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Transfer of the curvature aftereffect in dynamic touch

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ABSTRACT

A haptic curvature aftereffect is a phenomenon in which the perception of a curved shape is systematically altered by previous contact to curvature. In the present study, the existence and intermanual transfer of curvature aftereffects for dynamic touch were investigated. Dynamic touch is characterized by motion contact between a finger and a stimulus. A distinction was made between active and passive contact of the finger on the stimulus surface. We demonstrated the occurrence of a dynamic curvature aftereffect and found a complete intermanual transfer of this aftereffect, which suggests that dynamically obtained curvature information is represented at a high level. In contrast, statically perceived curvature information is mainly processed at a level that is connected to a single hand, as previous studies indicated. Similar transfer effects were found for active and passive dynamic touch, but a stronger aftereffect was obtained when the test surface was actively touched. We conclude that the representation of object information depends on the exploration mode that is used to acquire information.

1. Introduction

A haptic curvature aftereffect is a phenomenon in which a flat surface feels concave after the prolonged touching of a convex surface, and vice versa. The occurrence of this phenomenon has been demonstrated for different exploration modes. Gibson (1933) reported that when subjects ran their fingers along the edge of a convexly curved cardboard for three minutes, the subsequently explored flat edge felt concave. Recent studies have focused on the properties of static rather than dynamic curvature aftereffects.

Vogels, Kappers, and Koenderink (1996) studied the characteristics of an aftereffect when curved surfaces were touched by static contact with the entire hand. They found a linear dependence of the magnitude of the aftereffect on the curvature of the adaptation stimulus. In addition, they showed that the magnitude of the aftereffect increased with adaptation time (up to about 10 s) but decreased with increasing interstimulus intervals. Later, they showed that the aftereffect also occurred when small variations in the exploration manner were applied, but no aftereffect was found when the adaptation and test stimuli were touched by different hands (Vogels, Kappers, & Koenderink, 1997). Finally, they demonstrated that two consecutively presented adaptation surfaces together contributed to the magnitude of the aftereffect (Vogels, Kappers, & Koenderink, 2001). Recently, we presented the existence of an aftereffect when curved surfaces were statically touched by only a single fingertip (Van der Horst et al., 2008). Furthermore, we found a significant effect when the adaptation and test stimuli were touched by different fingers, but the magnitude of this transferred aftereffect was only about 20–25% of the original effect.

In the present study, we investigated the existence and transfer of an aftereffect when curved surfaces were explored dynamically by a single finger. Studying the aftereffect and its transfer can provide more insight into the representation of perceived curvature information.

1.1. Exploration modes to perceive curvature

The haptic perception and representation of curvature has been investigated for several manners of exploration. In this section, we consider a number of studies on static and dynamic curvature perception.

One way to perceive the shape of an object is through static contact of a single fingertip on a curved stimulus. This exploration manner is appropriate to obtain information from highly curved surfaces. Neurophysiological studies have provided evidence that curvature information is processed on the basis of the response profile of the population of mechanoreceptors in the fingerpad. This response profile correlates to the contact shape and the force that is applied to the finger (Goodwin, Browning, & Wheat, 1995; Goodwin, Macefield, & Bisley, 1997; Jenmalm, Birznieks, Goodwin, & Johansson, 2003; LaMotte & Srinivasan, 1993). However, psychophysical studies have shown that this exploration manner is

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unsuitable to perceive the shape of weakly curved surfaces, i.e., when the curvature is below the 84% threshold of about $7\,\mathrm{m}^{-1}$ (Goodwin, John, & Marceglia, 1991; Pont, Kappers, & Koenderink, 1999).

Nevertheless, the shape of weakly curved stimuli can be perceived by static touch when the contact length with the stimulus is increased by placing the whole finger or several fingers together on the stimulus surface (Pont, Kappers, & Koenderink, 1997; Pont et al., 1999). The thresholds decreased with increasing contact length, up to about $0.5\,\mathrm{m}^{-1}$ for a contact length of 15 cm.

