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# Unimanual and Bimanual Haptic Shape Discrimination

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# UNIMANUAL AND BIMANUAL HAPTIC SHAPE DISCRIMINATION

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In the current study 24 younger adults and 24 older adults haptically discriminated natural 3-D shapes (bell peppers, *Capsicum annuum*) using unimanual (one hand used to explore two objects) and bimanual (both hands used, but each hand explored separate objects) successive exploration. Haptic exploration using just one hand requires somatosensory processing in only one cerebral hemisphere (the hemisphere contralateral to the hand being used), while bimanual haptic exploration requires somatosensory processing in both hemispheres. Previous studies related to curvature/shape perception have found either an advantage for unimanual exploration over bimanual exploration or no difference between the two conditions. In contrast to the results of previous studies that found an advantage for unimanual exploration, the current study found that unimanual and bimanual haptic exploration produced equivalent shape discrimination performance. The current results also document a significant effect of age on haptic shape discrimination: older adults exhibited moderately reduced shape discrimination performance compared to younger adults, regardless of the mode of exploration (unimanual or bimanual).

## Introduction

Most animals possess a body configuration that exhibits an external radial or bilateral symmetry. Symmetry refers to the organization of the parts of an organism, and bilateral specifies that the two sides (left and right) are mirror images of each other (Alters, 2000). Although this symmetry is not as prevalent in internal organs, external features such as limbs exhibit a high degree of symmetry. It is thought that animals evolved bilaterally symmetric limbs to achieve the advantages of balanced locomotion (Allard & Tabin, 2009; Corballis, 1989). In humans, this balanced locomotion is the reason that we are able to walk upright on our two legs. Additionally, it has been hypothesized that this bipedal locomotion allowed early primates and hominids the freedom to use their hands and arms to manipulate and identify objects (Dominy, Ross, & Smith, 2004). In addition to legs, humans also display bilateral symmetry in our arms, hands, and fingers. If bilateral symmetry of legs and feet evolved to provide balanced locomotion, what potential benefit to survival could two hands provide? Being very sensitive to tactile stimuli, the hands provide the central nervous system and brain with important sensory information. Our hands are used to grasp and manipulate important environmental objects (e.g., food, tools, etc.). These objects not only are manually explored by the hands and fingers, they also stimulate sensory receptors (mechanoreceptors) within the skin of the hand and fingers. The resulting afferent tactile information enters the spinal cord through the dorsal nerve root and ascends ipsilaterally to the cuneate nucleus in the medulla (Purves et al., 2001). This nucleus projects to the ventral posterior (VP) nucleus of the thalamus in the cerebral hemisphere contralateral to the side of the body where the stimulation originally occurred. The VP neurons send their output to the primary somatosensory cortex (Brodmann's area 3b), which then distributes the sensory information to Brodmann's areas 1, and 2, as well as the secondary somatosensory cortex (Kaas, 2009), and area 5 in the posterior parietal cortex (Jones & Powell, 1969). Along this pathway, receptive field characteristics of neurons change considerably. Neurons in area 3b that are activated by tactile input from the hand only receive excitatory input from the contralateral hand and fingers, while neurons in areas 2 and 5 have bilateral receptive fields, reflecting the fact that they receive excitatory input from both hands (not solely the contralateral hand).

Penfield and Boldrey (1937) mapped the human brain using direct electrical stimulation; they found that the primary somatosensory cortex lies in the parietal lobe of the cerebral cortex, along the Rolandic fissure (i.e., central sulcus) of the brain. From these same experiments, Penfield and Boldrey also were able to determine that tactile information from any part of the body was processed in the hemisphere contralateral to the side of the body where the stimulus originated. For example, if one were to touch an object with the right hand, the subsequent tactile information would be sent to the primary somatosensory cortex in the left hemisphere of the brain.

Because tactile information from a hand is initially processed in the contralateral cerebral hemisphere, the use of one hand to evaluate an object is fundamentally different than using both hands to perform the same task. If two objects are haptically explored by a single hand, the resulting tactile sensory information is sent to the same hemisphere of the brain; therefore, the contralateral hemisphere is primarily responsible for comparing the objects in terms of shape, texture, size, etc. When two different hands are used to compare objects (i.e., one object explored by the right hand compared with another object explored by the left hand), both hemispheres of the brain are required. Successful judgments in this latter case require that information be sent across the corpus callosum (Gazzaniga, Bogen, & Sperry, 1963), since bilateral sensitivity to touch necessitates interhemispheric (between two hemispheres) transfer of sensory information (Iwamura, 1998; Iwamura, Iriki, & Tanaka, 1994; Reed, Qi, & Kaas, 2011). Such communication is not necessary when only one hand is used.

