

STRING-MEDIATED INERTIAL FORCE-BASED HAPTIC PERCEPTION OF DISK
DIAMETER

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by
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Abstract

STRING-MEDIATED INERTIAL FORCE-BASED HAPTIC PERCEPTION OF DISK DIAMETER

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The design of the current study tested the hypothesis that disk diameter can be perceived haptically solely through rotational inertia. Past research on haptic perception suggests that humans can accurately identify the physical properties of an object without any access to visual information. Researchers contend that, in the absence of vision, the distribution of the inertial forces of an object can be used to perceive other physical properties of said object. The literature suggests that the haptic perception system is sensitive to the distribution of inertial forces and haptic perception relies on the object's inertial distribution to identify predictable relationships between the inertial properties and other physical properties, otherwise known as the inertia tensor hypothesis. The inertia tensor hypothesis proposes that inertial information is the most salient sensory information in haptic perception and alone is sufficient for identifying the physical properties of objects. However, prior studies demonstrating evidence in favor of the inertia tensor hypothesis allow access to additional mechanical properties other than solely inertia. This study used an apparatus that

limited information availability solely to rotational inertia. If rotational inertia alone is sufficient for perceiving physical properties of objects, I predicted that participants would be able to accurately judge disk diameter from inertial information administered haptically. When exposed to disks varying in diameter, I expected that participants would consistently discriminate between the magnitudes of the object's diameter. Findings were generally in support of the inertia tensor hypothesis and demonstrated the generalizability to a novel event.

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Dedication

I dedicate this thesis to Kenneth M. Steele, Patrick A. Cabe, and Andrew R. Smith.

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String-mediated Inertial Force-based Haptic Perception of Disk Diameter

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Abstract

Haptic perception is described as the process of recognizing objects through active touch. Everyday life requires the ability to sense properties of objects in the environment around us and interact with those objects. The haptic system, through a combination of somatosensory perception from the skin and proprioception through the limbs, provides an interface by which humans can physiologically identify objects in our environment. Rotational inertia, the force required to change the velocity of an object rotating on its axis, has been documented to inform the haptic system about object properties. Commonly, participants judged lengths of wielded rods, with access to inertia about all the rods' principal axes. I examined whether people can identify disk diameter using an apparatus with rotation restricted to a single axis, providing information solely through rotational inertia. Participants rotated visually-occluded disks by reciprocally pulling up and down on two strings, each operated by a single finger. Participants were to identify the size of 5 disks from a 7-disk display, with unlimited sampling time. The results of Experiment 1 showed that participants readily differentiated disks. Judgments accurately and reliably tracked actual disk diameters. It was possible that acoustic information generated from the apparatus was confounded with changes in disk sizes in Experiment 1. A second experiment used the same procedure with the addition of earplugs to reduce possible sound information. The results of Experiment 2 showed that participants were slightly more accurate in tracking disk diameters than in Experiment 1, demonstrating that participants were not relying on sound information primarily to make judgments. Another possible alternative explanation for the accuracy in the first two experiments is that participants were able to learn to associate the limited visual responses provided with

a given disk stimuli, thus inflating performance. To test this, a third experiment used a larger range of responses and participant adjustment of a visual display allowing for finer gradations between responses. The results of Experiment 3 showed that participants reliably differentiated and accurately scaled disk diameters, replicating earlier results. The current study extends previous findings on the sufficiency of inertial forces to predict accurate haptic perception of object properties, specifically disk diameter in a novel task. Although this study demonstrates the sufficiency of inertial information for haptic perception of disk diameter, future research is required to discern if inertial information is necessarily the primary informant of haptic perception.

Keywords: haptic perception, dynamic touch, rotational inertia, inertia tensor

String-mediated Inertial Force-based Haptic Perception of Disk Diameter

Louis Braille, known for his development of the Braille reading and writing system, lost his vision entirely at 3 years old (Grunwald, 2008). In absence of vision, Louis Braille immediately recognized that he could communicate with and explore the neighboring world through the salience of tactile information. He went on to revolutionize the tactile alphabet by determining the most discriminable letterings. Before Braille pioneered his pronounced dot system, tactile alphabets were comprised of linear and curvilinear letterings that users often found confusing and difficult to discern (Grunwald, 2008). At just 15 years old, Braille had encoded the entire French alphabet and published his system, which is still used today. The history of Louis Braille, at its core, speaks to the foundation of haptic perception research; his story encapsulates the significance of understanding how individuals can interpret tactile stimuli, discriminate among their magnitudes, and use such information to perceive properties.

J. J. Gibson formally addressed how humans use tactile information to perceive the world around them. Gibson (1966) characterized the haptic perception system as a system that is suited for perceiving the physical world around us by utilizing one's limbs and bodies. Furthermore, Gibson (1966) contended that haptic perception depends entirely on stimulus array information – where all perceptual information is provided by the invariant energy flows that humans use in haptic perception. From Gibson's perspective, perceptual systems are sensitive to and resonate with the physical energy changes that are present in stimulus arrays. Despite being quite severe in his views, Gibson's theoretical perspective that perception is a representation of physical energies

spearheaded the method of analyzing perceptible interactions by means of physical-mathematical relationships (Cabe, 2010).

From a Gibsonian perspective, humans' perceptual systems derive stimulus information from the interaction between changes in physical energy and the structure of the environment to be perceived. Research conducted after Gibson's era corroborates the notion that perceptual information has an explicit relationship to the physical energy distributions that are detectable by our perception systems (Lederman, Ganeshan, & Ellis, 1996). Respective to the realm of haptic perception, it is commonly observed that our upper limbs and hands possess a unique ability to discriminate among stimuli and directly perceive the physical energies that surround our existence; for example, one can pick up a bottle of water and determine whether it is full or not based on the weight properties of the water. Since the era of Gibson, our biological and anatomical understanding of human sensory systems has improved drastically. Modern research now contends that physical energies perceived haptically involve our hands, forearms, muscles, tendons, ligaments, and joints; moreover, specialized nerve endings and mechanoreceptors in our skin ascertain changes in physical energies related to pressure (Grunwald, 2008; Solomon & Turvey, 1988; Solomon, Turvey, & Burton, 1989). This depiction of our haptic sensory system corroborates Gibson's theory that perceptions may be defined through physical-mathematical relationships of our receptiveness to the physical changes. If perceptual information is used via relationships to the physical energies they represent, then the question is to which physical-mathematical relationships are our haptic sensory subsystems sensitive. Which relationships predict consistent and accurate representations

of the physical world? More pertinent to the research question at hand, what spatial properties of objects does the perceptual system use in dealing with the world?

A review of the literature in the domain of haptic perception routinely demonstrates a physical-mathematical relationship present between moments of inertia and the spatial properties of an object that those rotational inertial forces inform (Cabe, 2010; Solomon & Turvey, 1988; see also reviews by Carello & Turvey, 2000, 2004, and Turvey & Carello, 1995). Rotational moment of inertia is defined as the force necessary for acceleration to occur about a rotational axis; in other words, rotational moment of inertia is the resistance of an object to changes in angular velocity. A physical-mathematical relationship exists between objects' properties and rotational inertia since rotational inertia is a function of an object's volume and mass. For example, where L illustrates the length of a cylinder, M is the mass of the disk, and R represents the radius of a disk, longitudinal moment of inertia can be expressed as:

$$I_{longitudinal} = \frac{M R^2}{2} \text{ or } I_{diametrical} = \frac{M L^2}{12} \quad (1)$$

These formulae demonstrate the physical mathematical relationship between inertia and an object property (e.g. the length of a cylinder or the radius of a disk). Consequently, these studies and their distinguished relationships support the Gibsonian paradigm that perception is a product of physical energies present in the environment.

Further exploring the inertial-object relationships, prior research suggests that humans have access to haptic perception as young as infancy (Streri & Spelke, 1988). As early as 4 years old, children can utilize inertial information to accurately perceive physical object properties; however, perceptual acuity is not as precise as adult

populations who are more attuned to haptic information (Fitzpatrick & Flynn, 2010; Kloos & Amazeen, 2002).

Solomon and Turvey (1988) established that inertial forces provided information to the haptic system in a way that engendered reliable object property judgments of rod length. In a series of nine experiments, Solomon and Turvey (1988) had participants wield rods of varying lengths, occluded from vision; participants were then asked to report their perceived distance reachable with the occluded rod. Through a series of experiments designed around the affordance of reachability, Solomon and Turvey (1988) demonstrated converging evidence for the dependence on inertial information felt about the wrist (which served as the rotational axis required for rotational inertia to occur). Their findings demonstrated that perceived rod length estimations closely tracked actual rod lengths. In discussing their results, Solomon and Turvey (1988) suggested that participant performance was contingent on invariants present in the inertial information detected about the wrist; furthermore, Solomon and Turvey (1988) proposed that inertial information is the most salient sensory stimuli for the haptic system. These results led to the introduction of the inertia tensor model into haptic perception literature.

The inertia tensor is an ellipsoid model that is constructed by the three required orthogonal inertial forces necessary for acceleration about three spatial axes – with those axes intersecting through the center of mass of the object; therefore, the inertia tensor is a model generated from a three-element vector of rotational inertia (I_1 , I_2 , I_3 ; often translated as eigenvalues or eigenvectors of the inertia tensor, see Figure 1). The various inertial force elements are ranked based on magnitude from largest (I_1) to smallest (I_3) and illustrate how the mass of a specific object is distributed. To clarify, the combination

of necessary inertial forces for movement of an object in a given direction constructs the inertia tensor and the inertia tensor informs spatial properties of objects by illuminating how the mass of that object is allocated. Since Solomon and Turvey (1988) introduced the concept of the inertia tensor via wielding, the model has flourished and produced dozens of related publications in the literature (Cabe, 2010; Carello, Flascher, Kunkler-Peck, & Turvey, 1999; Fitzpatrick, Carello, & Turvey, 1994; Peck, Jeffers, Carello, & Turvey, 1996; Solomon et al., 1989; see also reviews by Carello & Turvey, 2000, 2004, and Turvey & Carello, 1995). The inertia tensor model has been used to examine perceptual judgments of branched objects (Fitzpatrick et al., 1994; Pagano & Turvey, 1993; Turvey, Burton, Pagano, Solomon, & Runeson, 1992), configuration of solid objects (Burton, Turvey, & Solomon, 1990), object diameter (Fitzpatrick et al., 1994), object heaviness (Amazeen & Turvey, 1996), and surface properties (Chan & Turvey, 1991), among other object properties. Following this plethora of inertia tensor research, the eigenvalues of the inertia tensor were generally deemed as necessary and sufficient for perceiving spatial properties of objects through haptic perception; such that wielding an object caused participants' haptic systems to generate these eigenvalues and differences between the eigenvalues led to differences in perception.