A different way to perceive the shape of an object is by dynamic contact between a single fingertip and the object surface. In a number of psychophysical studies, the curvature of the stimuli was below the threshold for static touch with a single fingertip (Davidson, 1972; Gordon & Morison, 1982; Pont et al., 1999). Hence, movement was required to perceive the shape of the surface. Also in this case, the discrimination threshold decreased with the increasing contact length. For a contact length of 20 cm, a discrimination threshold of $0.4\,\mathrm{m}^{-1}$ was found. Similar thresholds were found for static and dynamic touch, when the same contact length was used (Pont et al., 1999).

Several other studies have investigated curvature perception by dynamic touch, but the curvature of the stimuli that were used varied from 19 to $120\,\mathrm{m}^{-1}$, which is above the threshold for static touch with a single finger (Bodegård, Geyer, Grefkes, Zilles, & Roland, 2001; Bodegård et al., 2000; Provancher, Cutkosky, Kuchenbecker, & Niemeyer, 2005; Van der Horst & Kappers, 2007; Van der Horst & Kappers, 2008). In such cases, dynamic contact was not required to perceive the shape of the stimulus, but it might have improved the accuracy.

1.2. Representation of curvature information

Static and dynamic touch provide different ways to acquire shape information from an object. Higher performance can be achieved for dynamic touch than for static touch, in which only a single finger is used. Dynamic contact between the finger and the stimulus provides additional information about the shape of the stimulus. This suggests that curvature information is processed in a different way for dynamic touch. Consequently, the representation level of the curvature information may depend on the exploration mode.

More insight into the representation of curvature information can be obtained by studying the aftereffect and its transfer. In vision, establishing aftereffect transfer has successfully uncovered the representation of perceived phenomena like motion (see e.g., Mather, Verstraten, & Anstis, 1998; Moulden, 1980; Tao, Lankheet, van de Grind, & van de Wezel, 2003; Wade, Swanston, & de Weert, 1993). In haptics, the aftereffect transfer paradigm has only scarcely been employed. Our recent study on the static curvature aftereffect demonstrated a partial transfer of this effect. We suggested that an important part of the representation is situated at a neural level that is directly connected to the processing of the responses of the mechanoreceptors in the individual finger; a small part of the representation is located at a higher, bimanual stage (Van der Horst et al., 2008).

Analogous to the static aftereffect, establishing the existence and transfer characteristics of a dynamic curvature aftereffect could provide information about the representation of dynamically perceived curvature. If similar results are obtained for dynamic touch as were found for static touch, this would suggest that, irrespective of the differences in exploration mode, curvature is represented at similar levels. In contrast, finding different patterns would indicate that curvature representation occurs in different ways, depending on the mode of exploration.

1.3. Active and passive dynamic touch

A distinction is made between active and passive dynamic touch. In active dynamic touch, the subject moves the finger over the surface of a fixed stimulus; in passive dynamic touch, the stimulus moves underneath a finger that the subject keeps at a fixed position. Passive dynamic touch shares with active dynamic touch that there is an analogous moving contact between the finger and the stimulus. Therefore, similar results might be expected for active and passive dynamic touch. However, passive dynamic touch has in common with static touch that the finger stays in the same location. If self-induced movement is an important factor, then the results for passive touch should deviate from the results for active touch.

2. Experiment 1

In the first experiment, we studied the existence and transfer of a dynamic aftereffect in active and passive dynamic touch.

The first goal was to demonstrate the existence of a curvature aftereffect in dynamic touch. Gibson (1933) reported the occurrence of an aftereffect after three minutes of adaptation. However, in the current study, we used a shorter adaptation time (11 s), comparable to the adaptation times that have been used in studies on the static aftereffect.

The second purpose of this experiment was to establish whether, and to what extent, the dynamic aftereffect transfers between both hands. The transfer characteristics might be similar to those of the static aftereffect, since the ability to perceive curvature is comparable for static and dynamic touch, when there is controlled for contact length. However, having the same ability to acquire shape information does not necessarily imply that this information is represented at the same level. Moreover, no comparable results were found for static and dynamic touch when only a single finger was used. Thus, the transfer pattern might deviate from the transfer characteristics of static aftereffects, as previously reported (Van der Horst et al., 2008; Vogels et al., 1997). In order to make a proper distinction between static curvature representation and dynamic curvature representation, we used stimuli in the curvature range below the threshold for single-finger static touch. Consequently, the shape could not be deduced from the immediate contact between the finger and the stimulus, but movement was required.

