed because they do not fully compensate for gravity effects. It is not yet clear precisely in what way this effect is brought about, but we can reasonably assume that gravity acts differently on convex and concave movements. For example, when observers start moving their index finger along a convex edge, they accelerate in a direction (upwards and to the left or the right) that is partially opposite to gravity (downwards), whereas towards the end of the sweep they decelerate, in which case gravity is again working against their movement. To put it more precisely, for convex surfaces the component of the gravity vector that is tangential to the surface opposes both the acceleration and deceleration phases of the movement. For concave surfaces, on the other hand, the opposite is the case. Note that a possible gravity effect on movement speeds would be similar to the effect that the added resistive force had in one of the active conditions in McFarland and Soechting Research (2007). The absence of any effect of this manipulation on the RT illusion argues against the gravity hypothesis.

The second hypothesis relates speed differences to differences in moments of inertia for convex and concave movements. This explanation is the same as the inertial anisotropy hypothesis proposed for the RT effect. We designed the setup such that postures of the observer's arm were as similar as possible for all surface types, but, of course, movements across different surfaces require different combinations of joint rotations. In the course of the experiments, we observed that participants made more whole-arm movements and had less wrist rotation for convex surfaces, whereas for concave movements the opposite was the case. Thus, inertial resistance might be larger for convex movements than for concave movements and so the former would require more energy. If the observer does not compensate for this inertial anisotropy, the resulting movement speed would indeed be lower for the convex surface than for the concave surface, as we found in our experiment.

A third hypothesis has been suggested by one of the participants. This participant noticed that while the finger moves across the surfaces, it can more easily lose contact with a convex surface than with a concave one. Indeed, if at some point during movement the observer stops exerting forces, the index finger will in rough approximation continue to move along a straight line tangential to the surface at that particular point. For the concave surface, the index finger is then pressed against the steel plate, whereas

for the convex surface the index finger, so to speak, takes off. One could say that the finger moves on the inside of the plate for the concave surface and on the outside for the convex surface. To prevent this from happening, the observers will move their index finger slightly more slowly across the convex surface.

If the take-off hypothesis were indeed to explain differences in movement speeds and if observers did not take these speed differences into account, then one might expect PSEs to be larger for observers who move their index finger at higher speeds, as it is easier to lose contact with the convex surface when moving faster. However, we did not find any correlation between PSE magnitudes and movement speeds. This argues against the take-off hypothesis, but does not disprove it, since it could still very well be that observers who move their index finger at higher speeds simply press their finger with a greater force against the surface, thereby canceling the effect of movement speed.

4.2. Secondary effects

We will now briefly discuss two secondary effects that may possibly have influenced length estimations in addition to the effects of movement speed as discussed above. We will show that these effects are negligible or can even be discarded.

First, we mention the possibility of secondary effects of overshooting on length estimations: additional biases in length judgments could have been introduced due to overshooting movements being larger for one or the other surface type. However, note that differences in overshooting extent were much smaller than actual PSEs reported. Moreover, this effect, if any, must interact with the effect of movement speed, since only for three of six conditions did differences in overshooting extent agree with the direction of the PSE.

Second, Dassonville (1995) reports that observers who receive a short tactual vibration to the index finger while making a fast pointing movement to a visual target, mislocalize the location of this vibration at a position that lies at a fixed time interval beyond the actual location of the tactual stimulus. In the case of length estimations, the locations of the end points of the strip may thus be misperceived, affecting perceived length in turn. Suppose that the perceived location of the first end point that is passed in a sweep is shifted along the curved trajectory in the direction of movement: the perceived location lies somewhere on the strip itself. The location of the last end point is shifted in a similar fashion, and it is now perceived to lie somewhere beyond the actual strip's end point. Since the shifts are assumed to be constant when expressed in time, the shifts expressed in distance depend on the velocities of the moving index finger at the moment that the end points were crossed. If the velocity at which the first end point in a sweep is crossed is larger than the velocity at which the last end point is crossed, a small shrinkage of perceived length would occur: the shrinkage equals the difference between the velocities at the first and last end points multiplied by the time constant. Since in our experiment observers had to discriminate lengths across different surfaces, secondary effects may occur if speed differences between the first and last end points vary systematically between the various surface types. As we have shown, in only one case were speed differences between first and last end points systematically different for the two surface types tested, but the direction of this effect was opposite to the direction of the reported length biases.