The question of whether or not intrahemispheric processing of haptic information is superior to interhemispheric processing has been addressed in previous psychophysical research by comparing the use of one hand (unimanual manipulation) for haptic judgments to the use of two hands (bimanual manipulation). In one such study, Kappers, Koenderink, and te Pas (1994) investigated the haptic discrimination of quadric surfaces (hemispheres, cylinders, saddle-shaped surfaces, and ellipsoids). On each trial of their experiment, participants judged whether each pair of surfaces possessed the "same shape" or had "different shapes". The results of this study showed that performance was better for unimanual exploration, in which the two surfaces were examined successively with the same hand, than for bimanual examination, in which both hands were used to feel both surfaces simultaneously. In a similar study involving cylindrically curved surfaces, Kappers and Koenderink (1996) once again found a superiority of haptic discrimination performance for a one-handed condition versus a two-handed condition. No difference between right and left hand unimanual performance was found in this study as well. In contrast, a more recent study by Sanders and Kappers (2006) reported that there was no difference between unimanual and bimanual curvature discrimination performance for cylindrically curved objects.

Additional research has compared unimanual and bimanual perceptual performance in other ways. Although some of the research indicated superior performance for one-handed haptic conditions, other research demonstrated that performance was equivalent. Squeri et al. (2012) compared haptic curvature sensitivity using bimanual conditions and unimanual conditions. They found that unimanual thresholds were not lower than bimanual thresholds. Another study by Nefs, Kappers, and Koenderink (2005), comparing tactile grating spatial frequency discrimination between unimanual and bimanual conditions, found that thresholds were lower for conditions where one hand was used to make discriminations than for conditions where two different hands were used.

The effectiveness of two hands versus one hand to perform haptic discrimination has been measured using simple curved objects (Kappers & Koenderink, 1996; Kappers et al., 1994; Sanders & Kappers, 2006; Squeri et al., 2012), tactile gratings (Nefs et al., 2005), and three-dimensional (3-D) nonsense shapes composed of several adjacently-attached metal cubes (Fagot, Lacreuse,

& Vauclair, 1994). In this context, it is surprising that naturally-shaped objects have never been used; after all, the human somatosensory system evolved to perceive natural objects. Would the results of these previous studies generalize to the perception of natural object shape?

In addition to ecological validity, it is also important to consider whether increases in age differentially affect the unimanual and bimanual perception of object shape. Aging has been shown to affect perceptual abilities negatively in a variety of different tasks involving touch and kinesthesis (Norman, Norman, Swindle, Jennings, & Bartholomew, 2009; Stevens, 1992), and haptics (Cheeseman, Norman, & Kappers, 2016; Kleinman & Brodzinsky, 1978; Norman, et al., 2016). In contrast, tactile shape perception for 2-Dimensional (Norman et al., 2013) and 3-Dimensional (Norman et al., 2006, 2015) objects appears to remain relatively unaffected by age. For example, Norman et al. (2015) investigated the effect of aging on haptic and visual solid (3-D) shape recognition and found that older adults (adults 61 years of age or older) performed just as well as younger adults (adults between 19 and 42 years of age) on an old/new object recognition task, even after a 20 minute delay between the study and testing session. A potential effect of age on perceptual ability is only part of what must be considered when assessing unimanual and bimanual shape perception; a potential effect of age on intra- and interhemispheric communication of tactile/haptic information must also be taken into account.

Aging has been shown to affect both intrahemispheric and interhemispheric processing. Moes, Jeeves, and Cook (1995) evaluated intrahemispheric and interhemispheric transfer using a bimanual coordination task, which involved drawing lines at various angles using an Etch-a-Sketch™. To create lines at various angles, participants controlled a cursor using two dials (the right dial moved the cursor vertically while the left moved it horizontally). Drawing purely vertical (90°) or horizontal (0°) lines required the use of only one dial (and consequently only one hand), but both dials (and both hands) were required to create more diagonal lines at various angles (67.5°, 45°, 22.5°, 157.5°, 135°, 112.5°). The participants used either their left or right hand (counterbalanced across trials) to control the appropriate dial (left or right) in the unimanual conditions. In the two hand conditions, trials were counterbalanced so that the right hand did not always control the right dial and the left hand did not always control the left dial. The requirement of using two hands to move both dials simultaneously (sometimes at different speeds and in opposite directions, depending on the angle of the line) to create diagonal lines necessitated the use of both cerebral hemispheres and therefore required interhemispheric communication. Moes et al. found that older adults were significantly slower and less accurate on both unimanual and bimanual trials than younger adults, which was taken to be indicative of less efficient intra- and interhemispheric information transfer, respectively. Other studies have investigated the effect of aging on intrahemispheric processing by assessing white-matter integrity using Diffusion tensor imaging (DTI) (Hsu et al., 2008; Voineskos et al., 2012). The results of these DTI studies show that aging negatively impacts intrahemispheric white-matter connectivity by reducing the integrity of myelinated fibers.

