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Dynamic Tactile Information is Sufficient for Precise Curvature Discrimination

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DYNAMIC TACTILE INFORMATION IS SUFFICIENT FOR PRECISE CURVATURE DISCRIMINATION

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Our tactile perceptual experiences occur when we interact, actively and passively, with environmental objects and surfaces. Previous research has demonstrated that active manual exploration enhances the tactile perception of object shape. Nevertheless, the factors that contribute to this enhancement are not well understood. The present study evaluated the ability of 14 older adults to discriminate curved surfaces by actively feeling objects with a single index finger and by passively feeling objects that moved relative to a restrained finger. The curvature discrimination thresholds obtained for passive-dynamic touch were significantly lower than those that occurred during active-dynamic touch. This result demonstrates that active exploratory movements of the hand and fingers do not necessarily lead to the best curvature discrimination performance; rather, performance was best in the current study when dynamic tactile stimulation occurred in the absence of active movement. The results of the present study also clarify those obtained by Norman et al. (2013), who found that active-dynamic touch was superior to static touch -- the current findings extend this previous research and indicate that passive-dynamic touch can yield performance that is even higher than what is obtained for active-dynamic touch.

Introduction

The perception of surface properties from physical contact is an essential, but often overlooked, ability that we rely on to interact with objects in daily life. The scientific study of the sense of touch first began in the early 19th century with the work of eminent German physiologist E. H. Weber (Grunwald & John, 2008). Since then, numerous psychophysical methods have been developed to test the sensitivity of touch (for a review, see Klatzky & Lederman, 2003). These methods are used to assess the discrimination, estimation, or identification of simple surface properties such as texture, temperature, length, size, and shape. The shape of any smoothly-curved object can be mathematically described in terms of the maximal and minimal curvatures of local surface regions (Koenderink, 1990); therefore, to understand how aging affects the perception of surface curvature is to understand how older adults perceive a fundamental aspect of object shape.

Norman et al. (2013) evaluated the abilities of younger and older adults to discriminate simple curved objects with convex and concave surfaces. These authors found that older adults needed much larger magnitudes of curvature to reliably discriminate between convex and concave surfaces when exploration was prohibited after making contact with a stimulus object. However, when participants could sweep their index finger back and forth across the surfaces, there was no effect of age. Other studies of aging and shape perception have also demonstrated that older adults tend to perform as well as younger adults when they are allowed to explore object surfaces using their hands and fingers (Norman et al., 2006, 2011). Therefore, it seems that aging does not affect object shape perception in situations where the handling of objects is unrestricted.

For tasks not involving shape, our sense of touch is not so well preserved with increases in age. For example, the ability to detect fine spatial patterns on the fingerpad decreases by about one percent per year across the lifespan (Legge, Madison, Vaughn, Cheong, & Miller, 2008; Stevens & Patterson, 1995). Plausible explanations for this finding of reduced tactile acuity have implicated age-related degeneration of tactile receptor populations (Cauna, 1965), reduced blood flow in cutaneous tissue (Stevens, Alvarez-Reeves, Dipietro, Mack, & Green, 2003), and changes to the physical structure of the skin (Vega-Bermudez & Johnson, 2004), but none of these potential explanations have been experimentally supported. While the age-related decline of tactile acuity is a topic that clearly warrants further investigation, it should be noted that previous studies have not found any strong relation between tactile acuity and the ability to perceive the shape of objects (Norman et al., 2006, 2011, 2013).

Gibson (1962) was one of the first to distinguish between *active* and *passive* interactions that contribute to our tactual experience of objects and surfaces. When something passively touches the skin, for example, this stimulation tends to elicit brief and local patterns of tactile receptor activation. In this case, we may feel the tactile sensations that occur when an object brushes against our skin, but yet not know (or perceive) what that object is. However, when we use our hands and fingers to explore a solid object, the abundant spatiotemporal tactile information generated by these exploratory movements allows us to easily perceive its shape (Gibson, 1966). As stated in Moberg (1958, p. 454), the hand can “see even when the subject has his eyes closed”; that is to say, according to these researchers (Gibson, Moberg), the perception of object shape obtained from active manipulation is effectively equivalent to that obtained from vision. This sense of active touch is called “haptics” (e.g., Gibson, 1966, p. 97–99).

In studies comparing the effectiveness of active and passive touch in shape perception tasks, it is often found that performance is generally improved when active touch is employed (e.g., Kappers & Koenderink, 1996; Lederman & Klatzky, 1987; Norman et al., 2012). Even so, our understanding of how active touch contributes to this enhancement remains incomplete. A few early studies attempted to dissociate the sensory cues available during active touch using a procedure wherein geometric “cookie-cutter” forms were applied to a participants’ palm and then systematically rotated while maintaining contact with the skin (e.g., Cronin, 1977; Gibson, 1962; Heller & Myers, 1983). Continuously changing the orientation of the stimulus objects was intended to provide dynamic tactile information about their shape in the absence of any additional information gained from active manipulation.

In Gibson’s experiments (1962), on each trial participants felt one of six different cookie-cutters from behind a curtain, and then identified its shape by referring to a drawing that depicted all of the possible stimuli. On average, when the stimuli were passively applied (i.e., without changing their orientation), participants correctly matched the shape of the felt object to its drawn image on 49 percent of the trials. When stimuli were rotated in the palm of the hand, however, this ‘passive-dynamic’ method of application increased average matching accuracy to 72 percent correct. Despite the significant improvement in performance that occurred with this additional dynamic tactile stimulation, active touch was still far superior; when participants actively felt the edges of the stimuli using the fingers of one hand, average matching accuracy was 95 percent correct. According to Gibson, active touch is better able to interpret the patterns of stimulation to form our perceptions of objects because exploratory movements are – by their very nature – purposive and self-directed (Gibson, 1962).