The third goal was to determine whether active and passive dynamic touch demonstrate similar aftereffects. The same results might be obtained, since there is a comparable moving contact between the finger and the stimulus. However, there might be differences in the magnitude of the aftereffect and the extent of transfer, since there is self-induced movement in the active but not in the passive case.

2.1. Methods

2.1.1. Design

Four conditions were studied in a two (exploration) × two (finger) design. The exploration mode was either active or passive dynamic touch. In the active mode, the stimuli were explored by a self-induced movement with the index finger over the surface of a stationary stimulus. In the passive mode, the stimuli moved underneath a statically sustained finger. A further distinction was made between the employment of either a single finger or different fingers. In the same-finger mode, the same index finger was used to touch both the adaptation and the test stimulus; in the opposite-finger mode, the right index finger touched the adaptation stimulus, and the left index finger touched the test stimulus.

2.1.2. Setup

Subjects were seated behind a table, with their arms resting on a support. The stimuli could be placed in two slits on a platform in front of the support. Only the right slit was used in the same-finger mode. In the opposite-finger mode, the adaptation stimulus was placed in the right slit, and the test stimulus was placed in the left slit. In the passive conditions, the platform moved back and forth at a constant speed

Fig. 1. Experimental setup. The arms rested on a support that was 19 cm above the tabletop. The stimuli were placed in slits on a platform, which was 14 cm above the tabletop. The distance between the centres of the slits was 40 cm. In this example, the subject explores the concave adaptation stimulus with the right index finger before touching the test stimulus with the opposite index finger. In the active conditions, the stimuli remained in a fixed position; in the passive conditions, a computer controlled stepping motor moved the platform. The surface of the stimuli was circularly curved. The length of the stimuli was 200 mm, and the width was 20 mm. The height at the side of the stimuli was 40 mm.

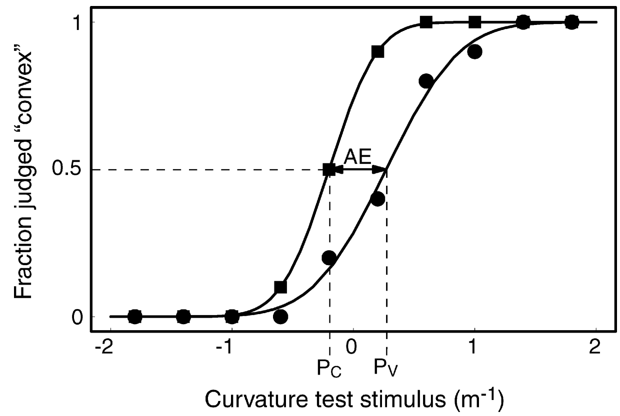

Fig. 2. Examples of two psychometric curves of one subject in an active, same-finger condition. The response is plotted against the curvature of the test stimulus. The psychometric curves were obtained by fitting cumulative Gaussians to the data. The circular data points represent the response when adaptation was performed with the convex adaptation stimulus; the square data points result from adaptation with the concave adaptation stimulus. The points of subjective equalities are given by P_V and P_C, respectively. The magnitude of the aftereffect (AE) is defined as the difference between P_V and P_C.

of 0.11 m/s, driven by a computer controlled stepping motor. The platform remained in position in the active conditions. Fig. 1 illustrates the setup of the experiment.

2.1.3. Stimuli

The stimuli were produced from polyvinyl chloride (PVC). The top surface was a circular cylinder part, which curved either outward (convex) or inward (concave). One convex adaptation stimulus and one concave adaptation stimulus were used, with curvature values of +3.8 and $-3.8\,m^{-1}$, respectively. The curvature of the 10 test stimuli varied from -1.8 to $+1.8\,m^{-1}$, in steps of $0.4\,m^{-1}$.

2.1.4. Procedure

During a trial, the adaptation stimulus was touched by the index finger of the right hand for 11 s. Three back-and-forth movements were made during the adaptation phase. After 4 s, the test stimulus was touched with an index finger for a single side-to-side movement. The task of the subject was to indicate whether this test stimulus felt convex or concave. Practice trials were conducted to accustom the subjects to the proper exploration time. No feedback was provided.