Interhemispheric connectivity appears to be compromised with age as well, as demonstrated by poorer performance (in comparison with younger adults) on tasks such as cross-hand finger localization (Beaton, Hugdahl, & Ray, 2000), bimanual movement control (Moes et al., 1995), and increased interhemispheric transfer time (IHTT), as measured by the crossed-uncrossed difference (CUD) on visuomotor tasks (Bellis & Wilber, 2001; Jeeves & Moes, 1996; Reuter-Lorenz & Stanczak, 2000). CUD measures IHTT by subtracting the simple reaction time to a visual stimulus ipsilateral to the hand making the motor response (uncrossed) from the simple reaction time to a visual stimulus contralateral to the hand making the motor response (crossed). Collectively, these findings indicate that, for behaviors that require the two hemispheres of the brain to communicate, age affects both the quality and the efficiency of the information transfer. This deficit in communication between hemispheres is further supported by several DTI studies (Hsu et al, 2008; Sullivan & Pfefferbaum, 2006; Voineskos et al., 2012), which found an age-related decline in interhemispheric white-matter tract integrity. When considered together, it is reasonable to believe that the age-related decline in interhemispheric white-matter integrity results in deficits in behavioral tasks requiring between-hemisphere communication.

Although previous studies have sought to determine whether one mode of hemispheric processing is superior to the other by comparing haptic discrimination of various objects (Fagot et al., 1994; Kappers & Koenderink, 1996; Kappers et al., 1994; Nefs et al., 2005; Sanders & Kappers, 2006; Squeri et al., 2012) and have typically found an advantage for intrahemispheric processing, no study to date has investigated intra- and interhemispheric processing using ecologically valid objects. One purpose of the current study was to determine whether the results of these previous studies generalize to the perception of natural object shape. Another purpose of this study was to determine whether age would have a differential effect on intra- or interhemispheric processing of natural shape information. Given that previous research has demonstrated that older adults are able to accurately discriminate natural 3-D shape as well as younger adults (Norman et al., 2006, 2015), it is possible that older adults could perform as well as younger adults on a bimanual or unimanual natural-shape discrimination task. However, age has been shown to produce declines in both intrahemispheric and interhemispheric white-matter connectivity (Hsu et al., 2008; Sullivan & Pfefferbaum, 2006; Voineskos et al., 2012). Therefore, it is also possible that the performance of older adults could be hindered by compromised white-matter integrity.

The conflicting results concerning unimanual versus bimanual haptic discrimination coupled with the absence of previous research related to the hemispheric processing of ecologically valid objects makes it difficult to develop a clear hypothesis for this study. Unimanual performance may be superior to bimanual performance (and vice versa), but it is also possible that performance will be equal for the two types of haptic manipulation. The possible effect of aging (caused by reductions in inter- and intrahemispheric transfer) is also difficult to foresee. It may be that older adults show no deficit in either type of haptic exploration, or perhaps there will only be a deficit for bimanual exploration, given the well-documented decline in white-matter integrity that occurs in conjunction with aging. Regardless of the outcome, the results of this study will help resolve current ambiguities in research involving the inter- and intrahemispheric processing of haptic information.

## Method

*Figure 1.* Set of the 8 bell peppers used in the study. From upper left to bottom right are objects 1, 2, 3, 5, 7, 8, 11, and 12.

*Figure 2.* A depiction of one of the stimulus objects (bell pepper 5) being held in the hand. Scaling these 3-D printed copies to one-eighth of the objects' original size allowed the entire objects to be explored using only one hand.

**Experimental Stimuli**

The stimuli used for this experiment were 3-D printed copies of the eight bell peppers (objects 1, 2, 3, 5, 7, 8, 11, & 12; see Figure 1). These same bell peppers were used in previous experiments (Crabtree & Norman, 2014; Norman & Bartholomew, 2011; Norman, Clayton, Norman, & Crabtree, 2008; Norman et al., 2012). Compared to the original bell peppers, the current objects were reduced in size (uniformly scaled) to one-eighth of their original volume to easily fit in one hand (see Figure 2). The objects were printed by a Bits From Bytes 3-D Touch printer using a type of thermoplastic known as Polylactic acid (PLA). These eight individual bell peppers were chosen because they represent the most easily confused objects (Norman, Norman, Clayton, Lianekhammy, & Zielke, 2004).

**Design**

This study employed a 2 x 3 experimental design with Age and Hand Condition as between-subjects factors. The factor of Age consisted of two levels: Younger and older. Younger adulthood was defined as falling within the range of 18-31 years of age, while older adulthood was characterized as 60 years of age or older. Hand Condition was divided into three levels: Unimanual left hand only, unimanual right hand only, and bimanual. In the bimanual condition, the hand that received the first object presentation (right or left) was counterbalanced, with half of the participants being given the first object in their right hand for each trial (the remaining half being given the first object in their left hand at the start of each trial).