Two later studies (Cronin, 1977; Heller & Myers, 1983) that deserve consideration used stimuli and procedures analogous to those used in Gibson's (1962) shape-matching experiments, but each study obtained quite different results. In Cronin's study, active touch afforded no advantage over passive-dynamic application, and yet both of these conditions yielded performance that was superior to that obtained for standard passive application. In contrast to the results of both Cronin (1977) and Gibson (1962), Heller and Myers (1983) found that active touch was superior to the passive conditions, but there was no significant difference between the performances obtained for standard passive application and passive-dynamic application. In the context of these conflicting findings, it should be noted that the procedures used for passive-dynamic application in these two later studies might have differentially affected performance. Additionally, unlike Gibson's (1962) procedure for active touch, participants in both of these later studies could only use the palm of their hand to actively feel the stimuli and were not permitted to use their fingers. Notice that restricting active touch in this way defeats the purpose of the exploratory movements emphasized by Gibson (1962). Taken together, these early attempts to assess the role of dynamic tactile information demonstrate the importance of applying stimulation in a consistent manner.

The past two decades have seen rapid development of technologies that enhance our interactions with machines in real and virtual environments by providing tactile and haptic feedback to the user (for a review, see Gallace & Spence, 2014). To be used effectively by human operators, these technologies must be able to produce the patterns of stimulation that our nervous system is tuned to detect, and for this reason, it has become increasingly necessary to study the sensory cues that are relied upon to perceive and interact with objects. In a recent study by Wijntjes, Sato, Hayward, and Kappers (2009), a device was constructed that could isolate and reproduce the tactile patterns of stimulation that typically occur when a finger sweeps across the surface of a simple curved object. To use the device, participants moved a small metal plate from side to side with their index finger. During this translational motion, a sensor tracked the position of the plate and a computer then adjusted its height and orientation in real time. The results of this study revealed that curvature discrimination performance was identical across all conditions in which the orientation of the plate was adjusted during active movement. This finding agrees with a number of previous studies showing that curvature discrimination performance is primarily dependent on one's ability to detect changes in surface orientation across different local regions of an object (Pont, Kappers, & Koenderink, 1996, 1997, 1998, 1999). Interestingly, when only the height of the plate was adjusted, participants needed about four times the amount of simulated curvature to reliably discriminate virtual surfaces (Wijntjes et al., 2009). Therefore, at least for curvature discrimination, it seems that the changes in finger height that accompany active movement contribute little to no useful information when discriminating curvature magnitudes smaller than ~2.5/m.

Dostmohamed and Hayward (2005) similarly evaluated the discrimination of virtual curvature using a device that allowed dynamic adjustment of the orientation of a metal plate. Active exploration of these virtual surfaces was accomplished by manually moving the plate from side to side, but in this study the entire device was mounted on a gantry that was easily rolled in one direction on a flat tabletop. Alternately, during "semi-active" exploration, the orientation of the plate was manipulated with a computer mouse controlled by a participant's opposite hand. Relative to active exploration, participants using semi-active exploration needed larger changes in surface orientation to reliably discriminate virtually curved surfaces. The results of this study suggest that active exploration enhances the perception of curvature.

Smith, Chapman, Donati, Fortier-Poisson, & Hayward (2009) evaluated the role of changes in finger height during both active and passive discrimination of virtually curved surfaces using a modifed version of the apparatus previously described. In the initial active touch condition, participants moved the plate from side to side with the index finger, and the height of the plate was dynamically adjusted to simulate convex, concave, or flat surfaces. Most importantly, during active movement all height adjustments made by the apparatus were recorded. In the subsequent condition evaluating passive-dynamic touch, the height adjustments recorded from the first condition were re-presented to the index finger while the participant's wrist and elbow were physically restrained. In this way, the exact pattern of stimulation that occurred during active movement was felt again without purposeful exploration. The results of this clever experiment revealed that curvature discrimination performance was superior in the *absence* of self-directed exploratory movement. These results are certainly intriguing and represent a divergence from previous conclusions about active touch.

From this review, it is clear that further investigation was needed to clarify the role of dynamic tactile stimulation in the discrimination of real (physically) curved surfaces. To date, no study has evaluated the discrimination of actual curved surfaces that move relative to a restrained finger. The present study was undertaken to fulfill this need, and to extend the findings of Norman et al. (2013) by having older adults discriminate the curvature of objects by actively and passively feeling their surfaces. As in Norman et al. (2013), participants judged whether object surfaces were concave or convex using active-dynamic touch (i.e., the participants used their index fingers to freely explore the stimuli), but in the current study a new condition was included to examine how well older adults could discriminate surface curvature from passive-dynamic touch (i.e., the hand and index finger of the participants were immobilized while the stimulus objects translated underneath). The new passive-dynamic condition produced essentially the same tactile input that occurred in the active-dynamic condition, but in the new passive condition active exploration was precluded. This arrangement allowed us to determine whether dynamic tactile input per se (independent of arm and wrist movement) is sufficient for older adults to precisely discriminate surface curvature.

Method

Apparatus

A custom-built apparatus consisting of a variable-speed electric motor and slider-crank mechanism was used to control the movement of the stimuli in the passive-dynamic condition. An Apple MacBook computer was used to randomly order the presentation of the experimental stimuli and record the participants' responses.

Experimental Stimuli

The same stimulus objects used by Pont et al. (1996, 1997, 1998, 1999), Van der Horst, Willebrands, and Kappers (2008), and Norman et al. (2013) were used in this experiment; they are machine-milled polyvinyl chloride (PVC) plastic blocks (20 cm × 2 cm × ~5 cm). The blocks featured convex or concave top surface curvatures, which ranged in magnitude from 0.2 to 2.2/m in increments of 0.4/m. Tactile gratings (JVP Domes, Stoelting, Inc.) with groove widths ranging from 6 to 0.75 mm were used to assess the participants' tactile acuity. The 12 objects used in the Moberg pick-up test of manual dexterity were the same as those used by Dellon (1981), which included the following: washer (15 mm outside diameter, 6 mm inside diameter), wing-nut (10 mm × 21 mm), nail (36 mm long, 2 mm diameter shaft), square nut (8 mm diameter), large hex nut (16 mm diameter), small hex nut (8 mm diameter), safety pin (5 mm × 28 mm), paper clip (6 mm × 30 mm), key (53 mm long, approximately 12 mm in width), dime (17 mm diameter), nickel (21 mm diameter), and flat-head screw (18 mm long, 5 mm diameter shaft).