4.3. Mechanisms underlying length estimations

One could come up with many complex explanations to account for systematic errors in length estimates when observers use limb movements to judge distance traversed. Note that any explanation involves taking a number of different steps. Since distance traversed is inferred from the kinematics of the tracing movement, that is to say, from the characteristics of the movement profile, one would have to explain not only what brings about particular movement characteristics, but also how the observer perceives properties, such as time, velocity, and acceleration, for movements along different pathways and in what particular way these percepts are processed to constitute a length percept. We now discuss two types of mechanisms that fit with our data set. Each mechanism thus has to answer two questions: First, what induces speed differences? Second, what is the basis for the observer's misjudgments of curved lengths? According to the first account, curvature effects are due to a discrepancy between planned or desired movement profiles on the one hand and profiles as they are actually realized on the other hand, and, as such, the curvature effects have the nature of a motor error. According to the second mechanism, systematic biases in the perception of movement speeds for convex and concave surfaces cause the observers to move their finger at different speeds across the two surfaces while perceiving their movement speeds to be the same. This mechanism explains the curvature effects in terms of a perceptual error.

4.3.1. Undetected speed differences

According to the first explanation, observers plan to move their finger with equal – physical – speeds across the different surface types, in which case movement duration would be a veridical measure of distance traversed. However, motor commands sent to the muscles do not meet this requirement. For example, observers do not fully compensate for inertial anisotropies of convex and concave arm movements or for effects of gravity, and consequently in neither case do they satisfy the dynamic constraints of the desired arm movements. These factors can be called curvature-extrinsic, because they are not specific to curvature but would arise in different settings too: the inertial anisotropy hypothesis has been proposed to explain the RT effect (Wong, 1977) and one could imagine that gravity effects also play a role in tasks that differ from ours. The illusion must then arise because observers think they are moving their finger at the same speed across the different surface types so that they can take time as a measure of perceived length.

An important question that has to be answered is why observers do not notice speed differences. What does it actually mean if speed differences are undetected? This question has not been addressed in earlier research. One might conclude that speed differences have been too small for the observer to detect. However, these small speed differences lead to differences in movement duration which in turn yield robust curvature biases. Although mechanisms for perceiving time and movement speed of limbs may be quite distinct, it is reasonable to assume that these mechanisms are tuned to each other. Thus, we think it is unlikely that subthreshold speed differences would lead to suprathreshold time differences. Another possibility is that sensory feedback indicating differences in actual movement speeds is simply ignored due to the cognitive load of the task, and observers assume from movement onset that they are moving their index finger at the same speed. Because participants generally make four sweeps and can choose their own speed range, this possibility also seems unlikely.

4.3.2. Misperceived speeds

A second explanation that could account for the reported curvature effects is that perception of speed is not veridical for convex and concave surfaces. In other words, speeds across the two surface types are perceived differently, which in turn causes curvature biases in length perception. Note that when we are talking about movement speeds of the index finger, we are actually referring to speeds in external space, that is, without any reference to the body (in this case: speed with respect to the strip's edge). Given then