Despite the overwhelming support and replication of the inertia tensor model for identifying physical properties haptically, most of the research corroborating the inertia tensor model was conducted utilizing a wielding paradigm – where the wrist is assigned as the rotational axis. In an experimental setting, it is challenging, if not impossible, to have participants actively wield an object without providing access to additional mechanical invariants such as the static moment of the object (the physical energies of an

object when no motion is present) as well as the direct mass of the object (Kingma, Beek, van Dieën, 2002; Kingma, van de Langenberg, & Beek, 2004; van de Langenberg, Kingma, & Beek, 2006). As soon as a participant obtains the object for wielding, they are subjected to perceiving static qualities of that object.

Due to the issues of static moment and mass, other research has challenged the generalizability of the inertia tensor model as the governing informant of haptic perception, opening the floor for debate within the literature. For instance, as soon as some individual grasps an object in a wielding paradigm, it is possible that the individual is accessing other physical information about the object outside of strictly the inertial information felt about the wrist. In a series of vision-absent wielding studies aimed at discovering physical variables beyond the inertia tensor that may be necessary for haptic perception of object properties, Kingma et al. (2002, 2004) and van de Langenberg et al. (2006) tested the relationship between object properties and the rotational eigenvalues of the inertia tensor as well as several other mechanical invariants present during wielding (static moment, static torque, and combinations of weight and static torque). When analyzing physical-mathematical relationships amongst objects, these studies reported finding stronger correlations with static mechanical invariants as opposed to the eigenvalues of the inertia tensor; for instance, in some cases simply the mass of an object was more predictive of the objects' physical properties rather than inertial information perceived through the wrist. Thus, their findings suggest that other physical variables may be more salient sensory stimuli than rotational inertia (Kingma et al., 2002, 2004; van de Langenberg et al., 2006). Additionally, in some instances, the results of their wielding experimentation showed that object length perception and object heaviness

perception were unrelated to the inertia tensor (Kingma et al., 2004). These findings were in direct opposition of the inertia tensor model.

Although the number of publications in support of the inertia tensor model is large, the issue of other mechanical invariants intermixed in the stimuli and their subsequent perception required further investigation. The results in opposition of the inertia tensor model created a case that extraneous physical variables beyond the inertia tensor may be required and other physical variables may be sufficient for accurate object property judgments. Cabe (2010) investigated the exact physical variables that inform judgments of haptic perception. Cabe (2010) designed an apparatus that provided only inertial information in the absence of vision in order to test the criticisms of available static invariants during wielding. The apparatus allowed participants to manipulate objects (cylinders) rotationally by rolling them seated on a series of small wheels. By not allowing participants to wield objects, but instead rotate them via an apparatus, Cabe (2010) was able to decouple the extraneous static invariants from participant perception and test isolated eigenvectors of the inertia tensor. Participant judgments of object lengths were shown to be reliable and accurate when supplied with solely rotational inertia in a novel perceptual task. That is, estimated object lengths generated by participants followed actual object lengths. Furthermore, Cabe (2010) was able to demonstrate that the longitudinal moment of inertia (I_3 , in this case, the smallest of the three orthogonal moments of inertia) was sufficient for haptic cylinder length judgments. These findings support the inertia tensor model and demonstrate that I_3 (the weakest force and least informative inertia tensor eigenvector) could facilitate consistently reliable perceptual judgments in the absence of any extraneous mechanical invariants.

The current research aims to utilize an apparatus and a novel perceptual task that provides stimuli information solely through rotational inertia (in absence of vision, static invariants, and mass) by adopting a similar methodology as employed by Cabe (2010). If the inertia tensor hypothesis is correct, it is predicted that participants will be able to accurately judge disk diameter from only inertial information administered haptically. Specifically, when exposed to objects of differential physical magnitudes (i.e., disks of varying diameters), it is expected that participants will consistently and accurately differentiate disk diameter, rank the disks in an ordinal fashion based on diameter, and attach numerical values to discriminable diameters on a scale. Because disk diameter can be expressed mathematically as a function of rotational inertia, inertia theorists would suggest an individual's perceptual systems are sensitive to this physical-mathematical relationship; thus, Carello and Turvey's (2004) theory suggests the hypothesis that global differences will be present between judgments of perceived disk diameter. Furthermore, statistically significant differences are expected to be observed between disks of adjacent diameter (e.g., judgments of a 12 cm disk will be significantly different than judgments of a 14 cm disk). The final prediction is that a positive, linear relationship will be found between perceived judgments of disk diameter and actual disk diameter.

Findings in support of these predictions would suggest that moments of inertia and the inertia tensor are sufficient for perceiving spatial properties of objects. Confirmation of these predictions would provide support for the generalizability of the inertia tensor model. The experimental design presented here tests prominent theoretical implications in haptic perception that inertial properties of objects can be utilized to determine physical and spatial properties of said objects. The goal of the initial

experiment is to demonstrate the effect in a simple fashion and then explore the generality through a series of manipulations in additional experiments. This research adds a novel procedure to the literature. Haptic perception of disk diameter solely through rotational inertia alone has not been observed in the literature. Findings will help inform the field of haptic perception regarding how individuals use object properties without access to vision.

Experiment 1 investigated the capability of participants to reliably and accurately identify disk diameter from inertial information by simply rotating a disk occluded from vision by reciprocally pulling up and down on strings attached to a shaft on which the disk was mounted as a flywheel. The second experiment investigated an alternative explanation for the pattern of accurate results in Experiment 1: the presence of acoustic information from spinning disks in the original procedure. In Experiment 2, participants followed the same procedure as Experiment 1 with the exception being that they wore earplugs. The third experiment used a similar methodology as the first two experiments in which participants rotated visually occluded disks by pulling up and down on a string attached to a shaft. Experiment 3 investigated a potential alternative explanation for the series of results in the first two experiments. In prior experiments, participants had limited responses choices with only seven response options. The notable difference in the methodology of Experiment 3 was the implementation of a new response mechanism with opportunity for greater variability within participant responses. Experiment 3 tested whether the limited choices among responses was responsible for the obtained accuracy in Experiments 1 and 2.

Experiment 1

Method

Participants. Thirty undergraduate participants of any gender and at least 18 years of age were recruited voluntarily using the SONA system at Appalachian State University. Participants were screened by self-report for neuromuscular disorders that might interfere with performing the task and none were excluded for that reason. Data from two participants were excluded due to malfunctions with the apparatus (e.g., the string broke during the procedure). Participants received course credit for their participation. The Institutional Review Board approved the current research on 04/20/2017. IRB approval information is located in Appendix A.

Apparatus and materials. The basic apparatus is a metal frame creating an open box – across the top of which is fitted a horizontal shaft (see Figure 2). The entire frame is approximately 38 cm high x 46 cm wide x 36 cm deep. The central component supporting the shaft is 15 cm deep. Disks of varying diameter can be attached to the shaft by means of a thumb screw through the center of the disk and threaded into one end of the shaft. A string wraps around the shaft, mid-way along the shaft's length, with metal rings (approximately 4 cm in diameter) attached to each end of the string. In use, the participant places his or her hands into the open end of the apparatus (with the disk attached to the shaft at the opposite end) and inserts a forefinger into each of the two metal rings. Pulling down on one string unwraps that string from the shaft, while simultaneously wrapping the other end of the string around it. Alternating up-down movement of the ends of the strings produces reciprocating rotations of the shaft and, thus, the attached disk; in short, alternatively pulling the strings accelerates the disk from

a stop, then decelerates the disk back to a stop, as each rotation progresses. A box-like cover enclosed the framework (see Figure 3), leaving open the end through which participants insert their hands. The opposite end of the enclosure is a vertical sheet (125 cm wide x 64 cm high) that occludes the disk stimuli as well as the actions of the experimenter from the view of the participant.

The five operational disks were made of 0.32 cm-thick aluminum, with diameters ranging from 12 cm to 20 cm, increasing in 2 cm increments (see Figure 4). The mass of the operational disks are as follows: 96 g, 126 g, 169 g, 215 g, and 257 g. The moments of inertia for each of the disk stimuli were calculated with respect to the central axis for each disk stimuli using the masses presented above.

The experimenter and the participant were separated by a disk array visual representation of possible responses (see Figure 4). The visual representation matched actual disk diameters and was seated at eye-level to avoid any angle of vision effects. Participants were able to report values from 1 (smallest) to 7 (largest); however, physical disk sizes ranged from Disk 2 to Disk 6. This procedure was used as an attempt to control for central tendency bias because pilot participants were hesitant to report values on the ends of the disk array spectrum. The participant rotated each disk and verbalized his or her judgment of the diameter of the disk by stating the number of the circle on the visual representation that the participant judges to be equivalent to diameter of the rotated disk. In practice, a short curtain was attached to the participant's end of the enclosure and draped across the participant's wrists or forearms to hide the inner parts of the apparatus (see Figure 5).

Procedure. First, the experimenter obtained informed consent of the participant (see Appendix B for the consent form). Then, the experimenter read standardized instructions to the participant, explaining the details of the task. The experimenter demonstrated how to insert the forefingers into the metal rings attached to the string and how to move the rings to rotate the shaft. The experiment proper began after ensuring the procedure was clear to the participant.

Each trial began with the participants' hands outside the apparatus. The experimenter attached the disk to be used for that trial to the shaft and instructed the participant to insert his or her forefingers into the rings and to begin rotating the disk by reciprocally pulling on the strings. Participants were allowed to rotate the disk as long as they desired before forming a judgment and verbalizing a response. When he or she felt that they had adequately perceived the stimuli, the participant told the experimenter the number of the circle on the visual representation that the participant perceived equal to the diameter of the rotating disk. The participant then stopped rotating the disk and removed his or her hands from the apparatus. The experimenter removed the disk and replaced it with the subsequent disk to be used for the succeeding trial.

Disks were presented across blocks of five trials, with the five disk diameters randomized within each block. Participants were presented with six blocks of trials that were counterbalanced to circumvent any order effects based on stimuli presentation. An experimental session was typically completed within 30 min, including instructions, testing, and debriefing.