Procedure

The basic procedures for the curvature discrimination task were similar to those used by Pont et al. (1996, 1997, 1998, 1999) and Norman et al. (2013). On every trial, participants reached underneath an opaque curtain to feel the top surface of a stimulus block until its curvature was judged to be either convex or concave. The participants performed this task in two conditions: (1) active-dynamic touch, and (2) passive-dynamic touch. In the active-dynamic touch condition, the blocks remained in a fixed position while the participants used their index finger to laterally explore their top surfaces. An aperture was used to limit exploration to the middle 10 cm extent of the blocks. Each participant performed both experimental conditions, in a counter-balanced order (i.e., the touch conditions were assessed within-subjects).

The new condition of the current study (passive-dynamic touch) employed a procedure similar to those used by van der Horst et al. (2008) and Smith et al. (2009). As in the active-dynamic condition, only the index finger contacted the blocks, but in this condition the blocks moved (i.e., translated) underneath and perpendicular to the long axis of the finger. In order to prevent active manipulation, the participants' hand, wrist, and arm were carefully restrained into a fixed position; the participants' index finger could only move up and down (to maintain contact with the block). After the participant's hand and arm were secured, the blocks then translated $\pm$ 5 cm relative to the fingertip at an average rate of 10 cm per second. Under these circumstances, the index finger passively felt the same 10 cm extent of the block that could be actively felt in the active-dynamic condition.

The testing in each condition began with a block of trials evaluating the participants' ability to discriminate convex and concave curvature magnitudes of 2.2/m. Subsequent blocks of trials evaluated discrimination of curvature magnitudes in descending increments of 0.4/m (e.g., curvature magnitudes of 2.2, 1.8, 1.4, 1.0, 0.6, and 0.2/m). The order of presentation within a block was randomly determined, and there was an equal probability of presenting a convex or concave stimulus on any given trial. For each individual participant, discrimination performances above and below a *d'* (Macmillan & Creelman, 1991) value of 1.35 were obtained; these two *d'* values were then used to calculate a threshold estimate (i.e., the curvature magnitude needed to discriminate at a *d'* value of 1.35) using linear interpolation. In order to reduce the total number of trials to a manageable number, the participants initially completed blocks of 12 trials for each curvature magnitude. If a participant made 10 or more correct judgments, testing would begin again with a new block of trials devoted to the next smaller curvature magnitude. If fewer than 10 of the 12 trials with a given curvature magnitude were discriminated correctly, however, the participants would then complete a new block of 40 trials with the *current* curvature magnitude, and all subsequent curvature magnitudes would be tested with 40-trial blocks. This procedure was utilized for all curvature magnitudes except 0.2/m (i.e., the minimum curvature magnitude of the stimulus set), which was always tested with 40-trial blocks.

Tactile acuity was also assessed for all participants. To assess acuity, tactile gratings were applied to the distal pad of the participants' index finger by the experimenter for approximately 1 second; participants judged whether the orientation of the bars of the grating was parallel or perpendicular to the long axis of the finger. The order of presentation (parallel vs. perpendicular) was randomly determined, and there was an equal probability of either stimulus orientation on any given trial. The first block of 40 trials tested each participant's ability to discriminate the orientation of a tactile grating with a large groove width (e.g., 4.0 to 6.0 mm, see Norman & Bartholomew, 2011; Norman et al., 2011, 2013). Subsequent blocks of 40 trials used gratings with smaller and smaller groove widths (e.g., 3, 2, 1.5, 1.2, & 1.0 mm) until a participant's discrimination performance dropped below a *d'* value of 1.35. Threshold estimates for tactile grating orientation discrimination were then calculated in the same manner (linear interpolation) as described for surface curvature discrimination.

Given the prevalence of arthritis among older adults in the United States (see Hootman & Helmick, 2006), it was decided to evaluate the participants' manual dexterity. The participants completed a modified version of the Moberg pick-up test to evaluate manual dexterity (Dellon, 1981; Desrosiers, Hébert, Bravo, & Dutil, 1996; Moberg, 1958). In this task, the participants picked up 12 small metal objects (see Dellon, 1981) and placed them inside a container as rapidly as possible, and the cumulative time required to place the objects in the container was recorded. People with no substantial deficits in manual dexterity can perform this task well without seeing the objects. The participants performed this picking-up task with and without vision, and the difference in the recorded times was their score on the test. This test was performed twice, with the smaller of the two scores serving as the measure of manual dexterity included in the analysis.

Participants

Fourteen older adults (seven male and seven female; *M* = 71.4 years of age, *SD* = 4.9, range = 67 to 80 years) participated in the study. All participants were recruited from south-central Kentucky. Three of the participants in the current study also participated in the previous Experiment 1 of Norman et al. (2013), in which they performed the curvature discrimination task using static-touch (i.e., they were not permitted to actively explore the stimulus blocks). All participants were naïve regarding the purpose of the current study. A financial incentive of ten dollars was offered to compensate participants for their time and effort. The study was undertaken with the approval of the Institutional Review Board of Western Kentucky University (see Appendix), and each participant signed an informed consent document prior to testing.

Results

As can be seen by examining Figures 1 and 2, curvature discrimination thresholds for the active-dynamic touch condition (*M* = .749/m, *SD* = .409) were higher than the thresholds obtained for the passive-dynamic touch condition (*M* = .414/m, *SD* = .244). This difference between the touch conditions was significant according to a non-parametric test (Wilcoxon signed ranks test, $T = 9$, $N = 13$, $p = .008$, two-tailed; see Siegel & Castellan Jr., 1988; Wilcoxon, 1945). These results indicate that when active-dynamic touch was used, 81 percent more curvature was required to reliably discriminate (i.e., with a *d'* of 1.35) convex from concave surface shapes compared to when passive-dynamic touch was used. On average, the active-dynamic curvature discrimination thresholds of the 14 older participants in the current study (*M* = .749/m, *SEM* = .109) and those of the 7 older participants in the previous study (*M* = .587/m, *SEM* = .104) were not significantly different ($t(19) = 0.9$, $p = .43$). The current results, therefore, for active-dynamic curvature discrimination were similar to those of Norman et al. (2013). Curvature discrimination thresholds obtained in the current study for each touch condition are depicted in Figure 3 along with those obtained by Norman et al. (2013) for the static touch condition.