that the sense of speed of limb movements is the result of complex transformations starting from signals from muscle spindles, mechanoreceptors, and possibly joint receptors, and given that physically simple trajectories are generally complex in biomechanical terms (e.g., movement of finger along a straight line), distortions in the spatial representations that are a prerequisite for these transformations might account for the misperception of speeds across convex and concave surfaces.
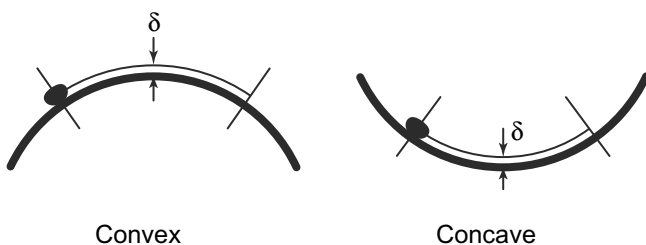
The similar results for the active and passive RT effect (McFarland & Soechting, 2007) lend support to this explanation, considering that at a physiological level there are considerable differences between active and passive arm movements. For example, there is no motor outflow for passive movements, and consequently no corollary discharges are generated to anticipate the reafferent sensory effects of movements (Miall & Wolpert, 1996). Furthermore, sensitivity of muscle spindles is severely reduced for passive movements, because due to the absence of motor commands there is no alpha-gamma coactivation (Clark & Horch, 1986). Finally, transmission of cutaneous feedback is decreased during voluntary movements (e.g., Chapman, 1994; Seki, Perlmutter, & Fetz, 2003), and detection thresholds for tactile stimuli are correspondingly increased, the increase appearing more intense for active movements than for passive movements (e.g., Chapman & Beauchamp, 2006; Vitello, Ernst, & Fritschi, 2006). Tactile sensitivity at the contact between finger and surface plays an important role in haptic length perception, because cutaneous feedback has to be monitored during active movement to check whether the limb is still in contact with the stimulus and because tactile slip may be an important cue for movement speed (Dépeault, Meftah, & Chapman, 2008; Essick, Franzen, & Whitsel, 1988).

An example of such a spatial distortion accounting for the misperception of movement speeds might be the radius of curvature being perceived differently for convex and concave surfaces. Curvature information is probably a crucial type of spatial knowledge needed for computing movement speeds. Suppose that the convex radius is overestimated by an amount δ, whereas the concave radius is underestimated by the same amount (Fig. 6). Then, the pathway that the observer perceives to be tracing (thin line) is different from the actual surface (thick line): the perceived convex trajectory is stretched and the perceived concave trajectory is shrunk with respect to the real surface. Therefore, if the observers move their finger at equal speeds along these perceptual trajectories, physical movement speeds (i.e., the speeds that we actually measured) are lower for the convex than for the concave surface. Let us assume that the observers' finger did indeed maintain equal speeds along the perceptual trajectories, then take

$$PSE = L_{Cx}^{PSE} - L_{Cv}^{PSE} \qquad (4)$$

and since

$$L_{Cx}^{PSE} + L_{Cv}^{PSE} = 36\,cm \qquad (5)$$

we can solve for δ in

$$L_{Cx}^{PSE}\frac{R+\delta}{R} = L_{Cv}^{PSE}\frac{R-\delta}{R} \qquad (6)$$

in which R is the actual radius and L^{PSE} the length of the pathway for the respective surface at PSE. Table 3 gives values for δ based on average PSEs for each of the six experimental conditions as reported in Table 1.

Previous research on haptic curvature discrimination (notably Pont, Kappers, & Koenderink, 1999) addressed the question of the possible cues conveying curvature information (height differences, attitude differences and local contact curvature information). Interestingly, Pont et al. (1999) showed that scanning length affects one's curvature percept, whereas we have shown that curvature affects one's length percept. However, in all their experiments participants had to take the sign of curvature into account. Van der Horst and Kappers (2008) did discrimination experiments in which observers had to decide which of two curvatures, one being convex and the other being concave, felt more curved. Observers thus had to disregard the sign of curvature. Indeed, for stimuli that had dimensions, orientations and curvatures similar to the surfaces used in this study, they found a systematic bias towards overestimations of radii of convex curvatures compared to concave. In other words, a particular curvature appeared flatter when it was convex than when it was concave. Unfortunately, Van der Horst and Kappers (2008) did not control for scanning length, which makes it hard to compare their results with those of this study. The point that we want to make here is that the systematic overestimations of convex and underestimations of concave lengths as reported in this paper might be caused by an interaction between length and curvature percepts, tentatively having the nature of a percept-percept coupling (Epstein, 1982). Finally, we find it intriguing that typical values for δ range roughly between 0.5 cm and 1 cm, which is the same range as the thickness of the index finger. We might then hypothesize that the part of the finger that the observers perceive to be tracing the pathway is not the skin area contacting the strip's edge, as it should have been, but is some point located more centrally inside the index finger.