Results

Data analysis began by translating the ordinal judgments provided by participants to scalar disk diameters for the purposes of statistical analysis. For example, a disk judged as a “1” was transferred to its scalar diameter in centimeters (10 cm for this value). First, a repeated measures analysis of variance (ANOVA) test was conducted to test for global differences among the judgments offered by participants; follow-up post hoc pairwise comparison *t*-tests were used to examine if participants were discriminating between adjacent disks. Lastly, a linear regression analysis was conducted to examine the direction and strength of the relationship between actual disk diameter and perceived judgments of disk diameter.

ANOVA. An initial 5 (disk diameters) x 6 (trial blocks) repeated measures ANOVA showed a strong main effect for diameter, $F(4, 116) = 469.88, p < .001, \eta_p^2 = .94$. The significant main effect for disk diameter indicates that judgments for disk diameter were significantly different for the different disks in the series (see Figure 6). The results indicate a nonsignificant main effect for blocks, $F(5, 145) = 1.29, p = .27$. The nonsignificant main effect for block indicates that there is no significant difference between performance from among any of the trial blocks (see Figure 7). The interaction between disk diameter and block was significant, $F(20, 580) = 1.94, p < .001, \eta_p^2 = .09$. The significant interaction indicated that participant performance differed across blocks. As seen in Figure 6, the interaction was caused by differences in performance for the first block of trials. A separate 5 (disk diameters) x 6 (trial blocks) repeated measures ANOVA was conducted excluding the data from the first block. Repeating the ANOVA with the first block omitted showed a similarly strong main effect for disk,

$F(4, 116) = 493.25, p < .001, \eta_p^2 = .94$. Likewise, the same nonsignificant interaction for block was witnessed, $F(4, 116) = 1.94, p = .11$; however, the interaction was no longer significant without the variability from the first block, $F(16, 464) = 1.25, p = .23$. The simple effect for the first block of judgments was examined using a one-way ANOVA (see Figure 8).

Post hoc pairwise comparisons, using average perceived judgments over all blocks for each participant, demonstrated significant differences among all 10 comparisons, all Bonferonni-corrected, $t(29) > 8.37$, all $p < .001$, all Cohen's $d > 1.50$. The post hoc pairwise comparisons indicate that each disk was perceived differently from adjacent disks (see Table 1 for pairwise comparisons). Post hoc pairwise comparisons were also conducted and Bonferonni-corrected using only disk diameter judgments from the first block to examine which disks were not being differentiated throughout the first five trials. Post hoc pairwise comparisons for only the first block indicate that participant performance suffered at the end points of the disk array during their first five trials (see Table 2).

Regression. A simple linear regression was calculated to predict perceived disk diameter based on actual disk diameter. A significant regression equation was found ($F(1, 898) = 1876.00, p < .001$) with an $R^2 = .676$. The relationship between judged diameter and actual diameter using all measures for all participants yielded a significant relationship ($r = .82, n = 900$ data points, $p < .001$) with a slope of 1.11 and an intercept of -1.01. The regression values indicate that if a participant was presented with a 12 cm diameter disk, the regression model would predict their response to be a 12.31 cm judgment. The regression slope demonstrates that judgments were highly reliable and

highly accurate. Using judgments averaged over blocks improved the regression, with a correlation of .95 ($n = 150$ data points), a slope of 1.07 and an intercept of -0.40.

Correlations for individual participants ($n = 30$ data points) were generally quite strong also. The median correlation was .87 (range, .57 to .93), all $p < .001$.

Discussion

Participants made diameter judgments when exposed only to inertial information to test the hypothesis that inertial information may inform judgments of disk diameter. The results from Experiment 1 indicate that participants were able to differentiate between disks of varying inertial magnitude. Furthermore, Experiment 1 demonstrated participants could make reliable and generally accurate judgments of disk diameter by means of reciprocally pulling a string to rotate disks of varying diameter. Participants were able to detect differences among objects' physical magnitude, to rank the disks in an ordinal fashion, and to place objects' ordinal diameter on close to a linear scale. Results from the repeated measures ANOVA detected that global differences were present among disk diameter judgments. Post hoc pairwise comparisons indicate that participants were able to discriminate among adjacent disks; thus, this finding supports the hypothesis that inertial information is sufficient for differentiating gradations between object physical properties. The strength of participants' ability to discriminate disks (all Cohen's $d > 1.50$) suggests that our perceptible systems may be sensitive to finer differentiations. Regression analysis demonstrated a positive, linear relationship present between perceived judgments of disk diameter and the actual disk diameters. The regression equation results support the prediction that a positive, linear relationship

would be produced between changes in actual disk diameter and changes in haptic experience using the current method.

The results show that performance (and any detectable practice effect) was primarily operating during the first block (see Figure 8) and participant performance was no longer significantly improving across subsequent blocks. The results indicate that the trial block by disk diameter significant interaction was primarily due to the large amount of variability present in the first block, which likely represented a lack of familiarity with the range of stimuli presented. This potential practice effect, in addition with the fact that analysis omitting the first block removed the significant interaction, provided justification for using the first five trials as a preliminary familiarization block. Ultimately, the pattern of results produced from Experiment 1 were in support of Carello and Turvey (2004), such that inertial properties of object are sufficient to inform the perception of those objects. Moreover, the findings from Experiment 1 corroborate findings in Cabe (2010) by demonstrating the sufficiency of inertia alone, without access to other mechanical invariants that may be experienced in classic welding paradigms used in earlier experiments.

The experiment produced strong effects, but there may be an alternative explanation for the strength of these results. Participants might have responded to noise differences present during rotations of disks with different diameters. The experimenter noted that when rotating the disks at high speed, the apparatus produced a noticeable difference in sound for the larger disk stimuli. This observation could account for some of the strength of the effect. Perhaps, participants were so accurate because they were using additional sound information outside of the inertia information to make their

judgments. Research conducted by Mortensen, Bech, Begault, and Adelstein (2009) seems to support the notion that auditory information may improve performance and experience. In their study, Mortensen et al. (2009) selectively limited sensory information and manipulated the degree of haptic, auditory, and visual information. Performance was best in Mortensen et al. (2009) when participants had access to all sensory modalities suggesting that auditory information could have influenced performance in the current paradigm. The goal of Experiment 2 was to identify if acoustic information was responsible for the accuracy of participant's responses.

Experiment 2

Prior literature has shown that auditory and visual information can aid the performance in a haptic task (Mortensen, et al., 2009). If this is the case, the inertia results from Experiment 1 may be confounded by the presence of acoustic information produced by rotating various disks. Experiment 2 aimed to implement the same procedure, but with participants wearing earplugs to cancel any influence sound may have had on their perceptions and judgments of disk diameter. If sound did not have a strong influence, the results should replicate Experiment 1; therefore, all hypotheses from Experiment 1 were again expected in Experiment 2. In short, the aim of this second experiment was to examine whether or not findings produced in the first experiment would replicate without access to additional acoustic information. Replication of the results of Experiment 1 would support the argument that sound differences cannot be an alternative explanation.

Method

Participants. Twenty-eight undergraduate participants of any gender and at least 18 years of age were recruited voluntarily using the SONA system at Appalachian State University. Participants were screened by self-report for neuromuscular disorders that might interfere with performing the task and none were excluded for that reason. Participants received course credit for their participation.

Apparatus and Stimuli. The same apparatus and stimuli used in the first experiment were used for the second experiment. The exception being that participants' access to the sound of the disk rotations was removed using foam earplugs.

Procedure. The same procedure used in the first experiment was used for the second experiment. Some minor changes to the script were implemented. This experiment included instructions that informed participants they would be required to wear earplugs. Instructions also emphasized that participants should not spin the disk too quickly, on the basis that sound was produced only when participants were moving the disk at fast speeds.

Results

Results from this experiment were analyzed treating the first block as a preliminary familiarization trial. Now only 25 trials across five blocks were included in the results. Data analysis began by translating the ordinal judgments provided by participants to scalar disk diameters for the purposes of statistical analysis. For example, a disk judged as a "2" was analyzed as its scalar diameter in centimeters (12 cm for this particular case). First, a repeated measures ANOVA test was conducted to test for global differences among the judgments offered by participants; follow-up post hoc pairwise

comparison *t*-tests were used to examine if participants were discriminating among adjacent disks in the series. Lastly, a linear regression analysis was conducted to examine the direction and strength of the relationship between actual disk diameter and perceived judgments of disk diameter.

ANOVA. An initial 5 (disk diameters) x 5 (trial blocks) repeated measures ANOVA showed a strong main effect for diameter, $F(4, 108) = 553.33, p < .001, \eta_p^2 = .95$. The significant main effect for disk diameter indicates that judgments for disk diameter were significantly different for the different disks in the series (see Figure 9). The results indicate a nonsignificant main effect for blocks, $F(4, 108) = .451, p = .77$. The nonsignificant main effect for block indicated that there was no significant difference in performance from among any of the trial blocks (see Figure 10). The interaction between disk diameter and block was also nonsignificant, $F(16, 432) = 0.96, p = .50$. The nonsignificant interaction indicated that that performance did not differ across blocks.

Post hoc pairwise comparisons, using average perceived judgments over all blocks for each participant, demonstrated significant differences among all 10 comparisons, all Bonferonni-corrected, $t(27) > 9.50$, all $p < .001$, all Cohen's $d > 1.90$. The post hoc pairwise comparisons indicate that each disk was perceived differently from adjacent disks (see Table 3).

Regression. A simple linear regression was calculated to predict perceived disk diameter based on actual disk diameter. A significant regression equation was found ($F(1, 698) = 2278.73, p < .001$) with an $R^2 = .76$. The relationship between judged diameter and actual diameter using all measures for all participants yielded a significant

relationship ($r = .87$, $n = 700$ data points, $p < .001$) with a slope of 1.22 and an intercept of -2.86. The regression values indicate that if a participant was presented with a 12 cm diameter disk, the regression model would predict their response to be a 11.78 cm judgment. The regression results indicated that judgments were both highly reliable and highly accurate.