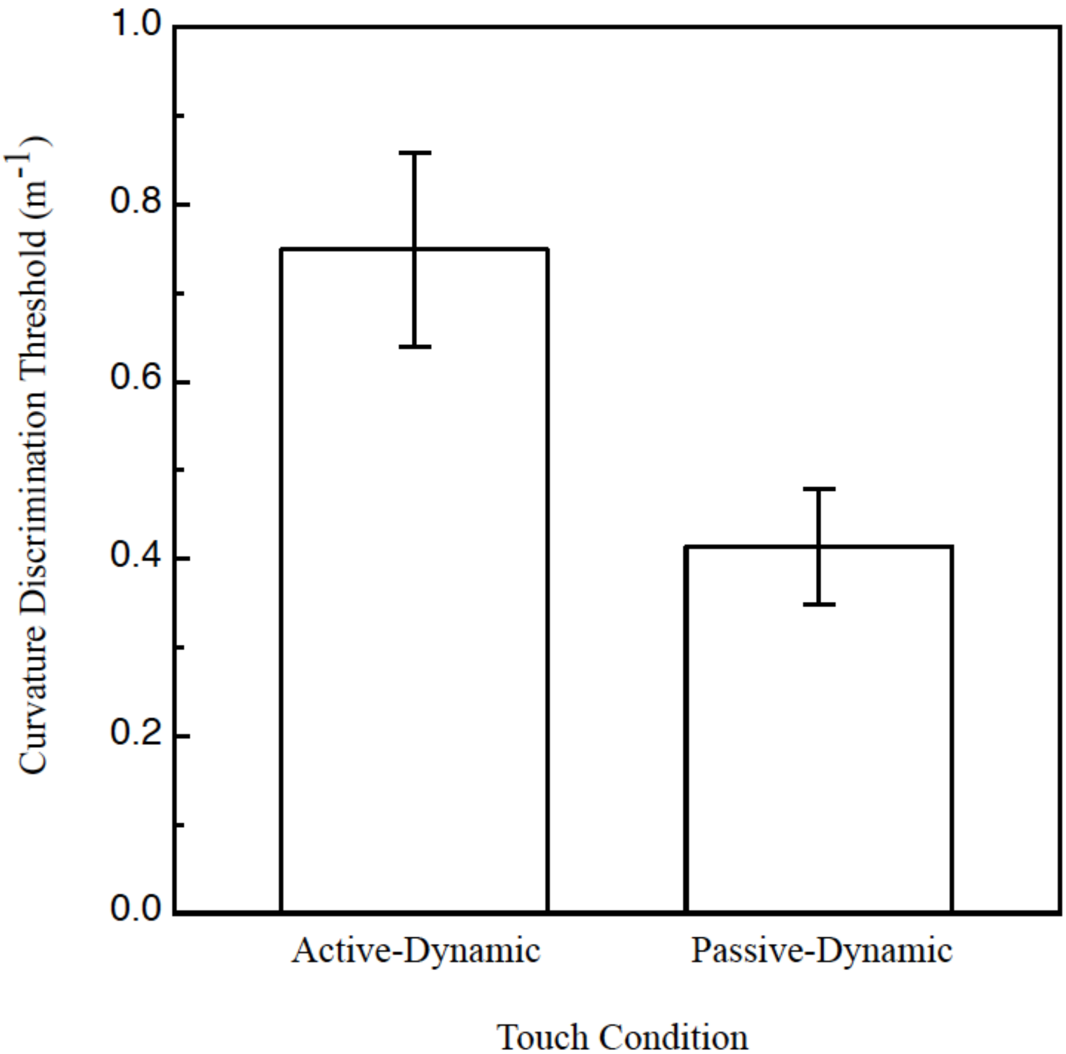

Figure 1. Average curvature discrimination thresholds are plotted separately for each touch condition. Error bars represent ± 1 *SE*.