4.4. Other mechanisms?

In discussing possible mechanisms underlying overestimations of convex and underestimations of concave lengths, we have provided concrete explanations for the occurrence of these curvature biases. As we already remarked, one can come up with other explanations. There may be mechanisms that work at a more cognitive level. For instance, perception of duration might be different for different types of movements, because certain movements are more complex and therefore require more cognitive effort (e.g., Sadalla & Magel, 1980; cf. Proffitt, Stefanucci, Banton, & Epstein, 2003). However, because cognitive effort is at present ill-defined, it is not clear a priori why one or the other type of movement

Fig. 6. Misperceived radii of curvature for convex and concave surfaces. Convex radius is overestimated by an amount δ and concave radius is underestimated by the same amount. Observer maintains equal speeds along perceptual trajectories (thin lines), causing speed differences along actual surfaces (thick lines).

Table 3
Overestimations of convex and underestimations of concave radii, based on the model for misjudgments of curved lengths

Condition	δ (cm)
CxF10	0.89
CxF20	1.44
CvF10	0.44
CvF20	0.21
CxCv10	0.54
CxCv20	0.74

Note: Calculations are based on average PSEs for the respective conditions.

would involve more effort. This explanation is therefore difficult to test.

4.5. RT effect

In this study, we have presented a new experiment in which observers make limb movements in order to judge distance traversed. As we argued in Introduction, it is reasonable to assume that the RT effect and the curvature effects reported in this paper share a common origin. Thus, by comparing these different experimental tasks we may transcend task dependencies and come closer to understanding the general principles governing distance estimates. For example, if it can indeed be shown that a distorted perception of convex and concave radii causes curvature effects, the interesting question that arises is whether an equivalent spatial distortion underlies the RT effect. Furthermore, McFarland and Soechting (2007) research predicts that if the index finger is being moved passively across convex and concave surfaces at equal speeds, convex lengths are still overestimated and concave lengths underestimated. Thus, their research on the RT effect argues against the undetected speed differences explanation and in favor of the misperceived speeds mechanism for curvature biases in this paper.

5. Conclusions

In this research, we have demonstrated that curvature induces systematic errors in haptic length perception. Observers made active movements to trace a curved pathway and judge the length of it. Surprisingly, we found that the sign of curvature had a differential effect on length estimates: convex lengths were overestimated, whereas concave lengths were underestimated. We have also shown that a kinematic mechanism underlies length estimates: curvature biases probably originate from a discrepancy between actual kinematic properties of arm movements and kinematic properties as inferred by the observer.

In particular, we observed a significant correlation between movement times and length estimates. The differences in movement durations for convex and concave lengths were caused by differences in movement speeds across the different surface types. For example, the index finger moved slowest across the convex surface, which led to longer movement times for this type of surface. Taking into account the research on the RT effect as discussed in Introduction and research on curvature perception as discussed above, we might guess that the basis for the illusion is a spatial distortion that causes movement speeds to be misperceived for convex and concave surfaces. Further research is needed to reveal the mechanisms underlying the reported effects.