Discussion

The results of Experiment 2 demonstrated participants could make reliable and accurate judgments of disk diameter, by means of reciprocally pulling a string to rotate disks of varying diameter even when they did not have access to acoustic information from the rotating disks. Similar to Experiment 1, participants were able to detect differences among the disk diameters, to rank the diameters in an ordinal fashion, and to rank the diameters onto a reliable scale. Results from the repeated measures ANOVA indicated that global differences were present among disk diameter judgments. Post hoc pairwise comparisons indicated that participants were able to discriminate between adjacent disks. This results provide support for the interpretation that inertial information is sufficient for differentiating relatively small gradations between object physical properties. The strength of participants' ability to discriminate disks (all comparisons indicated Cohen's $d > 1.80$) suggests that our perceptible systems may be sensitive to finer differentiations. Regression analysis demonstrated a positive, linear relationship present between perceived judgments of disk diameter and the actual disk diameters

The second experiment produced stronger effects than the first experiment. A possible explanation for this increase in effect is that participants may have been less distracted due to the earplugs, forcing them to focus solely on the forces they feel in their

forefingers. Distractions from classrooms outside of the lab may also have been operating in Experiment 1 and the use of earplugs may have limited that distraction as well. The current results contradict the results by Mortensen et al. (2009). In their paradigm, they found that participants trials using combined sensory modalities produced the best performance; however, the authors do note that the condition with unimodal haptic information most closely approximated the condition with combined sensory information. It could be the case that the haptic information provided throughout the current task is the best predictor of performance and that the excess auditory information served more as a distractor since it was not directly relative to the task at hand.

Although large effect sizes reported in Experiment 1 and Experiment 2 are not entirely rare in psychophysics research, there may be an alternative explanation for the results reported here. Perhaps, given the relatively small number of response alternatives available, participants might have learned to associate the stimuli's physical properties with particular displays for responses. Simply put, participants may have been able to rank order the stimulus array onto a limited visual response array, producing spurious accuracy. Experiment 3 examined this issue by enlarging the number of possible answers while using the same stimulus set. Participants could no longer rely on a limited range to guide their answers. If participants can use inertia information to deduce the size of a disk, then that relationship should still be present when the number of response choices are increased.

Experiment 3

The findings reported in Experiment 1 and Experiment 2 supported the theoretical logic and the effects are still quite substantial. But the methodology may have provided additional information. It is possible that the strength of relationships from the first two experiments could be inflated because participants had a constrained response set and a limited number of disk stimuli. Participants may have begun associating stimuli with a discrete response and this could have influenced their perception of the disk.

The strength of the effects in the prior two experiments may have been exaggerated because participants were not absolutely differentiating disk diameters based solely on inertia, but, instead, participants had learned to pair a given disk stimuli with a particular discrete response. Given that there were only five disks and only seven possible responses, it is possible that participants were constrained to associate characteristics of a particular stimulus with a particular display response. The purpose of Experiment 1 and Experiment 2 was to have participants quantitatively estimate the diameter of the disk based on the inertial information provided by the apparatus. However, quantitative estimation is more complex than solely numeric induction. There is evidence that estimation is comprised of three major components: domain-specific knowledge, use of heuristics, and numeric induction (Brown & Siegler, 1993). The goal of the third experiment was to have participants assign numeric values to the disk diameter without relying on a small number of predefined answers.

The procedure was changed to approximate an absolute judgment task by having participants choose from a wider array of response alternatives. A new, flexible response measure was implemented. The methodology involved a monitor displaying images that

the participant could alter while operating the apparatus, instead of fixed poster images as in previous experiments. The monitor displayed images of circles and participants could increase or decrease the size of the image by using a foot pedal switch. Participants were able to manipulate the size of the displayed image from an array of images and were instructed to choose the image that they believed to have a diameter equal to the diameter of the disk they were perceiving via reciprocally pulling the strings of the apparatus. This new response measure provided more and finer gradations among disk stimuli from 2 cm to 0.5 cm and increased the number of response alternative from 7 to 28 possibilities.

Prior theory would predict that individual's perceptual systems would be sensitive to and ultimately able to detect the physical changes in diameter. Prior literature would predict that the change in response measure should not eliminate the effect. However, it is not unlikely that a weaker effect might be demonstrated given the increased amount of response variability being introduced with the new paradigm. The number of potential responses increased from 7 responses to 28 responses. The prediction was that when presented with disks of different diameters, participants will reliably and accurately discriminate objects, rank the objects ordinally based on magnitude, and attach scalar values close in size to the actual objects. Additionally, the expectation is to replicate statistically significant differences among adjacent stimuli (a 12 cm disk will be reported as significantly different than a 14 cm disk). Lastly, the positive, linear relationship is predicted to persist even when using a new response paradigm. In short, the aim of this third experiment is to examine whether or not findings produced in the earlier experiments replicated when using a more flexible response measure.

Method

Participants. Twenty-nine undergraduate participants of any gender and at least 18 years of age were recruited voluntarily using the SONA system at Appalachian State University. Participants were screened by self-report for relevant neuromuscular disorders and none were excluded. Participants received course credit for their participation.

Apparatus and Stimuli. The same basic apparatus and stimuli used in the first and second experiment was used for the third experiment. Although the same basic apparatus was used, there were several modifications with respect to the response mechanism participants used to provide their judgments of the occluded object.

The visual poster of the disk array was replaced with a monitor displaying an image of a circle to represent a possible diameter response. Participants were able to alter the image displayed on the screen by using a foot pedal switch located below the apparatus. Participants could actively update their judgments of object size while simultaneously rotating the disk. Participants pressed left on the foot pedal to reduce the size of the displayed image and participants pressed right on the foot pedal to increase the size of the displayed image. Each press of the pedal altered the size of the image by changing the diameter by .5 cm in the specified direction.

All images were displayed using Microsoft PowerPoint presentation software and five images were the exact diameter of the actual disk. There were two monitors, with one on either side of the barrier separating the experimenter and the participant. The monitor on the side of the experimenter allowed the experimenter to reset the image displayed between trials as well as record participants' responses. The monitor on the

side of the participant only displayed the images, which participants used to report their judgments of disk diameter.

The third experiment used the same disks (ranging from 12 cm to 20 cm, increasing in 2 cm increments); however, the possible images participants were able to generate as their responses ranged from 9 cm to 23 cm, in 0.5 cm increments. There were no numbers attached to disk sizes from the participant's view. This range was chosen to give participants room to vary beyond the range of actual disk diameters as well as provide finer gradations between disks from the poster representation used in Experiment 1 and Experiment 2. In the first two experiments, participants' responses were limited to seven possible choices. In this third experiment, participants responses was expanded from seven to 28 possible choices.

Procedure. The procedure for the third experiment closely matched the first two experiments, with the difference being changes regarding the foot pedal mechanism.

After obtaining the informed consent of the participant, the experimenter read standardized instructions to the participant, explaining the details of the task. The experimenter demonstrated how to insert the forefingers into the loops attached to the shaft, how to move the rings to rotate the shaft, and how to operate the foot pedal switch. The experiment began after ensuring the procedure was clear to the participant.

Each trial began with the participants' hands outside the apparatus. The experimenter set the monitor to display the midpoint of possible images that comprise the response disk array (a 16 cm in diameter image of a circle). The experimenter attached the disk to be used for that trial to the shaft and instructed the participant to insert his or her forefingers into the rings and to begin rotating the disk by reciprocally pulling on the

strings. Participants were allowed to rotate the disk as long as they desired before making a judgment. When he or she felt that the stimulus had been adequately perceived and had selected the image believed to be equal to the actual disk diameter, the participant told the experimenter to confirm the image on the monitor as the response for the current trial. The participant then stopped rotating the disk and removed their hands from the apparatus. The experimenter removed the disk and replaced it with the disk to be used for the next trial. Before beginning the succeeding trial, the experimenter would reset the image on the monitor to the midpoint of the response disk array.

Disks were presented in blocks of five trials, with the five disk diameters randomized within each block. Participants were presented with six counterbalanced blocks of trials to circumvent any order effects based on stimuli presentation; the first block was treated as a familiarization block and was excluded from any analyses. Similar to earlier experiments, each experimental session was completed within 30 min, including instructions, testing, and debriefing.

Results

Results from this experiment were analyzed treating the first block as a preliminary familiarization trial. The 25 trials across five blocks were examined. Data analysis began by translating the numbers attached to judgments provided by participants via the images selected to actual, scalar disk diameters for the purposes of statistical analysis. Judgments provided by participants were values between 1 and 28 based on the image selected. The values provided by participants were translated into metric values ranging from 9 cm (1) to 23 cm (28). First, a repeated measures ANOVA test was conducted to test for global differences among the judgments offered by participants;

follow-up post hoc pairwise comparison *t*-tests were used to examine if participants were discriminating between adjacent disks. Lastly, a linear regression analysis was conducted to examine the direction and strength of the relationship between actual disk diameter and perceived judgments of disk diameter.

ANOVA. An initial 5 (disk diameters) x 5 (trial blocks) repeated measures ANOVA showed a strong main effect for diameter, $F(4, 112) = 263.26, p < .001, \eta_p^2 = .90$. The significant main effect for disk diameter indicates that judgments for disk diameter were significantly different for the different disks in the series (see Figure 11). The results indicate a nonsignificant main effect for blocks, $F(4, 112) = 0.78, p = .54$. The nonsignificant main effect for block indicated that there was no significant difference among performances of the trial blocks (see Figure 12). The interaction between disk diameter and block was also nonsignificant, $F(16, 448) = 1.31, p = .19$. The nonsignificant interaction indicated that that performance did not differ across blocks.

Post hoc pairwise comparisons, using average perceived judgments over all blocks for each participant, demonstrated significant differences among all 10 comparisons, all Bonferonni-corrected, $t(28) > 5.59$, all $p < .001$, all Cohen's $d > 1.47$. The post hoc pairwise comparisons indicate that each disk was perceived differently from adjacent disks (see Table 4).

Regression. A simple linear regression was calculated to predict perceived disk diameter based on actual disk diameter. A significant regression equation was found ($F(1, 723) = 1130.35, p < .001$) with an $R^2 = .61$. The relationship between judged diameter and actual diameter using all measures for all participants yielded a significant relationship ($r = .78, n = 725$ data points, $p < .001$) with a slope of 1.01 and an intercept

of -0.12. The regression values indicate that if a participant was presented with a 12 cm diameter disk, the regression model would predict their response to be a 12 cm judgment. These values from the regression analysis indicated that judgments were both highly reliable and highly accurate.

Discussion

Participants were asked to make diameter judgments when only exposed to the inertial properties of disks to test Carello and Turvey's (2004) conclusion that inertial information was sufficient to inform judgments of disk diameter. Participants used a novel response mechanism that provided finer gradations as well as more variability in participant responses. The results from Experiment 3 indicate that, as reported in Experiment 1 and Experiment 2, participants were able to discriminate between disks of varying inertial magnitude. Moreover, Experiment 3 demonstrated that participants were capable of making reliable and generally accurate judgments of disk diameter by means of string-mediated inertial force. The results replicated participants' ability to detect diameter differences among the disk stimuli, to rank the diameters in an ordinal fashion, and to place the ordinal diameter judgments onto a linear scale.