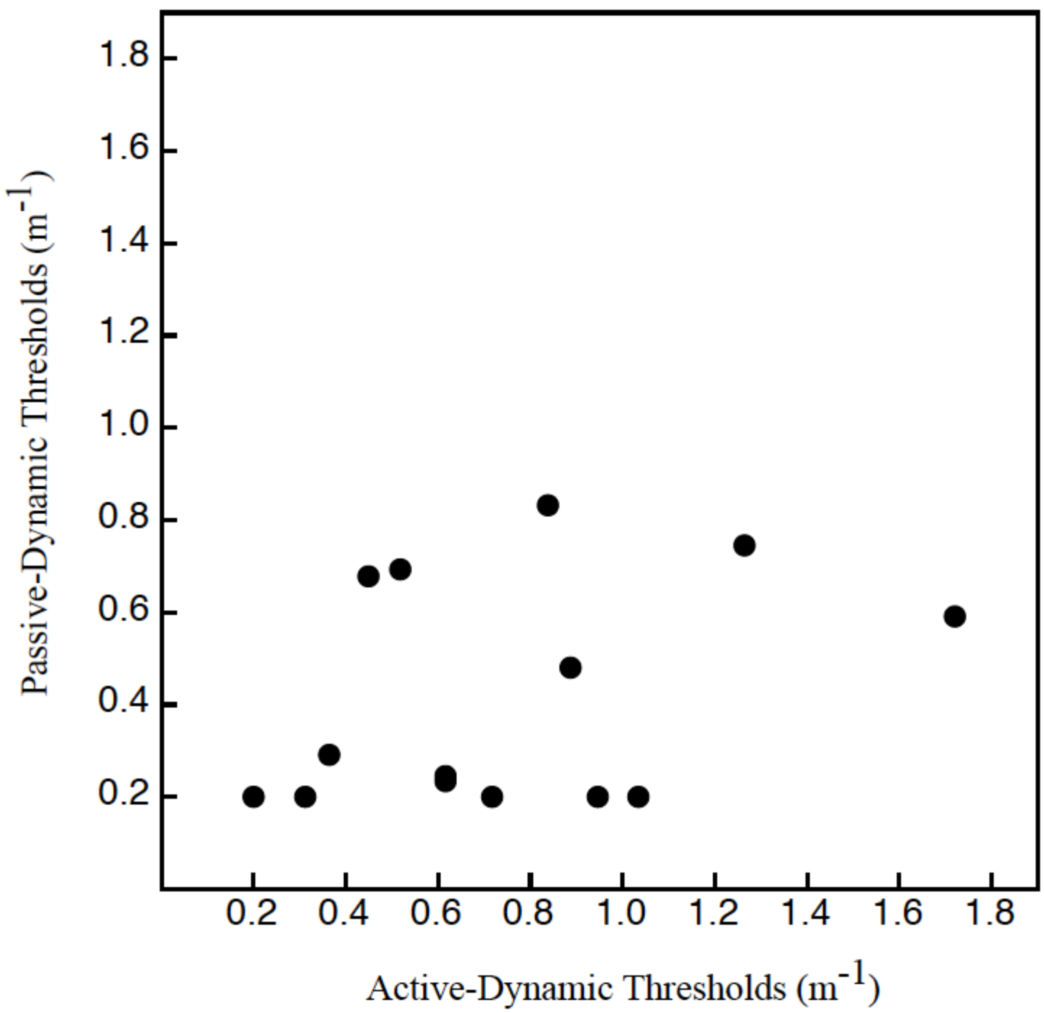

Figure 2. Passive-dynamic curvature discrimination thresholds are plotted as a function of the active-dynamic curvature discrimination thresholds for each participant.

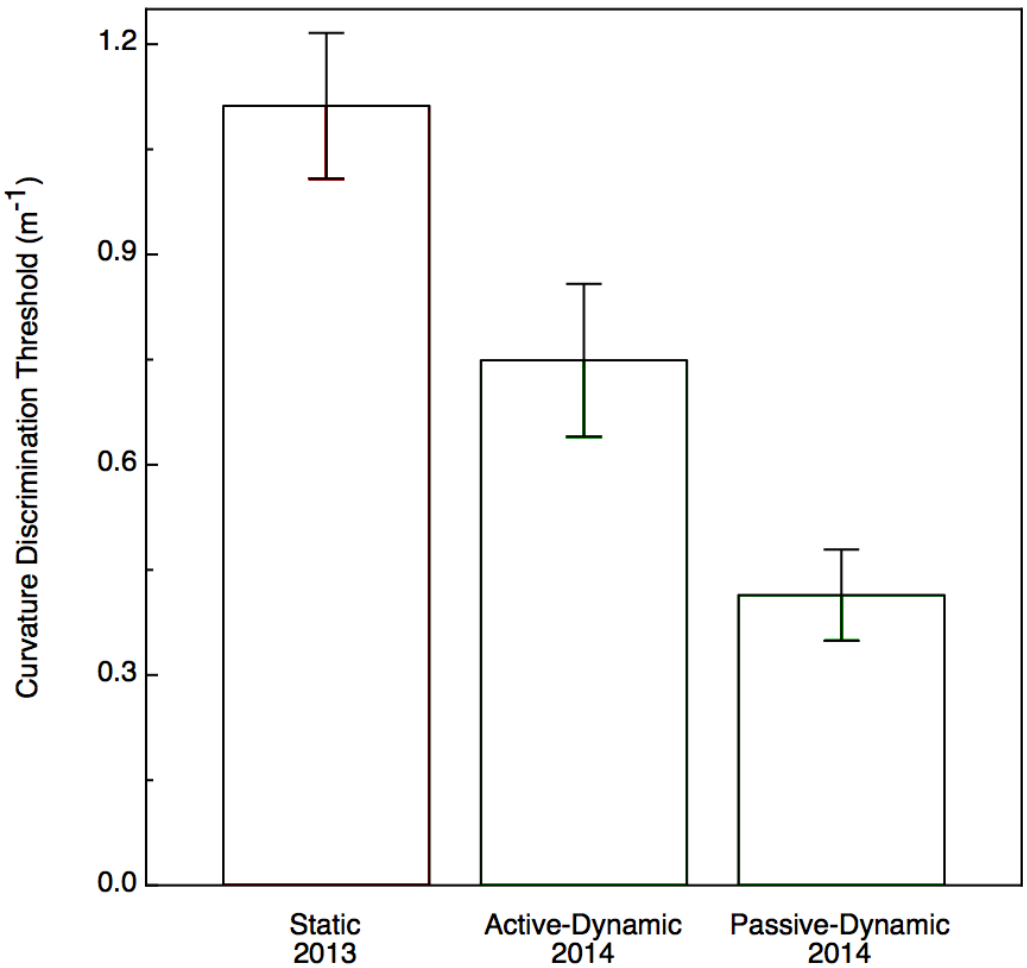

Figure 3. Average curvature discrimination thresholds obtained in the current study plotted with the static curvature discrimination thresholds obtained by Norman et al. (2013). Error bars represent ± 1 *SE*.

To evaluate the potential role of tactile acuity in curvature discrimination performance, the participants' grating orientation discrimination thresholds were separately correlated with their active-dynamic ($r = -.025$, $r^2 = .0006$, $p = .93$) and passive-dynamic ($r = -.08$, $r^2 = .0064$, $p = .79$) curvature discrimination thresholds. As in Norman et al. (2013), tactile acuity was unrelated to curvature discrimination performance. Performance measures for the Moberg pick-up test of manual dexterity were also separately correlated with the participants' active-dynamic ($r = .43$, $r^2 = .18$, p

= .13) and passive-dynamic (r = .19, r^2 = .036, p = .52) curvature discrimination thresholds. Although the correlations between manual dexterity and surface curvature discrimination performance were numerically higher than those between tactile acuity and curvature discrimination performance, they were not statistically significant.