Each condition consisted of 10 repetitions of a group of 20 trials (2 adaptation stimuli $\times$ 10 test stimuli). The presentation order of the trials within a group was randomized. A complete condition was measured in a single session, which took about 90 min. The order in which the experimental conditions were conducted was partly counterbalanced. One half of the subjects first performed the active conditions followed by the passive conditions; the other half of the subjects started with the passive conditions. The order in which the same-finger conditions and the opposite-finger conditions were conducted was counterbalanced among the subjects.

2.1.5. Subjects

Eight, paid subjects participated (four male and four female, mean age 21 years). All subjects were right-handed, as established by a standard questionnaire (Coren, 1993).

2.1.6. Analysis

For each subject and condition, the responses in the convex adaptation trials were separated from the responses in the concave adaptation trials. The fraction of "convex" responses was calculated for each curvature value of the test stimuli. A psychometric function (cumulative Gaussian) was fitted to the data to determine the point of subjective equality (PSE). The PSE is the curvature value that is judged as convex in 50% of the cases and as concave in 50% of the cases. In other words, on average, this curvature value is judged as flat. The magnitude of the aftereffect is defined as the difference between the PSE resulting from convex adaptation (P_V) and from concave adaptation (P_C). Fig. 2 shows an example of the psychometric curves

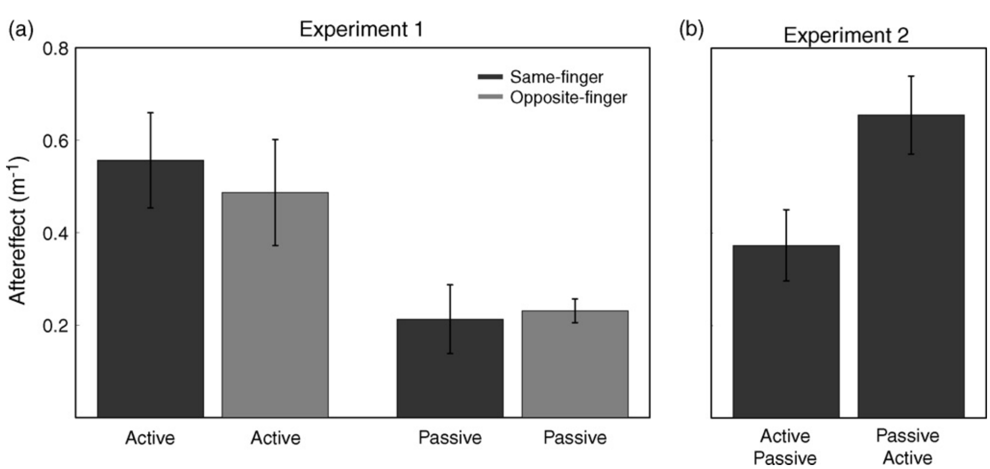

Fig. 3. (a) Mean results of the aftereffect for eight subjects. The error bars represent the standard errors. In the active conditions, the adaptation and test stimuli were explored by self-induced exploration with the index finger. In the passive conditions, the stimuli moved underneath the index finger. The dark bars represent the results for the conditions in which the adaptation and test stimuli were touched by the same index finger. The light bars represent the results for the conditions in which the adaptation stimulus was touched by the right index finger and the test stimulus was touched by the opposite index finger. (b) Mean results of the aftereffect for eight subjects. In the active–passive condition, the adaptation stimulus was explored actively, while the test stimulus was touched passively. In the passive–active condition, passive contact with the adaptation stimulus was followed by active exploration of the test stimulus.

for one subject and one condition. The PSEs and the magnitude of the aftereffect are indicated.

2.2. Results

The mean results for each condition are given in Fig. 3a. The error bars represent the standard errors. Visual inspection of this graph shows that an aftereffect was obtained in all conditions. Most importantly, similar magnitudes of the aftereffect were found in the same-finger conditions and in the opposite-finger conditions, which points to a complete transfer of the aftereffect. In addition, the magnitude of the aftereffect was higher in the active conditions compared to the passive conditions. Statistical analyses confirmed these observations. For each condition, a one-tailed, one-sample *t*-test was conducted to determine whether the aftereffect deviated from zero. Significant aftereffects were found in all conditions ($t_7 = 5.4$, $p < 0.001$ for the active same-finger condition; $t_7 = 4.2$, $p = 0.002$ for the active opposite-finger condition; $t_7 = 2.9$, $p = 0.012$ for the passive same-finger condition; $t_7 = 9.0$, $p < 0.001$ for the passive opposite-finger condition). A 2 × 2 ANOVA with a repeated measures design showed a significant main effect for the factor exploration ($F_{1,7} = 27.5$, $p = 0.001$) but no significant effects for the factor finger or for the interaction between exploration and finger ($F_{1,7} = 0.1$, $p = 0.7$ and $F_{1,7} = 0.2$, $p = 0.7$, respectively).