Inferential statistics produced from the repeated measures ANOVA detected global differences among disk diameter judgments, albeit slightly weaker in effect size compared to previous experiments. Follow-up post hoc pairwise comparisons illustrated that participants were able to discriminate between adjacent disks based on information about inertial magnitude. This finding supports the prediction that inertial information is sufficient for differentiating relatively small gradations among stimuli's physical properties. The effect sizes produced from the pairwise comparisons (all Cohen's $d >$

1.47) provide support that participants may have the ability to detect even finer differentiations than discovered in Experiment 1 and Experiment 2. Furthermore, a simple linear regression demonstrated a positive, linear relationship existed between perceived judgments of disk diameter and the actual disk diameter. Again, the regression data supports the hypothesis that this positive, linear relationship would be produced between perception and physical differences using the method described here.

The third experiment produced a slightly weaker effect size ($\eta_p^2 = .90$ compared to $\eta_p^2 = .95$ in Experiment 2). This effect size is still quite substantial, and the difference was expected given the constrained nature of responses of the prior experiments' response choices. Additionally, the third experiment was a more conservative demonstration given the potential influence of a centered anchor as participants started each trial at the midpoint of the scale. The pattern of results produced in Experiment 3 are consistent with the analysis from Carello and Turvey (2004). This experiment produced comparably large effect sizes along with the previous two experiments. It seems unlikely that earlier experiments could be explained by the relatively small number of disks used and the potential for a given participant to learn to associate stimuli's physical properties with particular discrete responses.

Experiment 3 adopted a response measure that approached absolute estimation rather than comparative estimation. Given this change to more possible responses, the persistence of a strong effect in Experiment 3 suggests the validity of this novel task at capturing the sufficiency of inertia to provide object information to the haptic system. Ultimately, results from this experiment corroborate the pattern of results obtained in previous experiments and it appears the response measure in the earlier studies was not

the explanation of the accuracy in Experiment 1 and Experiment 2. Future work is required to discern the role of other alternative explanations, namely the novel task and novel stimuli used in all the experiments of the current study.

General Discussion

The series of experiments presented here provide empirical support for interpretations reported in Carello and Turvey (2004) and Cabe (2010) that inertial information is a primary informant to the haptic system about object properties. Carello and Turvey (2004) tested this suggestion through a number of studies involving wielding rods and their work provided a theoretical explanation revolving around eigenvalues of the inertia tensor model. Later, Cabe (2010) demonstrated the ability to perceive physical magnitudes without accessing static moment or mass. Cabe (2010) explored the generality of Carello and Turvey's (2004) theory by having participants roll cylinders instead of wield rods and found sufficiency of the weakest vector in the ellipsoid model. The current methodology adopted a paradigm that attempts to inform haptic perception via inertial force without allowing access to other mechanical invariants such as the static mass of the object that is perceived when directly wielding said object. Using a novel apparatus in a novel paradigm, all three experiments provided evidence supporting the sufficiency of string-mediated inertial force-based perception of disk diameter. Experiment 1 demonstrated the effect in a simple fashion and the subsequent experiments tested the generality. Experiment 2 replicated findings from Experiment 1 after reducing additional acoustic information that may have influenced participant responses. Experiment 3 replicated the findings from Experiment 1 and Experiment 2 with a less-

constrained response mechanism where learning to associate the magnitude of a stimuli to a discrete response was much more difficult than in previous experiments.

The results of the current experiments provide strong support for the Carello and Turvey (2004) account that inertial information is sufficient to discriminate between object stimuli as well as rank those objects in some of ordinal fashion with accuracy. It appears that string-mediated inertial force can still provide enough haptic information to make accurate judgments, even when the object is not handled directly.

It is worth noting that the current series of experiments does not entirely rule out the Kingma et al. (2004) position. The current procedure did not manipulate mass and inertia separately. The two factors were confounded and the results could still be a product of perception influenced by the mass of the object, through inertia. For instance, since mass is related to inertia, it is possible that judgments were based on access to the object's mass rather than the object's inertia. Across all experiments, the strength of effect was stable which suggests that there was no significant interaction based on the presence or absence of acoustic information and there was no significant interaction based on the response mechanism, neither a discrete visual response set or an approximately scalar response mechanism.

Limitations

The chief limitation of the current study is that the procedure used a novel task. The results from these experiments may or may not replicate with inertia administered in a different way. For instance, experiments may produce different results if participants access the inertia by spinning the shaft itself rather than strings attached to the shaft. A

new procedure should administer inertia in another way and investigate if participants remain accurate.

A possible limitation is the novel set of disk stimuli used in the current study. Each experiment used the same range of stimuli. It is possible that increasing the number of disks and introducing finer gradations between stimuli could produce differential results. The five disk stimuli used in this study are well within the bounds of working memory capacity. Given the amount of time required to complete a trial, the amount of time between trials, and the fact that there was no other task competing for cognitive resources, it is possible that participants made memory representations of the differences in inertia. A simple way to test the possibility of participant reliance on working memory representations would be to increase the number of disks while keeping the difference between each disks' inertia comparable to the disks used in the current study. Another way to test the possibility of memory representations could be to introduce a secondary task to divide attention and compete for cognitive resources. If working memory capacity is driving the effect, results should indicate a decrease in performance in divided-attention conditions. Furthermore, it is likely that people are processing haptic information with divided-attention in real-world situations. Future research should investigate the possibility that the results reported here are partially a product of working memory.

Similarly, each experiment used the same range of masses. The range of masses for the disks could be increased or decreased to investigate potential changes in participant accuracy. Each disk used in this study was aluminum and masses ranged from 97 g to 257 g. If each disk was a denser material, the range of masses would be higher

and future experiments could test if increasing the range of masses produces different results. Additionally, each disk could be a lighter material and the range of masses would be lower. The masses used in the current study were discriminable by participants and thus provide little information about the just-noticeable-difference among stimuli. Using a lower range of masses could provide information about the just-noticeable-difference among stimuli for the novel task used in the current study. The accuracy of participant judgments in each experiment reported here seems to suggest that a higher range of masses would likely produce similar results but provides little information about a lower range of masses or the just-noticeable-difference among stimuli. Future research should examine potential changes in accuracy with a lower range of masses.

A potential limitation exists in the methodology for the third experiment. In this experiment, the image participants see beginning every trial was the same image – the midpoint of the response scale array (or a 16 cm image of a circle). This fact introduces the possibility of an anchoring effect, where participants are more likely to respond closely to where they started. Results from Experiment 3 show the simple effects of disk diameter across trials more closely correspond to actual disk diameters. In Experiments 1 and 2, there was a tendency for participants to underestimate diameters at the lower end of the array and overestimate diameters at the higher end of the array. The difference in results between Experiment 3 and Experiments 1 and 2 might be an anchoring effect or it might have been that the response scale used in Experiments 1 and 2 influenced the under- and overestimation of diameter at extreme stimuli values. Given the benefits of the scalar response mechanism and the strength of effects observed, the anchoring effect appears to be insignificant because it does not provide an alternative explanation for the

series of results – rather, this centered anchor only provides a more conservative demonstration of the effect. A method to test this limitation could manipulate the starting image on the array of possible responses to see if changes in the pattern of results is produced.

Although this series of experiments demonstrate that participants could readily differentiate circular disks varying in diameter, it is worth acknowledging that diameter co-varied with both moment of inertia and mass. That is, as mass increased so did diameter; likewise, as moment of inertia increased, diameter and mass also increased. This confound begs the question on whether participants may have based their judgments on mass rather than (or in accordance with) inertial information.

Implications for Future Research

Considering much of haptic perception research is funded by research groups for the blind and much of the inherent beneficence for haptic research is relative to blind populations, it is questionable whether or not the findings in this study will generalize to blind populations. Undergraduate college students have access to several mental representations from vision and previous encounters with objects; however, blind populations will not have the same mental representations of objects as college undergraduates. Despite blind individuals not having access to the same visual-mental representations, it is reasonable to predict that blind individuals may portray better performance in a task limiting information to only haptic information; the rationale behind this prediction is that blind populations have to rely more heavily on their haptic perception systems and, in turn, they may be more attuned to the nuances of haptic information since they rely on such information to interact and communicate with the

physical world. A method to test this in the future could involve testing for differences in thresholds between the sighted and the blind.

Future experiments should attempt to detangle mass and moment of inertia. In order to settle the question on what the governing informant is, one could construct disks that (a) have a constant moment of inertia with varying diameter and mass; (b) have constant mass, with varying diameter and moment of inertia; or (c) have constant diameter, with varying mass and moment of inertia. To pursue these manipulations, one could keep a given physical property constant while varying the other two physical properties by means of constructing disks that differ in thickness. Ultimately, this series of experiments provides ample evidence for the sufficiency of inertial information, but more work is required to test the necessity of inertial information in force-based haptic perception of object stimuli.

Conclusion

Haptic perception relies on using dynamic touch to perceive physical information in the environment. Humans are sensitive to the haptic information in the environment. For example, humans can estimate how much water is in a bottle just by simply picking it up. Theorists have argued the exact physical variables responsible for this sort of skill with the literature demonstrating strong support for inertial information as the governing informant to the haptic system. In this study, participants were asked to identify disk diameter in a novel task when presented with the rotational inertia of the disk. People were able to do so with high accuracy and reliability. Potential alternative explanations were tested in follow-up experiments and the initial results were confirmed. Each subsequent experiment reported accurate and reliable judgments of disk diameter. These

findings provide additional support to the sufficiency of inertial forces to explain haptic perception of disk diameter. Future experiments are needed to test the generality of the use of inertia information in other situations.