Discussion

In everyday situations, we can obtain information about felt objects either by moving our hands and fingers to actively explore the surface of an object, or by passively feeling a moving object contacting our skin. As in Norman et al. (2013), the present study has shown that older adults can discriminate curvature by actively exploring an object's surface with their finger, but interestingly, these participants performed better when movements of their hand, wrist, and arm were restricted. The present study is therefore the first to replicate the findings of Smith et al. (2009) with real objects. Contrary to earlier interpretations (e.g., Dostmohamed & Hayward, 2005; Lederman & Klatzky, 1987; Loomis & Lederman, 1986), the current results demonstrate that accurate discrimination of shape does not necessarily require active exploration. Furthermore, it is now evident that dynamic tactile input generated by relative movement of object and finger is an excellent source of information about surface curvature. The extremely small curvature magnitudes that were reliably discriminated by older adults in the current passive-dynamic condition (M = .414/m) are far below the thresholds observed for discrimination of virtual surfaces defined by changes in vertical height (see Wijntjes et al., 2009). Consequently, it is almost certain that dynamic tactile input was the only source of information available during near-threshold trials. Taken together, these results show very clearly that the good dynamic curvature discrimination performance of older participants in the study by Norman et al. (2013) was due to the availability of dynamic tactile stimulation, and not to active exploratory touch *per se*.

A few early studies attempted to test shape perception under conditions in which dynamic tactile input was dissociated from active manipulation (Cronin, 1977; Gibson, 1962; Heller & Myers, 1983); as was made clear in the introduction, they did not obtain consistent results. It is important to consider that in these previous studies, the stimuli were passively applied and then dynamically reoriented by the experimenter. The patterns of dynamic tactile stimulation felt by participants, therefore, must have varied with the movements of the individual experimenter who applied each stimulus. In contrast, the procedures used for the passive-dynamic curvature discrimination task in the current study assured that the participants' finger was stimulated in a consistent way each time. It seems reasonable to conclude that the lack of agreement between these previous studies and the current study is related to how the stimuli were moved relative to the skin. Although the results of the current study certainly help to clarify these past findings, it is also clear that the geometric "cookie-cutter" forms felt by the participants in the early studies are very different from the simple curved objects (circular arcs) used in the current experiment.

Previous research has consistently shown that for both static and dynamic touch, curvature discrimination performance is primarily dependent on one's ability to detect changes in surface orientation across different local regions of an object (Dostmohamed & Hayward, 2005; Pont et al., 1996, 1997, 1998, 1999; Wijntjes et al., 2009). Given that the discrimination thresholds obtained for passive-dynamic touch were significantly lower than those obtained for active-dynamic touch, local surface orientation was apparently better detected from passive-dynamic stimulation of the fingerpad (when the hand, wrist, and arm were restrained). Because curvature discrimination performance was much improved when arm and hand movements were eliminated, the current results also suggest that such movements may be detrimental when trying to detect very small differences in surface curvature.

Phillip Davidson first advanced the notion that active movement might actually interfere with haptic curvature perception in his 1972 study investigating exploration methods used by blind and sighted people to perceive curved surfaces. He noted that the method of exploration that led to the poorest performance was to use one or two fingers to sweep horizontally across the surface, which closely resembles the method of exploration used in the current study (and others) for active curvature discrimination (Norman et al., 2013; Pont et al., 1998, 1999). Davidson (1972) specifically suggested that interference might have occurred when the path of the moving arm coincided with the curvature of the felt surface; that is, when the movement of the arm was most likely to "obscure" the curvature of the stimulus (p. 52). Further support for Davidson's idea that arm movements may interfere with haptic curvature discrimination can be found in an article published by Gordon and Morison (1982). Based on their analysis of stimuli used in three earlier studies of haptic curvature perception, Gordon and Morison concluded that "the perception of curvature is most sensitive when scanning movements are small and do not involve movement of the forearm" (p. 450).

While passive-dynamic touch produced the best performance in the current study, one can see from an examination of Figure 3 that active-dynamic performance was still far superior to the static performance obtained by Norman et al. (2013). In light of the reviewed literature, it would seem that the paucity of dynamic tactile input during static touch made the task much more challenging, and that performance markedly improved (i.e., thresholds decreased) during active touch because dynamic tactile input was abundantly available. It is also apparent, however, that an additional consequence of active touch was interference generated by exploratory movements. Accordingly, when active exploration was precluded in the passive-dynamic condition, performance improved still further. The most parsimonious interpretation of these results, therefore, is to conclude that precise curvature discrimination depends on dynamic tactile input that is unhindered by active exploratory movement.

As noted in the introduction, it has often been found that performance is generally improved when active touch is employed (e.g., Dostmohamed & Hayward, 2005; Kappers & Koenderink, 1996; Lederman & Klatzky, 1987; Norman et al., 2012). These findings have been interpreted to demonstrate the superior capacity of active touch to obtain information about object shape, but more recently, this has been called into question. For example, according to van der Horst et al. (2008), evidence that passive-dynamic tactile stimulation to the finger of one hand can bias curvature discrimination by the other hand indicates that self-generated movement is not required to generate a high level representation of curvature in the brain. It is also notable that much evidence has accumulated revealing that sensory inputs are inhibited during exploratory movements (e.g., Chapman, 1994; Chapman, Jiang, & Lamarre, 1988; Seki, Perlmutter, & Fetz, 2003).

Exactly how movements of the hand, wrist, and arm might interfere with the task of discriminating small differences in the curvature of surfaces is not presently known;

however, some of the participants in the active-dynamic condition made observations during the task that have been both helpful and informative. For certain active-dynamic trials utilizing curvature magnitudes approaching their individual thresholds, these participants sometimes stated that the current stimulus did not feel like a perfectly convex or concave surface. Instead, it felt both convex *and* concave. That is, on some (but not all) trials in the active-dynamic condition, the stimulus was apparently misperceived as a sinusoidal-like surface. If in fact our participants were experiencing a haptic illusion in the active-dynamic condition, this misperception would obviously make curvature discrimination more difficult. The presence of this illusion could potentially account for the difference in thresholds obtained for the active-dynamic and passive-dynamic conditions. In order to verify these reports, the author and three others performed the curvature discrimination task, and in each case the same illusion described by our participants was sometimes observed during active-dynamic, but not passive-dynamic touch.