**Procedure**

On any particular trial, participants were handed one of the eight peppers behind an occluding screen. They were permitted to haptically explore the initial object for three seconds. After an interstimulus interval (ISI) of three seconds, the participant was handed a second object. Once again, the participant explored the object haptically for three seconds. After feeling both objects, the participant was required to judge whether the two objects possessed the same shape or had different 3-D shapes. For each participant, there were a total of 96 trials, half of which were “same trials” (the same object presented twice), with the remaining half being “different trials” (different objects presented successively). The order of “same” versus “different” trials was randomly determined for each participant. For “different trials” the pairs of objects presented were objects 1 and 3, 1 and 7, 2 and 11, 3 and 7, 3 and 8, and 5 and 12. These same object pairings were used by Norman and Bartholomew (2011) and Crabtree and Norman (2014).

Participants were randomly assigned to one of the three hand conditions (left hand unimanual, right hand unimanual, and bimanual). In the unimanual right-hand condition, participants felt both objects successively with the right hand. In the unimanual left-hand condition, participants felt both objects successively with the left hand. In the bimanual condition, the first object was presented to the left or right hand for three seconds. After the three second ISI, the participant had three seconds to haptically explore the second object in the opposite hand (e.g., if the first object was presented to the left hand, the second object was presented to the right hand).

**Participants**

There were a total of 48 participants in this study, 24 younger adults (*M* = 22.5 years old, *SD* = 3.2, range = 19 to 31 years) and 24 older adults (*M* = 73.4 years old, *SD* = 6.1, range = 62 to 87 years). Within each age group, there were eight participants for each of the three experimental conditions. All participants were either right handed (47 of the 48 participants) or ambidextrous (one participant), and were naïve regarding the purpose of the experiment. The study was approved by the Institutional Review Board of Western Kentucky University, and each participant signed an informed consent document prior to testing.

## Results

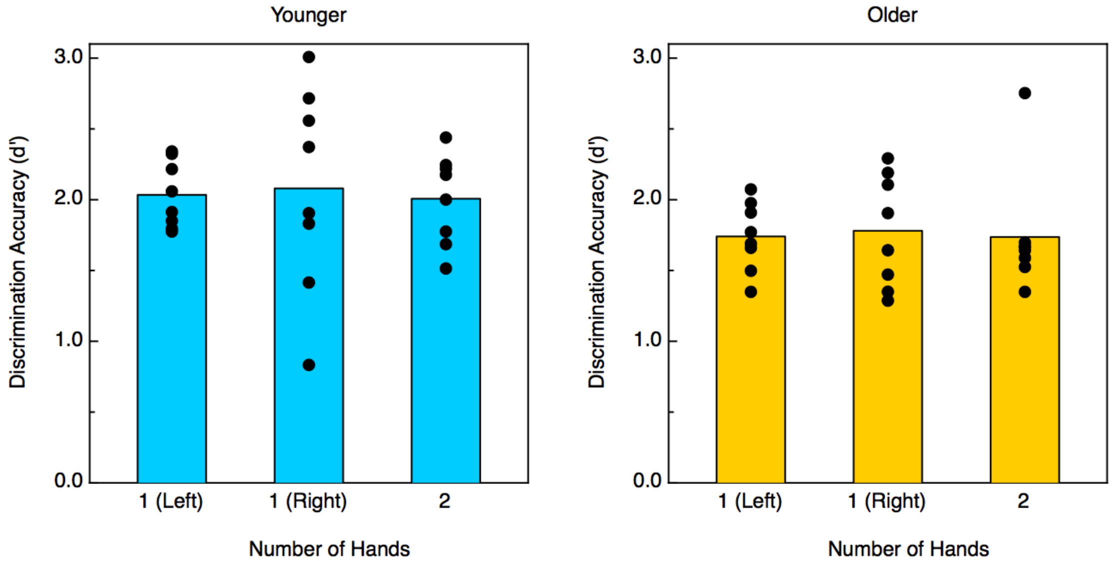


*Figure 3.* Overall results for the haptic shape discrimination task. Performance is plotted for the 24 older adults (right panel) and 24 younger adults (left panel) in terms of d'. Bars depict mean performance in each condition, while filled circles denote individual performance for each participant. While younger adults performed moderately better than older adults overall, there was no difference in performance between the various hand conditions in either group.