References

- Amazeen, E. L., & Turvey, M. T. (1996). Weight perception and the haptic size-weight illusion are functions of the inertia tensor. *Journal of Experimental Psychology: Human Perception and Performance*, *22*, 213-232. doi:10.1037//0096-1523.22.1.213
- Brown, N. R., & Siegler, R. S. (1993). Metrics and mappings: a framework for understanding real-world quantitative estimation. *Psychological Review*, *100*, 511-534.
- Burton, G., Turvey, M. T., & Solomon, H. Y. (1990). Can shape be perceived by dynamic touch? *Perception & Psychophysics*, *48*, 477-487.
- Cabe, P. A. (2010). Sufficiency of longitudinal moment of inertia for haptic cylinder length judgments. *Journal of Experimental Psychology: Human Perception and Performance*, *36*, 373-394. doi:10.1037/a0018395
- Carello, C., Flascher, I., Kunkler-Peck, A., & Turvey, M. T. (1999). Evaluation of context effects in dynamic touch. *Ecological Psychology*, *11*, 189-208. doi:10.1207/s15326969eco1103_1
- Carello, C., & Turvey, M. T. (2000). Rotational invariants and dynamic touch. In M. Heller (Ed.), *Touch, representation and blindness* (pp. 27-66). Oxford, United Kingdom: Oxford University Press.
- Carello, C., & Turvey, M. T. (2004). Physics and psychology of the muscle sense. *Current Directions in Psychological Science*, *13*, 25-28. doi:10.1111/j.0963-7214.2004.01301007.x

- Chan, T.C., & Turvey, M. T. (1991). Perceiving the vertical distances of surfaces by means of a hand-held probe. *Journal of Experimental Psychology: Human Perception and Performance*, *17*, 347-358. doi:10.1037/0096-1523.17.2.347
- Fitzpatrick, P., Carello, C., & Turvey, M. (1994). Eigenvalues of the inertia tensor and exteroception by the “muscular sense”. *Neuroscience*, *60*, 551-568.
doi:10.1016/0306-4522(94)90264-x
- Fitzpatrick, P., & Flynn, N. (2010). Dynamic (kinesthetic) touch perception in preschool children. *Ecological Psychology*, *22*, 89-118. doi:10.1080/10407411003719983
- Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston, MA: Houghton Mifflin.
- Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston, MA: Houghton Mifflin.
- Grunwald, M. (2008). *Human haptic perception: Basics and applications*. Basel, Sweden: Birkhäuser.
- Kingma, I., Beek, P. J., & van Dieën, J. H. (2002). The inertia tensor versus static moment and mass in perceiving length and heaviness of hand-wielded rods. *Journal of Experimental Psychology: Human Perception and Performance*, *28*, 180-191. doi:10.1037//0096-1523.28.1.180
- Kingma, I., van de Langenberg, R., & Beek, P. J. (2004). Which mechanical invariants are associated with the perception of length and heaviness of a nonvisible handheld rod? Testing the inertia tensor hypothesis. *Journal of Experimental Psychology: Human Perception and Performance*, *30*, 346-354.
doi:10.1037/0096-1523.30.2.346

- Kloos, H., & Amazeen, E. L. (2002). Perceiving heaviness by dynamic touch: An investigation of the size-weight illusion in preschoolers. *British Journal of Developmental Psychology, 20*, 171-183. doi:10.1348/026151002166398
- Lederman, S. J., Ganeshan, S. R., & Ellis, R. E. (1996). Effortful touch with minimum movement: Revisited. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 851-868. doi:10.1037//0096-1523.22.4.851
- Mortensen, D. H., Bech, S., Begault, D. R., Adelstein, B. D. (2009) The relative importance of visual, auditory, and haptic information for the user's experience of mechanical switches. *Perception, 38*, 1560-71. doi:10.1068/p5929
- Pagano, C. C., & Turvey, M. T. (1993). Perceiving by dynamic touch the extents of irregular objects. *Ecological Psychology, 5*, 125-151.
doi:10.1207/s15326969eco0502_2
- Peck, A. J., Jeffers, R. G., Carello, C., & Turvey, M. T. (1996). Haptically perceiving the length of one rod by means of another. *Ecological Psychology, 8*, 237-258.
doi:10.1207/s15326969eco0803_3
- Solomon, H. Y., & Turvey, M. T. (1988). Haptically perceiving the distances reachable with hand-held objects. *Journal of Experimental Psychology: Human Perception and Performance, 14*, 404-427. doi:10.1037//0096-1523.14.3.404
- Solomon, H. Y., Turvey, M. T., Burton, G. (1989). Perceiving extent of rods by wielding: Haptic diagonalization and decomposition of the inertia tensor. *Journal of Experimental Psychology: Human Perception and Performance, 15*, 58-68.
doi:10.1037/0096-1523.15.1.58

Streri, A., & Spelke, E. S. (1988). Haptic perception of objects in infancy. *Cognitive Psychology*, 20, 1-23. doi:10.1016/0010-0285(88)90022-9

Turvey, M. T., Burton, G., Pagano, C. C., Solomon, H. Y., & Runeson, S. (1992). Role of the inertia tensor in perceiving object orientation by dynamic touch. *Journal of Experimental Psychology: Human Perception and Performance*, 18, 714-727. doi:10.1037//0096-1523.18.3.714

Turvey, M. T., & Carello, C. (1995). Dynamic touch. In W. Epstein & S. Rogers (Eds.), *Perception of space and motion* (pp. 401-490). San Diego, California: Academic Press.

van de Langenberg, R., Kingma, I., & Beek, P. J. (2006). Mechanical invariants are implicated in dynamic touch as a function of their salience in the stimulus flow. *Journal of Experimental Psychology: Human Perception and Performance*, 32, 1093-1106. doi:10.1037/0096-1523.32.5.1093

Tables

Table 1.

Pairwise Comparisons of Disk Diameter Averaged Across Blocks

Diameter		Mean Difference	<i>t</i>	<i>df</i>	<i>p</i>	<i>d</i>
12	14	-2.09	-8.81	29	< .001	1.69
	16	-4.76	-15.88	29	< .001	2.90
	18	-7.26	-24.67	29	< .001	4.50
	20	-8.53	-33.20	29	< .001	6.06
14	16	-2.67	-12.84	29	< .001	2.34
	18	-5.17	-23.23	29	< .001	4.24
	20	-6.44	-28.93	29	< .001	5.28
16	18	-2.50	-14.67	29	< .001	2.68
	20	-3.78	-19.15	29	< .001	3.50
18	20	-1.28	-8.38	29	< .001	1.53

Note. The information provided in this table is the pairwise comparisons for all comparisons among disk stimuli for Experiment 1. The first column illustrates the two disk diameters being compared. Mean differences were used to calculate *t*-values, which in turn informed significance (*p*-values) and effect sizes (Cohen's *d*). Judgments of disk diameter were averaged across blocks for each participant.

Table 2.

Pairwise Comparisons of Disk Diameter for Block 1 Averages

Diameter		Mean Difference	<i>t</i>	<i>df</i>	<i>p</i>	<i>d</i>
12	14	-0.20	-0.34	29	.735	0.09
	16	-3.13	-4.68	29	< .001	1.03
	18	-5.40	-8.29	29	< .001	2.09
	20	-6.07	-11.28	29	< .001	2.45
14	16	-2.93	-5.05	29	< .001	1.00
	18	-5.20	-10.51	29	< .001	2.14
	20	-5.87	-11.18	29	< .001	2.53
16	18	-2.26	-3.80	29	< .001	0.73
	20	-2.93	-3.77	29	< .001	0.97
18	20	-0.67	-0.98	29	.335	0.26

Note. The information provided in this table is the pairwise comparisons for all comparisons among disk stimuli for Block 1 of Experiment 1. The first column illustrates the two disk diameters being compared. Mean differences were used to calculate *t*-values, which in turn informed significance (*p*-values) and effect sizes (Cohen's *d*). Judgments of disk diameter were averaged across Block 1 for each participant.

Table 3.

Pairwise Comparisons of Disk Diameter Averaged Across Blocks

Diameter		Mean Difference	t	df	p	d
12	14	-2.46	-10.03	27	< .001	1.90
	16	-5.56	-18.80	27	< .001	3.56
	18	-7.70	-31.56	27	< .001	5.97
	20	-9.56	-42.52	27	< .001	8.03
14	16	-3.10	-12.94	27	< .001	2.44
	18	-5.24	-19.03	27	< .001	3.59
	20	-7.10	-38.20	27	< .001	7.22
16	18	-2.14	-9.50	27	< .001	1.80
	20	-4.00	-21.34	27	< .001	4.03
18	20	-1.86	-10.85	27	< .001	2.04

Note. The information provided in this table is the pairwise comparisons for all comparisons among disk stimuli for Experiment 2. The first column illustrates the two disk diameters being compared. Mean differences were used to calculate t -values, which in turn informed significance (p -values) and effect sizes (Cohen's d). Judgments of disk diameter were averaged across blocks for each participant.

Table 4.

Pairwise Comparisons of Disk Diameter Averaged Across Blocks

Diameter		Mean Difference	<i>t</i>	<i>df</i>	<i>p</i>	<i>d</i>
12	14	-1.41	-5.59	28	< .001	1.47
	16	-4.11	-17.29	28	< .001	4.54
	18	-6.28	-18.60	28	< .001	4.89
	20	-7.70	-21.34	28	< .001	5.60
14	16	-2.71	-10.10	28	< .001	2.65
	18	-4.87	-14.59	28	< .001	3.83
	20	-6.29	-18.55	28	< .001	4.87
16	18	-2.17	-10.55	28	< .001	2.77
	20	-3.58	-14.40	28	< .001	3.78
18	20	-1.42	-9.41	28	< .001	2.47

Note. The information provided in this table is the pairwise comparisons for all comparisons among disk stimuli for Experiment 3. The first column illustrates the two disk diameters being compared. Mean differences were used to calculate *t*-values, which in turn informed significance (*p*-values) and effect sizes (Cohen's *d*). Judgments of disk diameter were averaged across blocks for each participant.

Figures

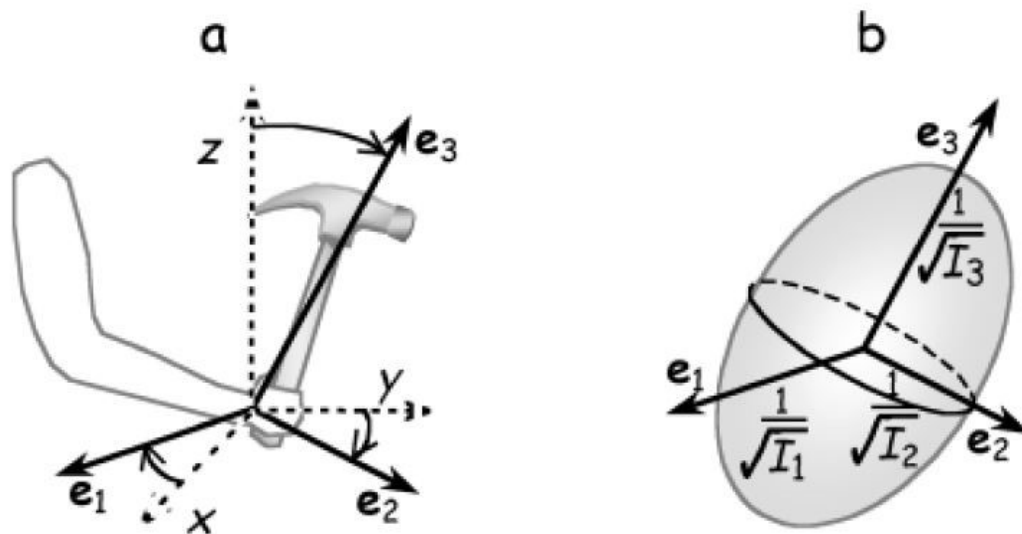


Figure 1. Wielding an object described in terms of inertial information via the inertia tensor model. As depicted by (a), the origin of inertial information for wielding an object is the wrist. Inertia of the object is calculated with respect to an arbitrary xyz axes. Principal moments of inertia (I_1, I_2, I_3) are transformed into symmetry axes (e_1, e_2, e_3) such that the mass is distributed evenly. As shown in (b), the inertia tensor model constructed from the inverse of the square root of the moments of inertia along the symmetry axes. Figure adapted from “Physics and psychology of the muscle sense,” by C. Carello and M. T. Turvey, 2004, *Current Directions of Psychological Science*, 13, p. 25-28.