There is an extensive literature documenting a great variety of tactile and haptic illusions that have arisen in laboratory experiments (for a review, see Lederman & Jones, 2011). Especially relevant to the current study are those haptic illusions in which vertical lengths are consistently overestimated relative to horizontal lengths of the same extent. This vertical-horizontal illusion has been demonstrated with curved stimuli, and its robustness is known to depend on radial scanning motions with a single hand positioned at the body midline (Heller et al., 2008, 2010). In Experiment 7 of Heller et al. (2008), participants used the index finger of one hand to trace the top surfaces of circular raised lines and were asked to draw their perceived shapes (see their Figure 6). Most notably, several of these reproductions closely resemble the sinusoidal shapes reported by our participants during active-dynamic curvature discrimination.

In summary, the current study provides compelling evidence that for older adults, the reliable discrimination of convex and concave surfaces depends primarily upon information that occurs during dynamic tactile stimulation. Accurate curvature discrimination (i.e., low thresholds) does not require active exploratory movements. The best possible performance occurs for situations where curved surfaces translate underneath a *restrained* finger.

References

Cauna, N. (1965). The effects of aging on the receptor organs of the human dermis. In W. Montagna (Ed.), *Advances in biology of skin* (Vol. 6., pp. 63–93). Elmsford, NY: Permagon. doi:10.1001/archderm.1966.01600270135033

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. doi:10.1139/y94-080

Chapman, C. E., Jiang, W., & Lamarre, Y. (1988). Modulation of lemniscal input during conditioned arm movements in the monkey. *Experimental Brain Research*, *72*, 316–334. doi:10.1007/BF00250254

Cronin, V. (1977). Active and passive touch at four age levels. *Developmental Psychology*, *13*, 253–256. doi:10.1037/0012-1649.13.3.253

Davidson, P. W. (1972). Haptic judgments of curvature by blind and sighted humans. *Journal of Experimental Psychology*, *93*, 43–55. doi:10.1037/h0032632

Dellon, A. L. (1981). It's academic but not functional. In A. L. Dellon (Ed.), *Evaluation of sensibility and re-education of sensation in the hand* (pp. 95–113). Baltimore, MD: Williams & Wilkins.

Desrosiers, J., Hébert, R., Bravo, G., & Dutil, E. (1996). Hand sensibility of healthy older people. *Journal of the American Geriatrics Society*, *44*, 974–978.

Dostmohamed, H., & Hayward, V. (2005). Trajectory of contact region on the fingerpad gives the illusion of haptic shape. *Experimental Brain Research*, *164*, 387–394. doi:10.1007/s00221-005-2262-5

Gallace, A., & Spence, C. (2014). Technologies of touch. In *In Touch with the future: The sense of touch from cognitive neuroscience to virtual reality* (1st ed., pp. 201–228). New York: Oxford University Press. doi:10.1093/acprof:oso/9780199644469.003.0009

Gibson, J. J. (1962). Observations on active touch. *Psychological Review*, *69*, 477–491. doi:10.1037/h0046962

Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston, MA: Houghton Mifflin.

Gordon, I. E., & Morison, V. (1982). The haptic perception of curvature. *Perception & Psychophysics*, *31*, 446–450. doi:10.3758/BF03204854

Grunwald, M., & John, M. (2008). German pioneers of research into human haptic perception. In M. Grunwald (Ed.), *Human haptic perception: Basics and applications* (pp. 15–39). Basel: Birkhäuser Verlag. doi:10.1007/978-3-7643-7612-3_2

Heller, M. A., Kappers, A. M. L., McCarthy, M., Clark, A., Riddle, T., Fulkerson, E., … Russler, K. (2008). The effects of curvature on haptic judgements of extent in blind and sighted people. *Perception*, *37*, 816–840. doi:10.1068/p5497

Heller, M. A., & Myers, D. S. (1983). Active and passive tactual recognition of form. *The Journal of General Psychology*, *108*, 225–229. doi:10.1080/00221309.1983.9711496

Heller, M. A., Walk, A. D. M., Schnarr, R., Kibble, S., Litwiller, B., & Ambuehl, C. (2010). Attenuating the haptic horizontal-vertical curvature illusion. *Attention, Perception, & Psychophysics*, *72*, 1626–1641. doi:10.3758/APP.72.6.1626

Hootman, J. M., & Helmick, C. G. (2006). Projections of US prevalence of arthritis and associated activity limitations. *Arthritis and Rheumatism*, *54*, 226–229. doi:10.1002/art.21562

Kappers, A. M. L., & Koenderink, J. J. (1996). Haptic unilateral and bilateral discrimination of curved surfaces. *Perception, 25*, 739–749. doi:10.1068/p250739

Klatzky, R. L., & Lederman, S. J. (2003). Touch. In A. F. Healy & R. W. Proctor (Eds.), *Handbook of psychology: Experimental psychology* (Vol. 4., pp. 147–176). Hoboken, NJ: Wiley.

Koenderink, J. J. (1990). *Solid shape*. Cambridge, MA: MIT Press.

Lederman, S. J., & Jones, L. A. (2011). Tactile and haptic illusions. *IEEE Transactions on Haptics*, *4*, 273–294. doi:10.1109/TOH.2011.2

Lederman, S. J., & Klatzky, R. L. (1987). Hand movements: A window into haptic object recognition. *Cognitive Psychology*, *19*, 342–368. doi:10.1016/0010-0285(87)90008-9

Legge, G. E., Madison, C., Vaughn, B. N., Cheong, A. M. Y., & Miller, J. C. (2008). Retention of high tactile acuity throughout the life span in blindness. *Perception & Psychophysics*, *70*, 1471–1488. doi:10.3758/PP.70.8.1471

Loomis, J. M., & Lederman, S. J. (1986). Tactual perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Cognitive processes and performance* (Vol. 2, pp. 1–41). New York, NY: Wiley.

Macmillan, N. A., & Creelman, C. D. (1991). *Detection theory: A user's guide*. New York: Cambridge University Press.

Moberg, E. (1958). Objective methods for determining the functional value of sensibility in the hand. *The Journal of Bone and Joint Surgery B*, *40*, 454–476.