2.3. Discussion

This experiment shows the existence of a dynamic curvature aftereffect and, most surprisingly, a full transfer of this effect. This result differs from the partial transfer of the static curvature aftereffect, as obtained in our previous study (Van der Horst et al., 2008). To place the finding in a broader perspective, only some specific visual motion aftereffects show a full interocular transfer. In general, there is only partial transfer of the effect, the strength of which depends on several stimulus and measurement parameters (Tao et al., 2003; Wade et al., 1993). Our finding of a complete transfer suggests that curvature perception by dynamic touch is a complex process that is represented at a high level in the brain. A further account of this finding will be provided in the general discussion.

Complete intermanual transfer was found for both active and passive touch, but the magnitude of the aftereffect was higher in the active conditions than in the passive conditions. The fact that we found a complete transfer of the aftereffect in both active and passive dynamic touch suggests that curvature information is represented similarly in both exploration modes; however, analogous phenomena do not necessarily share a common representation. Furthermore, the difference in magnitude of the aftereffect indicates that there are differences in curvature representation of active and passive dynamic touch. Therefore, we performed a second experiment to determine whether adaptation by active dynamic touch induces an aftereffect in passive dynamic touch, and vice versa.

3. Experiment 2

In the second experiment, the transfer between active and passive dynamic touch was investigated. Two conditions were considered. In the active–passive condition, adaptation was performed by active dynamic touch, and testing was performed by passive dynamic touch. In the passive–active condition, the order was reversed. In both conditions, subjects used only their right hands for adaptation and testing.

Before the experiment, we formulated two main hypotheses. One hypothesis was that there would not be a transfer between active and passive touch. This would imply that the existence and intermanual transfer of the aftereffect for active and passive touch are analogous phenomena but do not share a common representation. The other hypothesis predicted that there would be a transfer between active and passive touch, which would suggest that both exploration modes share a common representation. In this case, several results were possible. First, a similar aftereffect could be found in both conditions; only the representation shared by active and passive touch would be reflected by the aftereffect. Second, a higher aftereffect could be obtained in the active–passive condition; this would suggest that active and passive touch share the same representation, but adaptation is stronger for active touch. Third, a stronger aftereffect could be found in the passive–active condition. In this case, the manner of touch during the test phase, not the exploration mode in the adaptation phase, determines the magnitude of the aftereffect.

3.1. Methods

The same setup was used for this experiment as in the previous experiment. We did not use the $\pm 1.8\,\mathrm{m}^{-1}$ stimuli but increased the number of repetitions per stimulus. As a result, each condition consisted of 192 trials in total (12 repetitions of a group of 2 × 8 trials). The order in which the experiment was performed was counterbalanced among subjects. There were eight, right-handed subjects (four male and four female, mean age 21 years), none of whom were involved in the first experiment.

3.2. Results

The mean results for each condition are presented in Fig. 3b. Significant aftereffects were found in both conditions, as one-tailed, one-sample *t*-tests demonstrated ($t_7 = 4.8$, $p = 0.001$ for the active–passive condition; $t_7 = 7.8$, $p < 0.001$ for the passive–active condition). A dependent-samples *t*-test showed that the magnitude of the aftereffect was significantly higher in the passive–active condition than in the active–passive condition ($t_7 = 2.8$, $p = 0.025$).

Independent samples *t*-tests were performed in order to compare the results of the second experiment to the same-finger results of the first experiment. The magnitude of the aftereffect for the active–passive condition did not differ significantly from the active and passive conditions of the first experiment ($t_{14} = -1.4$, $p = 0.18$, $t_{14} = 1.5$, $p = 0.16$, respectively). The result for the passive–active condition was not significantly different from that of the active condition but was significantly higher than that of the passive condition ($t_{14} = 0.7$, $p = 0.5$ and $t_{14} = 3.9$, $p = 0.001$, respectively).