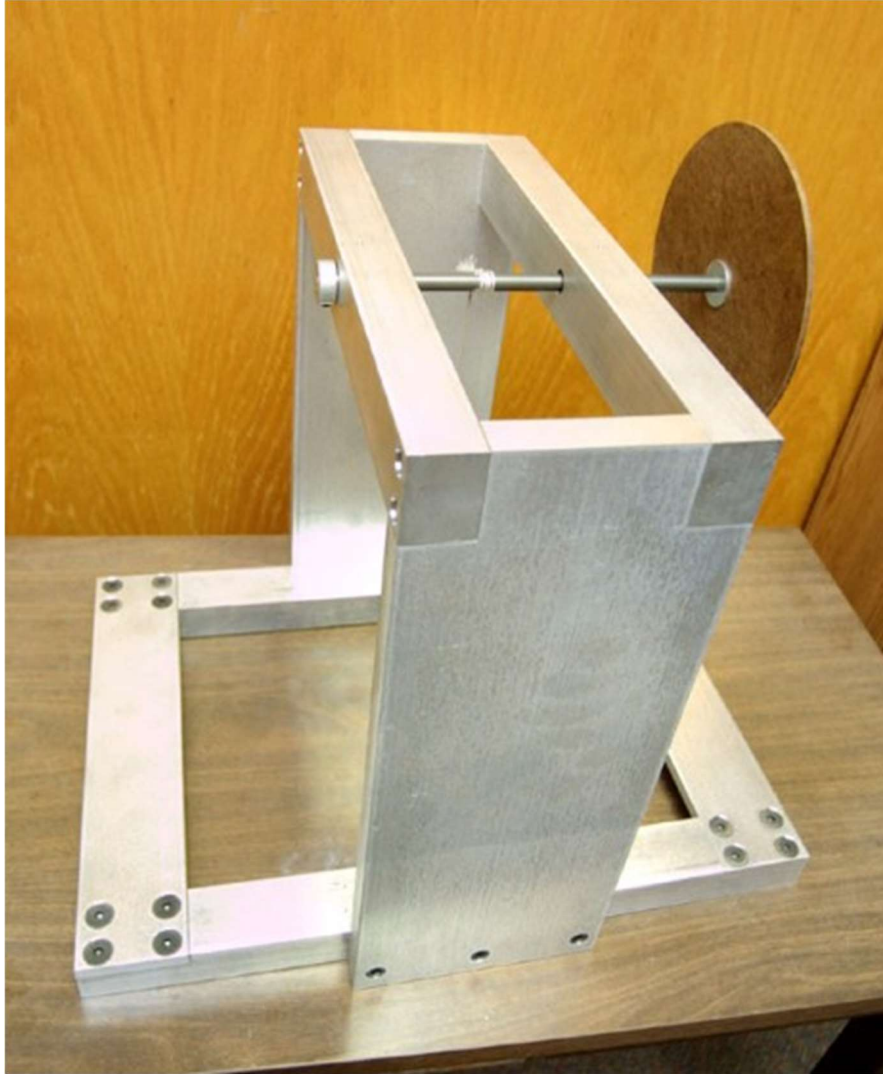


Figure 2. The frame of the apparatus, showing the central shaft to which the stimulus disks was attached. The entire frame is approximately 38 cm high x 46 cm wide x 36 cm deep. The central component supporting the shaft is 15 cm deep. Disks of varying diameter can be attached to the shaft by means of a thumb screw through the center of the disk and threaded into one end of the shaft. A string wraps around the shaft, mid-way along the shaft's length, with metal rings (approximately 4 cm in diameter) attached to each end of the string.



Figure 3. Views of the apparatus within its enclosure. Left panel: view from the participant's perspective. A box-like cover encloses the framework, leaving open the end through which participants insert their hands. The opposite end of the enclosure is a vertical sheet (125 cm wide x 64 cm high) that occludes the disk stimuli as well as the actions of the experimenter from the view of the participant. Right panel: view from the experimenter's perspective.

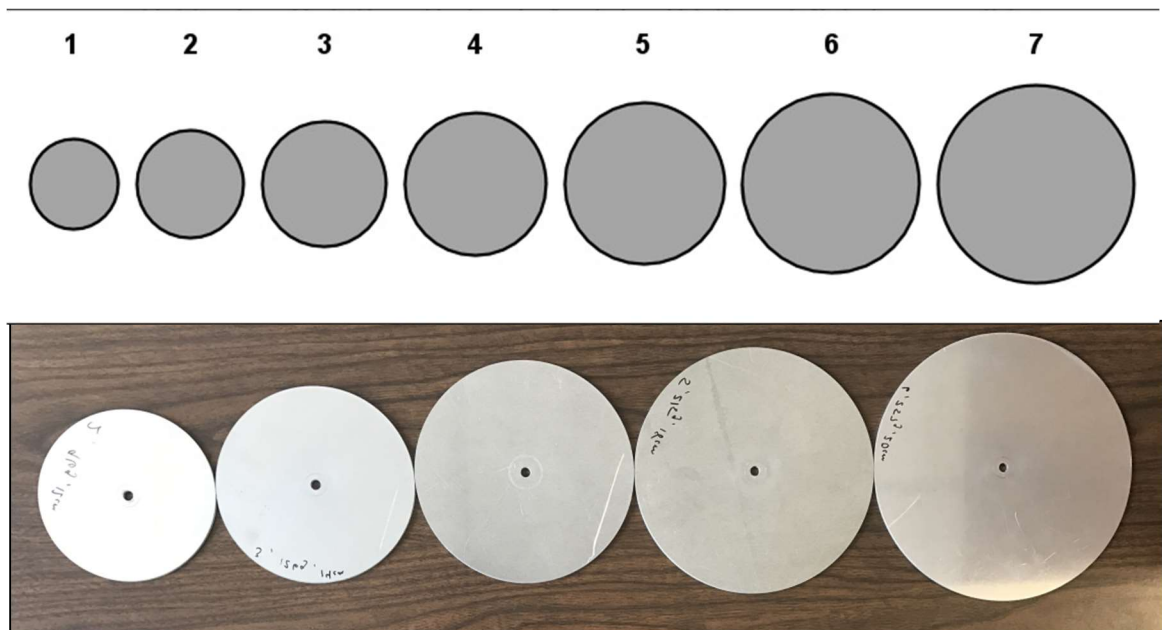


Figure 4. View of the stimuli. Top panel: visual poster representation of possible participant responses. Bottom panel: actual disk stimuli made from aluminum.

The five operational disks were made of 0.32 cm-thick aluminum, with diameters ranging from 12 cm to 20 cm, increasing in 2 cm increments. The mass of the operational disks are as follows: 96 g, 126 g, 169 g, 215 g, and 257 g.

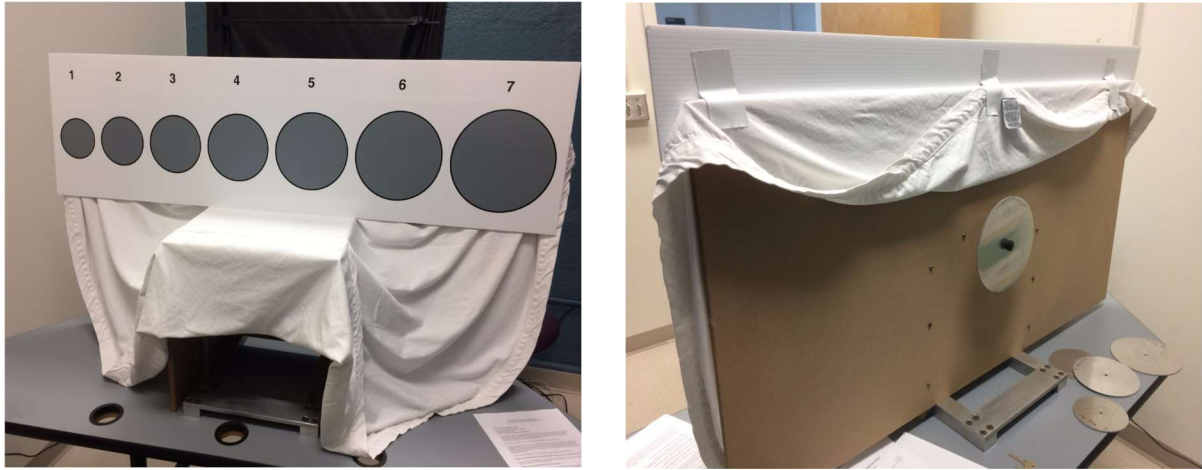


Figure 5. View of apparatus after all additions. A curtain was used to cover the box where participants place their hands. Visual representation attached to the screen that separates the participant and the experimenter. Left panel: view from the participant's perspective. Right panel: view from the experimenter's perspective.