The results for younger and older adults are shown in Figure 3. The figure plots shape discrimination performance in terms of d' (the signal detection measure of perceptual sensitivity [Macmillan & Creelman, 1991]) for the different haptic exploration conditions. The younger adults' haptic discrimination results are depicted in the left panel, while the performance of the older adults is depicted in the right panel. It is clear from the results shown in Figure 3 that there was no main effect of the number of hands ($F(2,42) = 0.08$, $p = 0.92$, $\eta_p^2 = 0.004$). This reflects the fact that there was no significant difference in performance between the various hand conditions. In addition, there was no significant interaction between hand condition and age ($F(2,42) = 0.01$ , $p = 0.995$, $\eta_p^2 = 0.001$), indicating that the lack of variation in performance across the various hand conditions was similar for both age groups. Although there was no significant effect of hand condition and no significant interaction between hand condition and age, there was a main effect of age ($F(2,42) = 5.5$ , $p = 0.025$, $\eta_p^2 = 0.12$), demonstrating that older adults had moderately reduced shape discrimination ability compared to younger adults.

## Discussion

The bilateral arrangement and contralateral processing of tactile information from the human hands (left hand to right hemisphere's area 3b, right hand to left hemisphere's area 3b) has made it possible to investigate interhemispheric cerebral communication by comparing haptic performance on tasks in which only one hand is used (unimanual haptic exploration) with performance on tasks where both hands are used (bimanual haptic exploration). The results of previous studies indicate that unimanual haptic exploration is either better than bimanual exploration (Kappers & Koenderink, 1996; Kappers et al., 1994; Nefs et al., 2005) or that the two modes of exploration are equivalent (Sanders & Kappers, 2006; Squeri et al., 2012). Given that all of the previous research comparing unimanual and bimanual haptic performance utilized unnatural 3-D shapes or simple stimuli (such as simple curved surfaces and tactile gratings), one purpose of the current experiment was to determine if these previous findings would generalize to ecologically valid and complex 3-D objects.

The results of the current study were clear: There was no difference in haptic shape discrimination performance between any of the hand exploration conditions; performance for the left hand unimanual condition was equivalent to the performance for the right hand unimanual condition. In addition, there was no difference between performance in either of the unimanual hand conditions and performance in the bimanual exploration condition (see Figure 3). These findings differ from those obtained by Kappers and Koenderink (1996), Kappers et al. (1994), and Nefs et al. (2005), all of whom found an advantage for unimanual exploration. One possible explanation for this difference is the experimental stimuli used. As discussed earlier, previous studies used less complex and unnatural stimuli, while the current study used complex, naturalistic stimuli. Another potential explanation is the difference in the procedures used for haptic exploration. The previous studies allowed participants to simultaneously feel stimuli in the bimanual conditions, but this is obviously not possible with unimanual exploration. The current study controlled for this, only allowing participants to feel stimuli in a successive manner for both the unimanual and bimanual conditions. It may be that there is a fundamental difference between successive and simultaneous haptic exploration that is driving this difference in outcome. Further research is needed to determine if either (or both) of these factors contribute to the obtained differences in results.

A second purpose of the current study was to investigate any potential adverse effect of aging on unimanual or bimanual haptic exploration. As discussed earlier, although previous research has found that older adults are able to discriminate naturalistic 3-D shapes as well as younger adults (Norman et al., 2006, 2015), aging has been shown to produce declines in both intrahemispheric (Hsu et al., 2008; Moes et al.,1995 Voineskos et al., 2012) and interhemispheric (Beaton et al., 2000; Bellis & Wilber, 2001; Hsu et al, 2008; Jeeves & Moes, 1996; Moes et al., 1995; Reuter-Lorenz & Stanczak, 2000; Sullivan & Pfefferbaum, 2006; Voineskos et al., 2012) connectivity and processing. Therefore, while older adults are capable of perceiving ecologically valid shapes as well as younger adults under some circumstances, they may have reduced unimanual and bimanual shape discrimination performance due to reduced inter- and intrahemispheric connectivity. At this point, it is important to point out that Norman et al. (2006) and Norman et al. (2015) may not have found an effect of age simply because, unlike the present study, their participants were not required to manipulate both objects in any particular trial with separate hands (which would necessitate the need for interhemispheric transfer of tactile/haptic information).

As can be seen in Figure 3, the older adults exhibited moderately reduced haptic shape discrimination performance compared to younger adults in every hand condition. This supports the idea that older adults have reduced intra- and interhemispheric processing. It is important to note, however, that the older adults still performed well in absolute terms (i.e., their d’ values were much higher than zero). Therefore, while aging does produce decrements in haptic shape discrimination ability, older adults are still able to effectively process haptic information within and between cerebral hemispheres.

## Conclusions

In contrast to previous research, the current study found no difference between unimanual and bimanual haptic shape discrimination performance. Increases in age resulted in moderately reduced discrimination performance for both unimanual and bimanual haptic exploration, but older adults nevertheless exhibited the same pattern of results as younger adults.

References

Allard, P., & Tabin, C. J. (2009). Achieving bilateral symmetry during vertebrate limb development. *Seminars in Cell & Developmental Biology*, *20*, 479-484. doi: 10.1016/j.semcdb.2008.10.011

Alters, S. (2000). Patterns and levels of organization. *Biology: Understanding life* (pp. 133-134). Boston, MA: Jones and Barlette.