Norman, J. F., & Bartholomew, A. N. (2011). Blindness enhances tactile acuity and haptic 3-D shape discrimination. *Attention, Perception & Psychophysics*, *73*, 2323–2331. doi:10.3758/s13414-011-0160-4

Norman, J. F., Crabtree, C. E., Norman, H. F., Moncrief, B. K., Herrmann, M., & Kapley, N. (2006). Aging and the visual, haptic, and cross-modal perception of natural object shape. *Perception*, *35*, 1383–1395. doi:10.1068/p5504

Norman, J. F., Kappers, A. M. L., Beers, A. M., Scott, A. K., Norman, H. F., & Koenderink, J. J. (2011). Aging and the haptic perception of 3D surface shape. *Attention, Perception & Psychophysics*, *73*, 908–918. doi:10.3758/s13414-010-0053-y

Norman, J. F., Kappers, A. M. L., Cheeseman, J. R., Ronning, C., Thomason, K. E., Baxter, M. W., Calloway, A. B., Lamirande, D. N. (2013). Aging and curvature discrimination from static and dynamic touch. *PloS One*, *8*, e68577. doi:10.1371/journal.pone.0068577

Norman, J. F., Phillips, F., Holmin, J. S., Norman, H. F., Beers, A. M., Boswell, A. M., Cheeseman, J. R., Stethen, A. G., Ronning, C. (2012). Solid shape discrimination from vision and haptics: Natural objects (Capsicum annuum) and Gibson's "feelies." *Experimental Brain Research*, *222*, 321–332. doi:10.1007/s00221-012-3220-7

Pont, S. C., Kappers, A. M. L., & Koenderink, J. J. (1996). The influence of stimulus length on static haptic curvature discrimination. In A. M. L. Kappers, C. J. Overbeeke, G. J. F. Smets, & P. J. Stappers (Eds.), *Studies in ecological psychology* (pp. 69–72). Delft: Delft University Press.

Pont, S. C., Kappers, A. M. L., & Koenderink, J. J. (1997). Haptic curvature discrimination at several regions of the hand. *Perception & Psychophysics*, *59*, 1225–1240. doi:10.3758/BF03214210

Pont, S. C., Kappers, A. M. L., & Koenderink, J. J. (1998). The influence of stimulus tilt on haptic curvature matching and discrimination by dynamic touch. *Perception*, *27*, 869–880. doi:10.1068/p270869

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. doi:10.3758/BF03206903

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. doi:10.1038/nn1154

Siegel, S., & Castellan Jr., N. J. (1988). *Non-parametric statistics for the behavioural sciences* (2nd ed.). New York: McGraw-Hill.

Smith, A. M., Chapman, C. E., Donati, F., Fortier-Poisson, P., & Hayward, V. (2009). Perception of simulated local shapes using active and passive touch. *Journal of Neurophysiology*, *102*, 3519–3529. doi:10.1152/jn.00043.2009

Stevens, J. C., Alvarez-Reeves, M., Dipietro, L., Mack, G. W., & Green, B. G. (2003). Decline of tactile acuity in aging: A study of body site, blood flow, and lifetime habits of smoking and physical activity. *Somatosensory & Motor Research*, *20*, 271–279. doi:10.1080/08990220310001622997

Stevens, J. C., & Patterson, M. Q. (1995). Dimensions of spatial acuity in the touch sense: Changes over the life span. *Somatosensory & Motor Research*, *12*, 29–47. doi:10.3109/08990229509063140

van der Horst, B. J., Willebrands, W. P., & Kappers, A. M. L. (2008). Transfer of the curvature aftereffect in dynamic touch. *Neuropsychologia*, *46*, 2966–2972. doi:10.1016/j.neuropsychologia.2008.06.003

Vega-Bermudez, F., & Johnson, K. O. (2004). Fingertip skin conformance accounts, in part, for differences in tactile spatial acuity in young subjects, but not for the decline in spatial acuity with aging. *Perception & Psychophysics*, *66*, 60–67. doi:10.3758/BF03194861

Wijntjes, M. W. A., Sato, A., Hayward, V., & Kappers, A. M. L. (2009). Local surface orientation dominates haptic curvature discrimination. *IEEE Transactions on Haptics*, *2*, 94–102. doi:10.1109/TOH.2009.1

Wilcoxon, F. (1945). Individual comparisons by ranking methods. *Biometrics Bulletin*, *1*, 80–83. doi:10.2307/3001968

Appendix

INSTITUTIONAL REVIEW BOARD
OFFICE OF RESEARCH INTEGRITY

DATE:	June 11, 2014
TO:	Jacob Cheeseman
FROM:	Western Kentucky University (WKU) IRB
PROJECT TITLE:	[619544-1] Aging and the tactile perception of three-dimensional shape/ structure
REFERENCE #:	IRB 14-479
SUBMISSION TYPE:	New Project
ACTION:	APPROVED
APPROVAL DATE:	June 11, 2014
EXPIRATION DATE:	June 11, 2015
REVIEW TYPE:	Expedited Review

Thank you for your submission of New Project materials for this project. The Western Kentucky University (WKU) IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a project design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Expedited Review based on the applicable federal regulation.

Please remember that informed consent is a process beginning with a description of the project and insurance of participant understanding followed by a *signed* consent form. Informed consent must continue throughout the project via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the consent document.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All UNANTICIPATED PROBLEMS involving risks to subjects or others and SERIOUS and UNEXPECTED adverse events must be reported promptly to this office. Please use the appropriate reporting forms for this procedure. All FDA and sponsor reporting requirements should also be followed.

All NON-COMPLIANCE issues or COMPLAINTS regarding this project must be reported promptly to this office.

This project has been determined to be a Minimal Risk project. Based on the risks, this project requires continuing review by this committee on an annual basis. Please use the appropriate forms for this procedure. Your documentation for continuing review must be received with sufficient time for review and continued approval before the expiration date of June 11, 2015.

Please note that all research records must be retained for a minimum of three years after the completion of the project.

If you have any questions, please contact Paul Mooney at (270) 745-2129 or irb@wku.edu. Please include your project title and reference number in all correspondence with this committee.