Interestingly, two studies (Norman, Lappin, & Norman, 2000; Norman, Norman, Lee, Stockton, & Lappin, 2004) reported analogous length biases in visual perception. Participants had to estimate lengths across flat and curved surfaces (cylinders, convex and concave hemispheres, and saddle shapes). These surfaces were real textured objects and were viewed stereoscopically: a full cue situation that might be comparable to the relatively unconstrained manner of exploration in this study. Estimation of lengths across curved surfaces was distorted also in the visual case. Particularly, lengths along the curved dimension of a convex cylinder were generally overestimated, although there was a dependency on the cylinder's orientation and distance to the cylinder (Norman et al., 2000). Apparently, perception of length across curved surfaces is distorted, no matter whether the surfaces are defined visually or haptically.

An interesting implication of the reported curvature effects is that local shape apparently interacts with length perception. This

means that distance estimates are not informative unless the geometry of the path is specified. Since movement of the hand or fingers across the surface of an object is a common exploration procedure for perceiving an object's shape (Klatzky & Lederman, 2003), the question is whether or how the effects reported here influence perception of an object's overall shape. Perhaps distance information is used for making the transition from local to global shape. For example, this type of information might be important for arranging the local surface patches in order to construct the overall shape of an object. Consequently, one might expect distortions in perception of global shape to co-occur. Another interesting research direction might be to take a more ecological approach and investigate how haptic length perception is affected when other object properties, such as compliance (cf. Song, Flanders, & Soechting, 2004) or texture (Corsini & Pick, 1969), come into play.

References

Armstrong, L., & Marks, L. E. (1999). Haptic perception of linear extent. *Perception and Psychophysics, 61*, 1211–1226.

Chapman, C. E. (1994). Active versus passive touch: Factors influencing the transmission of somatosensory signals to primary somatosensory cortex. *Canadian Journal of Physiology and Pharmacology, 72*, 558–570.

Chapman, C. E., & Beauchamp, E. (2006). Differential controls over tactile detection in humans by motor commands and peripheral reafference. *Journal of Neurophysiology, 96*, 1664–1675.

Clark, F. J., & Horch, K. W. (1986). Kinesthesia. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.). *Handbook of perception and human performance: Sensory processes and perception* (Vol. 1, pp. 13.1–13.62). New York: John Wiley and Sons.

Corsini, D. A., & Pick, H. L. Jr., (1969). The effect of texture on tactually perceived length. *Perception and Psychophysics, 5*, 352–356.

Dassonville, P. (1995). Haptic localization and the internal representation of the hand in space. *Experimental Brain Research, 106*, 434–448.

Dépeault, A., Meftah, E.-M., & Chapman, C. E. (2008). Tactile speed scaling: Contributions of time and space. *Journal of Neurophysiology, 99*, 1422–1434.

Epstein, W. (1982). Percept – percept couplings. *Perception, 11*, 75–83.

Essick, G. K., Franzen, O., & Whitsel, B. L. (1988). Discrimination and scaling of velocity of stimulus motion across the skin. *Somatosensory and Motor Research, 6*, 21–40.

Faineteau, H., Gentaz, E., & Viviani, P. (2003). The kinaesthetic perception of Euclidean distance: A study of the detour effect. *Experimental Brain Research, 152*, 166–172.

Gordon, J., Ghilardi, M. F., Cooper, S. E., & Ghez, C. (1994). Accuracy of planar reaching movements. II. Systematic extent errors resulting from inertial anisotropy. *Experimental Brain Research, 99*, 112–130.

Hilbert, D., & Cohn-Vossen, S. (1932). *Anschauliche geometrie*. Berlin: Springer.

Hollins, M., & Goble, A. K. (1988). Perception of the length of voluntary movements. *Somatosensory Research, 5*, 335–348.

Klatzky, R. L., & Lederman, S. J. (2003). Touch. In *Handbook of Psychology*. In I. B. Weiner, A. F. Healy, & R. W. Proctor (Eds.). *Experimental Psychology* (Vol. 4, pp. 147–176). New York: John Wiley and Sons.

Lederman, S. J., Klatzky, R. L., & Barber, P. O. (1985). Spatial and movement-based heuristics for encoding pattern information through touch. *Journal of Experimental Psychology: General, 114*, 33–49.