3.3. Discussion

This experiment reveals an aftereffect transfer from active to passive dynamic touch, and vice versa. The magnitude of the effect was higher in the passive–active condition than in the active–passive condition. The correspondence between the first and the second experiment is that a stronger aftereffect is obtained when the test stimulus is actively explored, irrespective of the manner of touching the adaptation stimulus.

4. General discussion

4.1. The existence of a dynamic curvature aftereffect

We demonstrated the occurrence of an aftereffect when curved surfaces are dynamically touched with a single index finger. This finding is a considerable extension of the original discovery of Gibson (1933), since we employed a quantitative approach and displayed the existence of the effect for a relatively short adaptation time. In this respect, the dynamic curvature aftereffect is similar to previously reported static curvature aftereffects (Van der Horst et al., 2008; Vogels et al., 1996).

4.2. Dynamic touch versus static touch

One of the most important findings of this study is the complete intermanual transfer of the dynamic curvature aftereffect. The magnitude of the aftereffects in the opposite-finger and same-finger conditions was the same. In contrast, no intermanual transfer has been demonstrated for the static whole-hand aftereffect (Vogels et al., 1997); only partial transfer has been found for the static single-finger aftereffect (Van der Horst et al., 2008). This dissimilarity between the transfer of the dynamic curvature aftereffect and transfer of the static curvature aftereffect indicates that the representation of curvature perceived by dynamic touch deviates considerably from the representation of curvature perceived by static touch. The origin of this difference might be found at the basis of curvature perception, namely, the way in which curvature information is achieved by the finger(s). In the subsequent paragraphs, we consider how curvature information can be derived from static and dynamic contact with a stimulus surface.

When a single finger is in static contact with a stimulus surface, the indentation profile of the stimulus on the finger is directly related to the shape of the surface (Fig. 4a). The curvature of the surface can be derived by assembling the responses of the cutaneous mechanoreceptor population in the finger pad (Goodwin & Wheat, 2004; Van der Horst et al., 2008). For weakly curved stimuli, the local, immediate contact of the finger on the stimulus does not provide sufficient information about the shape of the stimulus, since the curvature of the stimulus is below the threshold for single-finger static touch (Goodwin et al., 1991; Pont et al., 1999). However, the shape can be perceived by static touch when the whole hand or different parts of the hand are in contact with the stimulus surface. In this case, the shape may be derived from combining the local slant at each contact point with knowledge about the position of the fingers (see Fig. 4a). Note that for single-finger static touch as well as multi-finger static touch, the available information remains constant in time.

The situation is different for dynamic touch. Since the immediate contact of a single finger is insufficient, curvature information must be derived from the dynamic contact between the finger and the stimulus surface. Several events occur simultaneously and change over time when the finger makes a horizontal movement over the stimulus surface: the finger skin slips and stretches; the finger is displaced in the vertical direction; the orientation of the finger with respect to the external space (rotation around the finger axis) and to the stimulus surface (change in contact point) may be altered (Fig. 4b).

The question is how the shape of the stimulus can be deduced from various information sources. Theoretically, knowing the starting position, the vertical displacement is the only information