Beaton, A. A., Hugdahl, K., & Ray, P. (2000). Lateral asymmetries and interhemispheric transfer in aging: A review and some new data. In M. Mandal, M. Bulman-Fleming, & G. Tiwari (Eds.), *Side bias: A neuropsychological perspective* (pp. 101-152). Dordrecht, Netherlands: Springer. doi: 10.1007/0-306-46884-0_5

Bellis, T. J., & Wilber, L. A. (2001). Effects of aging and gender on interhemispheric function. *Journal of Speech, Language, and Hearing Research*, *44*, 246-263. doi: 10.1044/1092-4388(2001/021)

Cheeseman, J. R., Norman, J. F., & Kappers, A. M. L. (2016). Dynamic cutaneous information is sufficient for precise curvature discrimination. *Scientific Reports*, *6*: 25473. doi: 10.1038/srep25473

Corballis, M. C. (1989). Laterality and human evolution. *Psychological Review*, *96*, 492-505. doi:10.1037/0033-295x.96.3.492

Dominy, N. J., Ross, C. F., & Smith, T. D. (2004). Evolution of the special senses in primates: Past, present, and future. *The Anatomical Record Part A: Discoveries in Molecular, Cellular, and Evolutionary Biology*, *281*, 1078-1082. doi: 10.1002/ar.a.20112

Fagot, J., Lacreuse, A., & Vauclair, J. (1994). Hand-movement profiles in a tactual-tactual matching task: Effects of spatial factors and laterality. *Perception & Psychophysics*, *56*, 347-355. doi: 10.3758/BF03209768

Gazzaniga, M. S., Bogen, J. E., & Sperry, R. W. (1963). Laterality effects in somesthesis following cerebral commissurotomy in man. *Neuropsychologia*, *1*, 209-215. doi: 10.1016/0028-3932(63)90016-2

Hsu, J. L., Leemans, A., Bai, C. H., Lee, C. H., Tsai, Y. F., Chiu, H. C., & Chen, W. H. (2008). Gender differences and age-related white matter changes of the human brain: A diffusion tensor imaging study. *Neuroimage*, *39*, 566-577. doi: 10.1016/j.neuroimage.2007.09.017

Iwamura, Y. (1998). Hierarchical somatosensory processing. *Current Opinions in Neurobiology, 8,* 522-528. doi: 10.1016/s0959-4388(98)80041-x

Iwamura, Y., Iriki, A., & Tanaka, M. (1994). Bilateral hand representation in the postcentral somatosensory cortex. *Nature, 369,* 554-556. doi: 10.1038/369554a0

Jeeves, M. A., & Moes, P. (1996). Interhemispheric transfer time differences related to aging and gender. *Neuropsychologia*, *34*, 627-636. doi: 10.1016/0028-3932(95)00157-3

Jones, E. G., & Powell, T. P. S. (1969). Connexions of the somatic sensory cortex of the rhesus monkey: I. ipsilateral cortical connexions. *Brain, 92,* 477-502. doi: 10.1093/brain/92.3.477

Kaas, J. H. (2009). Somatosensory cortex, plasticity. In M. D. Binder, N. Hirokawa, & U. Windhorst (Eds.), *Encyclopedia of Neuroscience* (pp.

3770-3774). Berlin & Heidelberg: Springer. doi: 10.1007/978-3-540-29678-2_5502

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

Kappers, A. M. L., Koenderink J. J., & te Pas, S. F. (1994). Haptic discrimination of doubly curved surfaces. *Perception*, *23*, 1483-1490. doi: 10.1068/p231483

Kleinman, J. M., & Brodzinsky, D. M. (1978). Haptic exploration in young, middle-aged, and elderly adults. *Journal of Gerontology*, *33*, 521-527. doi: 10.1093/geronj/33.4.521

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

Moes, P., Jeeves, M. A., & Cook, K. (1995). Bimanual coordination with aging: Implications for interhemispheric transfer. *Developmental Neuropsychology*, *11*, 23-40. doi: 10.1080/87565649509540601

Nefs, H. T., Kappers, A. M. L., & Koenderink, J. J. (2005). Intermanual and intramanual tactual grating discrimination. *Experimental Brain Research*, *163*, 123-127. doi: 10.1007/s00221-005-2227-8

Norman, J. F., Adkins, O. C., Hoyng, S. C., Dowell, C. J., Pedersen, L. E., & Gilliam, A. N. (2016). Aging and the haptic perception of material properties. *Perception*, *45*, 1387-1398. doi: 10.1177/0301006616659073

Norman, J. F., Cheeseman, J. R., Adkins, O. C., Cox, A. G., Rogers, C. E., Dowell, C. J., ... & Reyes, C. M. (2015). Aging and solid shape recognition: Vision and haptics. *Vision Research*, *115*, 113-118. doi: 10.1016/j.visres.2015.09.001