Lederman, S. J., Klatzky, R. L., Collins, A., & Wardell, J. (1987). Exploring environments by hand or foot: Time-based heuristics for encoding distance in movement space. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 13*, 606–614.

Marchetti, F. M., & Lederman, S. J. (1983). The haptic radial – tangential effect: Two tests of Wong's "moments-of-inertia" hypothesis. *Bulletin of the Psychonomic Society, 21*, 43–46.

McFarland, J., & Soechting, J. F. (2007). Factors influencing the radial-tangential illusion in haptic perception. *Experimental Brain Research, 178*, 216–227.

Miall, R. C., & Wolpert, D. M. (1996). Forward models for physiological motor control. *Neural Networks, 9*, 1265–1279.

Norman, J. F., Lappin, J. S., & Norman, H. F. (2000). The perception of length on curved and flat surfaces. *Perception and Psychophysics, 62*, 1133–1145.

Norman, J. F., Norman, H. F., Lee, Y.-L., Stockton, D., & Lappin, J. S. (2004). The visual perception of length along intrinsically curved surfaces. *Perception and Psychophysics, 66*, 77–88.

Pont, S. C., Kappers, A. M. L., & Koenderink, J. J. (1999). Similar mechanisms underlie curvature comparison by static and dynamic touch. *Perception & Psychophysics, 61*, 874–894.

Press, W. H., Teukolsky, S. A., Vetterling, W. T., & Flannery, B. P. (2002). *Numerical Recipes in C++: The Art of Scientific Computing* (2nd ed.). Cambridge: Cambridge University Press.

Proffitt, D. R., Stefanucci, J., Banton, T., & Epstein, W. (2003). The role of effort in perceiving distance. *Psychological Science, 14*, 106–112.

Sadalla, E. K., & Magel, S. G. (1980). The perception of traversed distance. *Environment and Behavior, 12*, 65–79.

Seki, K., Perlmutter, S. I., & Fetz, E. E. (2003). Sensory input to primate spinal cord is presynaptically inhibited during voluntary movement. *Nature Neuroscience, 6*, 1309–1316.

Song, W., Flanders, M., & Soechting, J. F. (2004). Effect of compliance on haptic perception of curvature. *Somatosensory and Motor Research, 21*, 177–182.

Van der Horst, B. J., & Kappers, A. M. L. (2008). Haptic curvature comparison of convex and concave shapes. *Perception*.

Vitello, M. P., Ernst, M. O., & Fritschi, M. (2006). An instance of tactile suppression: Active exploration impairs tactile sensitivity for the direction of lateral movement. In *Proceedings of the Eurohaptics International Conference* (pp. 351-355). Paris.

Von Skramlik, E. (1933). Über die Beeinflussung unserer Tastwahrnehmungen durch Richtung und Schnelligkeit der Tastbewegung. *Zeitschrift für Sinnesphysiologie, 64*, 97–114.

Wapner, S., Weinberg, J., Glick, J. A., & Rand, G. (1967). Effect of speed of movement on tactual-kinesthetic perception of extent. *American Journal of Psychology, 80*, 608–613.

Wichmann, F. A., & Hill, N. J. (2001a). The psychometric function: I. Fitting, sampling, and goodness of fit. *Perception and Psychophysics, 63*, 1293–1313.

Wichmann, F. A., & Hill, N. J. (2001b). The psychometric function: II. Bootstrap-based confidence intervals and sampling. *Perception and Psychophysics, 63*, 1314–1329.

Wong, T. S. (1977). Dynamic properties of radial and tangential movements as determinants of the haptic horizontal – vertical illusion with an L figure. *Journal of Experimental Psychology: Human Perception and Performance, 3*, 151–164.

York, D., Evensen, N. M., López Martínez, M., & De Basabe Delgado, J. (2004). Unified equations for the slope, intercept, and standard errors of the best straight line. *American Journal of Physics, 72*, 367–375.