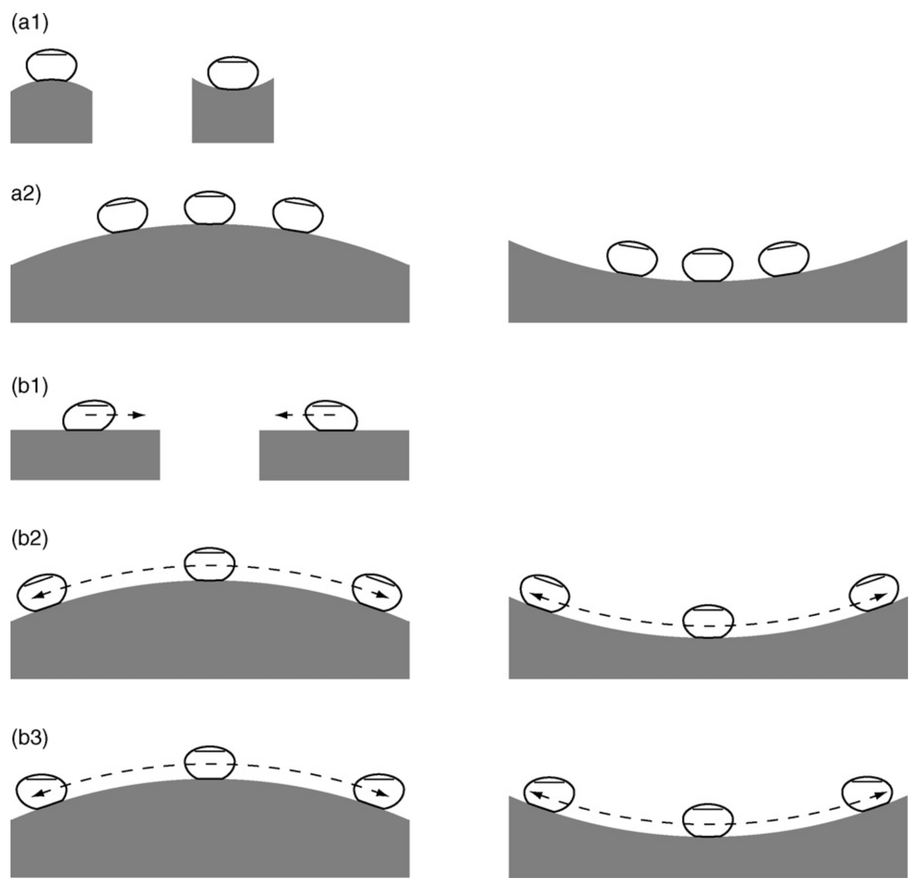

Fig. 4. (a1) Illustration of convex and concave stimuli in contact with a single finger by static touch. There is a direct relationship between the shape of the stimulus and its indentation profile on the finger. (a2) Static touch with different parts of the hand that contact the stimulus surface (in this case, three fingers). Local slant information from each contact point must be combined with information about the position of the finger in order to obtain curvature information from the stimulus surface. (b) Illustrations of information sources when there is dynamic contact between the finger and a stimulus. (b1) The finger slips and stretches due to friction between the finger and the stimulus. The deformation depends on the direction of movement contact, as indicated by an arrow. (b2) The orientation of the finger with respect to the external space can change (rotation), when the finger moves over the stimulus surface. In the example, the finger remains parallel to the stimulus surface. In this specific situation, the point of contact on the finger does not change. Besides, the finger displaces in the vertical direction, but this displacement is too small to provide sufficient information. (b3) The orientation of the finger with respect to the stimulus surface can change when the finger moves over the surface. As a consequence, the contact point can change. In the example, the finger does not rotate.

source that is directly related to the shape of the stimulus. However, for weakly curved stimuli, the height differences are too small to provide sufficient information about the shape of the stimuli (Pont et al., 1999). The remaining sources cannot individually provide information about the shape of the stimulus, since they are indistinguishable for convex and concave shapes. Therefore, they must be combined: a change in contact point only provides information about the shape when it is combined with knowledge about the rotation of the finger and the direction of movement. The latter can be derived from the self-induced movement of the finger or from the stretch and slip of the finger skin.

Information sources like rotation and change in contact point cannot provide instantaneous information, only information over time. Our finding of a complete transfer of the dynamic curvature aftereffect is in agreement with this analysis. Adaptation cannot occur at a low level, since information from individual sources is similar for convex and concave stimuli and non-informative at an instantaneous moment. Adaptation can only arise at a stage in which these different sources are integrated into a concept of curvature.

Pont et al. (1999) demonstrated a similar performance to discriminate curvature by static and dynamic touch. Nevertheless, the current study shows that a similar performance does not require the same representation but can be reached through different ways of processing information. Our finding of a high level of representation for dynamic touch deviates from the brain imaging study by Bodegård et al. (2001), which indicated that curvature was represented at a level that was connected to a single hand. However, the curvatures of the spheres that were rolled on the finger pad were clearly above the static single-finger threshold; thus, the dynamic component may not have contributed to the representation in this case. In contrast, dynamic contact was required in the current study, since the curvatures of the stimuli were too low to be perceived by static contact.