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., Cheeseman, J. R., Ronning, C., Thomason, K. E., Baxter, M. W., ... & Lamirande, D. N. (2013). Aging and curvature discrimination from static and dynamic touch. *PLoS One*, *8*(7): e68577. doi: 10.1371/journal.pone.0068577

Norman, J. F., Norman, H. F., Swindle, J. M., Jennings, L. R., & Bartholomew, A. N. (2009). Aging and the discrimination of object weight. *Perception*, *38*, 1347-1354. doi: 10.1068/p6367

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

Penfield, W., & Boldrey, E. (1937). Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation. *Brain*, *60*, 389-443. doi: 10.1093/brain/60.4.389

Purves, D., Augustine, G. J., & Fitzpatrick, D. (Eds.). (2001) *Neuroscience* (2nd ed.). Sunderland, MA: Sinauer Associates.

Reed, J. L., Qi, H. X., & Kaas, J. H. (2011). Spatiotemporal properties of neuron response suppression in owl monkey primary somatosensory cortex when stimuli are presented to both hands. *Journal of Neuroscience, 31,* 3589-3601. doi: 10.1523/jneurosci.4310-10.2011

Reuter-Lorenz, P. A., & Stanczak, L. (2000). Differential effects of aging on the functions of the corpus callosum. *Developmental Neuropsychology*, *18*, 113-137. doi: 10.1207/S15326942DN1801_7

Sanders, A. F. J., & Kappers, A. M. L. (2006). Bimanual curvature discrimination of hand-sized surfaces placed at different positions. *Perception & Psychophysics*, *68*, 1094-1106. doi: doi:10.3758/BF03193712

Squeri, V., Sciutti, A., Gori, M., Masia, L., Sandini, G., & Konczak, J. (2012). Two hands, one perception: How bimanual haptic information is combined by the brain. *Journal of Neurophysiology*, *107*, 544-550. doi: 10.1152/jn.00756.2010

Stevens, J. C. (1992). Aging and spatial acuity of touch. *Journal of Gerontology*, *47*, 35-40. doi: 10.1093/geronj/47.1.P35

Sullivan, E. V., & Pfefferbaum, A. (2006). Diffusion tensor imaging and aging. *Neuroscience & Biobehavioral Reviews*, *30*, 749-761. doi: 10.1016/j.neubiorev.2006.06.002

Voineskos, A. N., Rajji, T. K., Lobaugh, N. J., Miranda, D., Shenton, M. E., Kennedy, J. L., ... & Mulsant, B. H. (2012). Age-related decline in white matter tract integrity and cognitive performance: A DTI tractography and structural equation modeling study. *Neurobiology of Aging*, *33*, 21-34. doi: 10.1016/j.neurobiolaging.2010.02.009

# Appendix

INSTITUTIONAL REVIEW BOARD
OFFICE OF RESEARCH INTEGRITY

| | |
|---|---|
| DATE: | October 10, 2016 |
| TO: | Catherine Dowell |
| FROM: | Western Kentucky University (WKU) IRB |
| PROJECT TITLE: | [970528-1] Unimanual and Bimanual Haptic Shape Discrimination |
| REFERENCE #: | IRB 17-098 |
| SUBMISSION TYPE: | New Project |
| ACTION: | APPROVED |
| APPROVAL DATE: | October 10, 2016 |
| EXPIRATION DATE: | October 10, 2017 |
| 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 October 10, 2017.

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.

Curriculum Vitae

# Catherine J. Dowell

## PERSONAL INFORMATION:

Graduate Research Assistant
Department of Psychological Sciences
Western Kentucky University
1906 College Heights Blvd. #21030
Bowling Green, KY, 42101-1030

## EDUCATION:

M. S., Western Kentucky University — Expected May, 2018
Psychology (Psychological Science)

B. S., Western Kentucky University
major: Psychological Science (Biobehavioral)
minor: Biology

## PUBLICATIONS:

6) **Dowell, C. J.**, Norman, J. F., Moment, J. R., Shain, L. M., Norman, H. F., Phillips, F., & Kappers, A. M. L. (2018). Haptic shape discrimination and interhemispheric communication. *Scientific Reports*, *8*: 377. http://www.nature.com/articles/s41598-017-18691-2

5) Norman, J. F., Adkins, O. C., **Dowell, C. J.**, Hoyng, S. C., Shain, L. M., Pedersen, L. E., Kinnard, J. D., Higginbotham, A. J., & Gilliam, A. N. (2017). Aging and visual 3-D shape recognition from motion. *Attention, Perception, & Psychophysics*, *79*, 2467-2477. doi: 10.3758/s13414-017-1392-8

4) Norman, J. F., Adkins, O. C., **Dowell, C. J.**, Shain, L. M., Hoyng, S. C., & Kinnard, J. D. (2017). The visual perception of distance ratios outdoors. *Attention, Perception, & Psychophysics*, *79*, 1195-1203. doi: 10.3758/s13414-017-1294-9

3) Norman, J. F., Adkins, O. C., **Dowell, C. J.**, Hoyng, S. C., Gilliam, A. N., & Pedersen, L. E. (2017). Aging and haptic-visual solid shape matching. *Perception*, *46*, 976-986. doi: 10.1177/0301006617690168

2) Norman, J. F., Adkins, O. C., Hoyng, S. C., **Dowell, C. J.**, Pedersen, L. E., & Gilliam, A. N. (2016). Aging and the haptic perception of material properties. *Perception*, *45*, 1387–1398. doi: 10.1177/0301006616659073

1) Norman, J. F., Cheeseman, J. R., Adkins, O. C., Cox, A. G., Rogers, C. E., **Dowell, C. J.**, Baxter, M. W., Norman, H. F., & Reyes, C. M. (2015). Aging and solid shape recognition: Vision and haptics. *Vision Research*, *115*, 113-118. doi: 10.1016/j.visres.2015.09.001

## GRANT FUNDINGS:

Kentucky NSF EPSCoR grant, $2459 (National Science Foundation Award #1355438), research support for Summer 2016.

Faculty-Undergraduate Student Engagement (FUSE) Grant, $4,000, Spring 2016

## HONORS & SCHOLARSHIPS:

Graduate Research Assistantship: Fall 2017-Spring 2018

Regents Scholarship: August 2013-May 2017

Kentucky Educational Excellence Scholarship (KEES): $9,800 total

Undergraduate Research Award, Department of Psychological Sciences, Ogden College of Science and Engineering: April, 2017

Graduated Western Kentucky University Summa Cum Laude-May 2017

Joint Undergraduate-Masters Program: August 2016-May 2017

President's List:

Fall 2013; Spring 2014; Fall 2014; Spring 2015; Fall 2015; Fall 2016; Spring 2017

Dean's List: Spring 2016

## CONFERENCE PRESENTATIONS:

**Dowell, C. J.**, Norman, J. F., Higginbotham, A. J., Fedorka, N. W., & Norman, H. F. (2018). The effects of environmental context upon distance bisection. To be presented at the Annual Meeting of the Vision Sciences Society, St. Pete Beach, Florida, May, 2018.

Norman, J. F., Adkins, O. C., **Dowell, C. J.**, Shain, L. M., Hoyng, S. C., & Kinnard, J. D. (2017). The outdoor perception of distance ratios. Presented at the Annual Meeting of the Vision Sciences Society, St. Pete Beach, Florida, May 23, 2017.

Norman, J. F., Adkins, O. C., Hoyng, S. C., **Dowell, C. J.**, Pedersen, L. E., & Gilliam, A. N. (2016). Aging and the haptic perception of material properties. Presented at the Annual Meeting of the Tactile Research Group, Boston, Massachusetts, November 17, 2016.

Norman, J. F., Adkins, O. C., **Dowell, C. J.**, Hoyng, S. C., Gilliam, A. N., & Pedersen, L. E. (2016). Haptic-visual solid shape matching with variable numbers of fingers. Presented at the Annual Meeting of the Vision Sciences Society, St. Pete Beach, Florida, May 16, 2016.

**Dowell, C. J.**, & Hoyng, S. C. (2016). Haptic-visual solid shape matching with variable numbers of fingers. Presented at the Western Kentucky University Student Research Conference, April 2, 2016.

Norman, J. F., Cheeseman, J. R., Adkins, O. C., Cox, A. G., Rogers, C. E., **Dowell, C. J.**, Baxter, M. W., Norman, H. F., & Reyes, C. M. (2015). Aging and solid shape recognition. Presented at the Annual Meeting of the Tactile Research Group, Chicago, Illinois, November 19, 2015.

## MEMBERSHIPS:

Vision Sciences Society: 2016-present

## SPECIALIZED TRAINING:

Graduate Research Assistant: Fall 2017-Spring 2018

- Responsible for training new researchers on data collection, participant scheduling, and data entry
- Responsible for supervising undergraduate researchers
- Assistant with designing and planning experiments
- Assist with writing and publishing manuscripts

Undergraduate Research Assistant: Spring 2015-Spring 2016

- Assist with recruitment of study participants
- Assist with for collection and entry of participant data
- Assist with writing and publishing manuscripts

Collaborative Institutional Training Initiative (CITI) Certification: 2013-present

Social and Behavioral Responsible Conduct of Research Course 1: Completed 2013

Proficient in the use of SPSS

## TEACHING EXPERIENCE:

Taught undergraduate Research Methods Lab: August 2017-December 2017

## REFERENCES:

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