4.3. Active dynamic touch versus passive dynamic touch

Intermanual transfer of the aftereffect was found for both active and passive dynamic touch. This suggests that self-induced movement of the finger is not essential for perceiving curvature. In the previous section, we argued that information about the direction of movement is essential to distinguish a weakly curved shape. To be more precise, information about the direction of the relative movement between the finger and the stimulus is required. Since this information can be deduced from the stretch of the finger skin, information from the movement of the finger itself is redundant. This means that the same sources provide information about shape in both active and passive dynamic touch. Accordingly, curvature is similarly represented, as reflected by the existence and transfer of the aftereffect in both exploration modes and by the transfer from active to passive touch (and vice versa).

Despite the similarities between active and passive touch, significant differences in the magnitude of the aftereffect were found. In the first experiment, the aftereffect was stronger in the active mode than in the passive mode. In the second experiment, the effect was stronger in the passive–active condition than in the active–passive condition. The correspondence between these findings is that a smaller aftereffect was obtained when the test stimulus was touched passively instead of explored actively. It appears that self-induced exploration of the test stimulus enhances the aftereffect. This might be related to small differences in the exploration mode and information pickup between active and passive testing. Although the same sources provide information about shape, there may be differences in the contribution of the individual sources. For example, the amount of rotation and change in contact point might be different, or the amount of stretch may vary, depending on the force that the finger exerts on the stimulus and vice versa. Moreover, the weight given to individual information sources may depend on the exploration mode, similar to material properties that influence the weight given to individual sources in shape perception (Drewing, Wiecki, & Ernst, 2008).

A related aspect is that active and passive dynamic touch require different sensorimotor involvement. In active touch, the subject controls the movement of the finger on the stimulus surface. An accurate movement can be made when the efferent copy of the outgoing motor command is integrated with afferent sensory information (Flanagan, Bowman, & Johansson, 2006; Gritsenko, Krouchev, & Kalaska, 2007; Wolpert, Ghahramani, & Jordan, 1995). In passive dynamic touch, the movement is supplied by an external agent. However, there might be a role for the sensorimotor system, since the subject himself controls that the finger stays in position.[1] Nevertheless, the contribution of the sensorimotor system to the perception of curvature might be more important in active dynamic touch, which could result in an amplification of the aftereffect. Easton and Falzett (1978) showed that the pressure profile produced in active exploration of a surface is inversely related to the curvature of that surface. Suppose that the exerted pressure profile alters systematically due to adaptation to previously acquired curvature information. Following adaptation to a convex shape to convex curvature information, the pressure profile of exploring a flat surface corresponds to that of a slightly concave surface without adaptation. Accordingly, this flat surface will be judged as concave, which is consistent with the direction of an aftereffect. The enhancement of the aftereffect during active testing does not occur for passive testing, since the dynamic contact of the finger on the stimulus is not controlled by the subject. Concerning the adaptation phase, it is not unlikely that both actively and passively acquired curvature information can cause a change in the movement planning during active testing, since information from different perceptual inputs can influence motor planning (see e.g., Flanagan et al., 2006; Goodwin & Wheat, 2004; Gordon, Forssberg, Johansson, & Westling, 1991). Therefore, similar aftereffects could be obtained in the active–active condition of the first experiment and the passive–active condition of the second experiment. Future studies might measure in detail the movement and pressure profiles for active and passive touch as function of the curvature of the stimuli and the manner of adaptation.

4.4. Conclusion

The current study demonstrates the existence of a haptic dynamic curvature aftereffect and a complete intermanual transfer of this effect, which suggests that dynamically obtained curvature information is represented at a high level in the brain. In contrast to statically obtained curvature information, we argue that curvature can only be perceived by dynamic touch when information from several sources is combined and integrated in time. A comparison between active and passive dynamic touch shows a larger aftereffect for actively tested curvature. This finding raises interesting questions about the importance of self-induced movement in dynamic touch, which might be the subject of future studies. In conclusion, this study provides evidence that the representation of object information depends on the exploration mode that is used to obtain that information.

[1] The definition of passive dynamic touch as used in the current study differs from the more strict definitions of passive touch, in which there is no role for the efferent commands (Chapman, 1993; Loomis & Lederman, 1986, chapter 31).

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