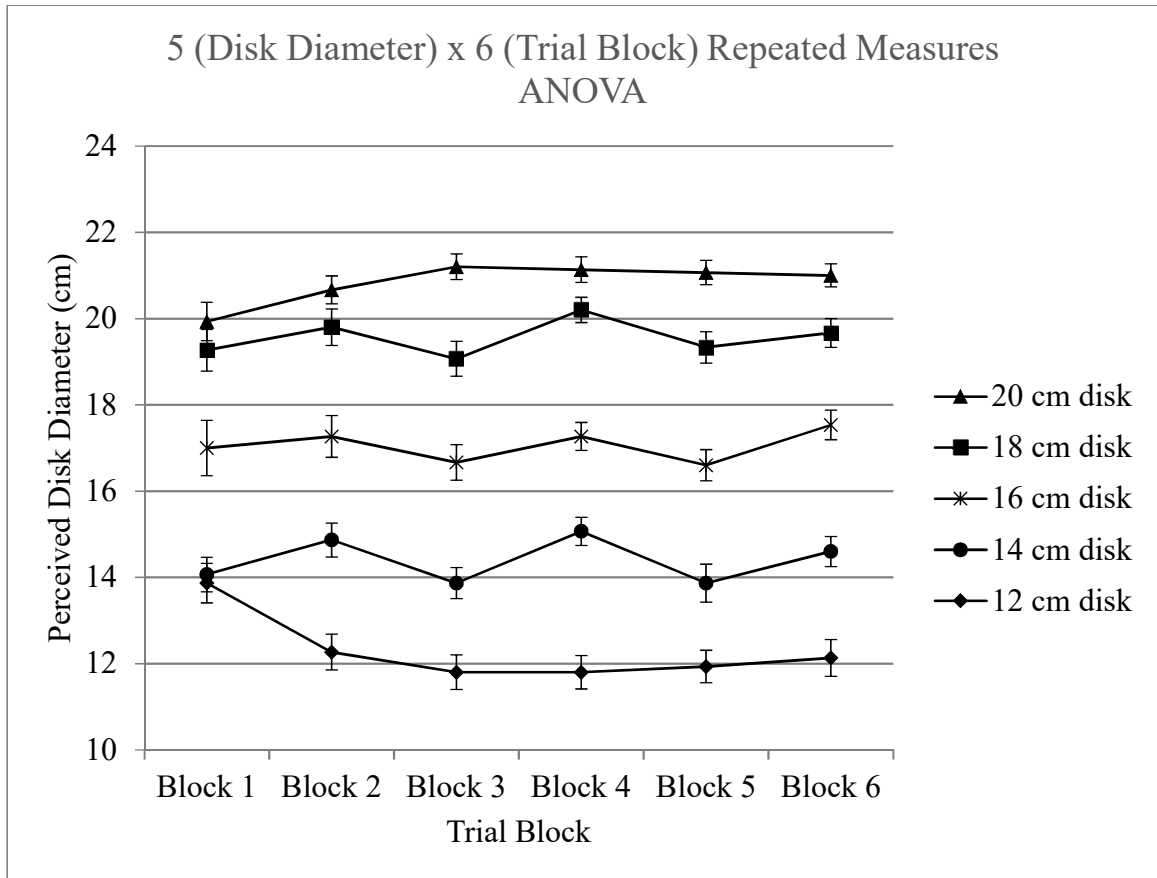


Figure 6. A plot illustrating the significant main effect for disk diameter from the repeated measures ANOVA for Experiment 1. On the y -axis are participants' perceived disk diameter judgments in centimeters. On the x -axis are the various trial blocks, ranging from one to six. Each separate line represents a different actual disk diameter, ranging from 12 cm to 20 cm by increments of 2 cm. Error bars were calculated using standard error.

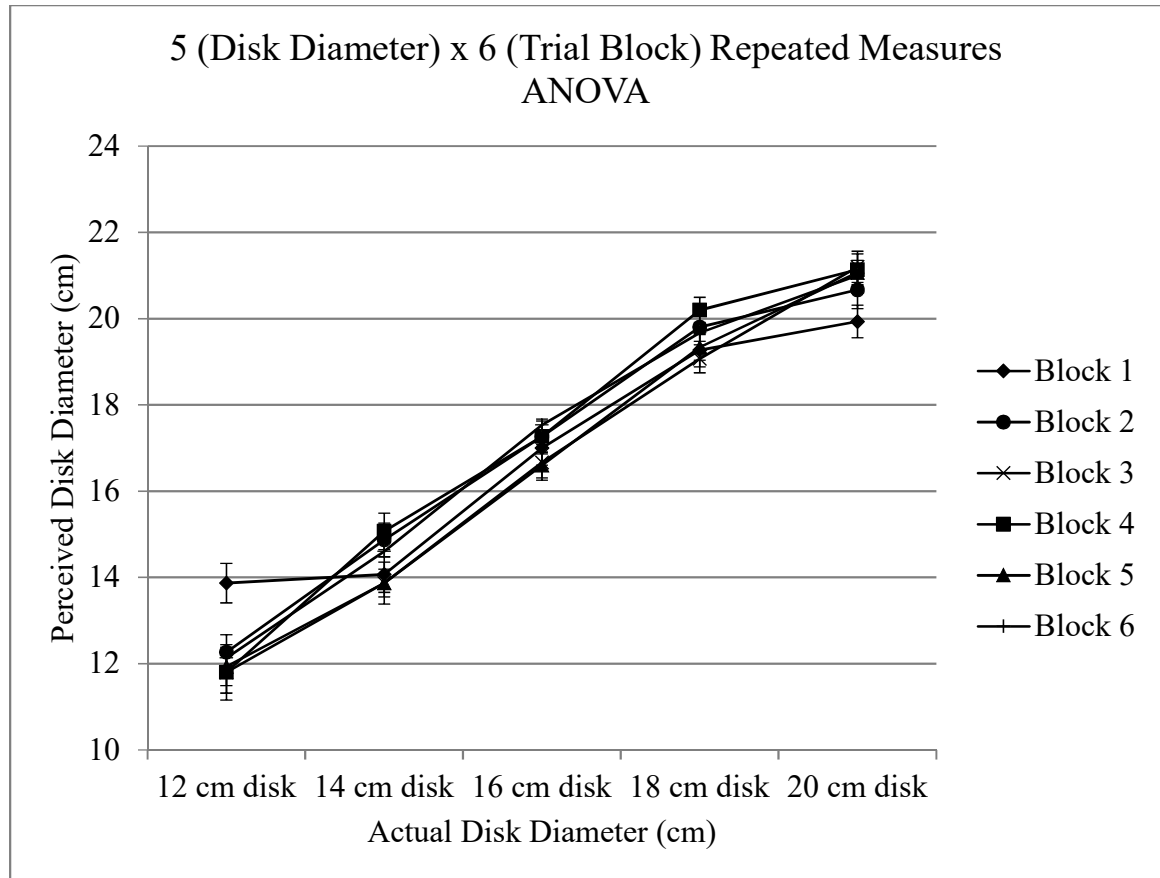


Figure 7. A plot illustrating the nonsignificant main effect for trial block from the repeated measures ANOVA for Experiment 1. On the y -axis are participants' perceived disk diameter judgments in centimeters. On the x -axis are the different actual disk diameters, ranging from 12 cm to 20 cm by increments of 2 cm. Each separate line represents a different trial block, ranging from one to six. Error bars were calculated using standard error.

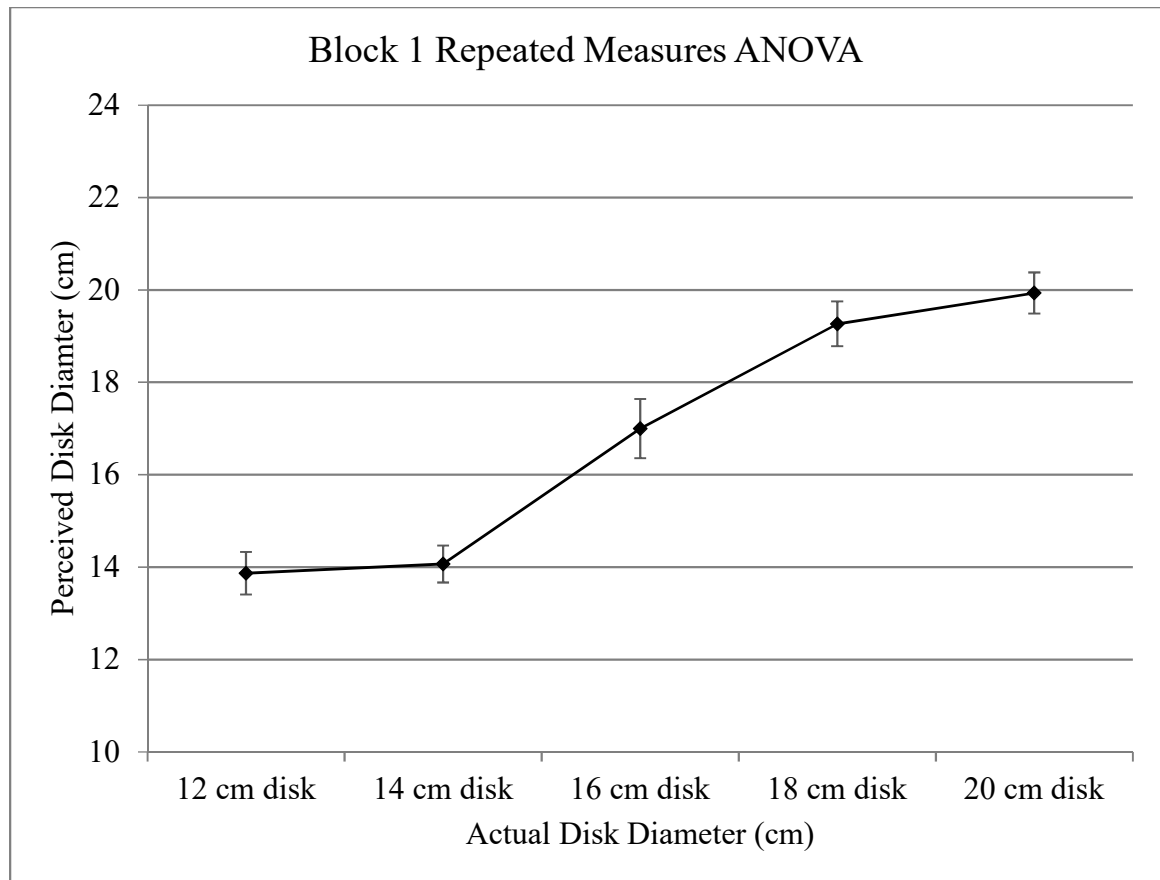


Figure 8. A plot illustrating the simple effect for disk diameter from the repeated measures ANOVA for Experiment 1, using data from only the first block. On the *y*-axis are participants' perceived disk diameter judgments in centimeters. On the *x*-axis are the different actual disk diameters, ranging from 12 cm to 20 cm by increments of 2 cm. Error bars were calculated using standard error.

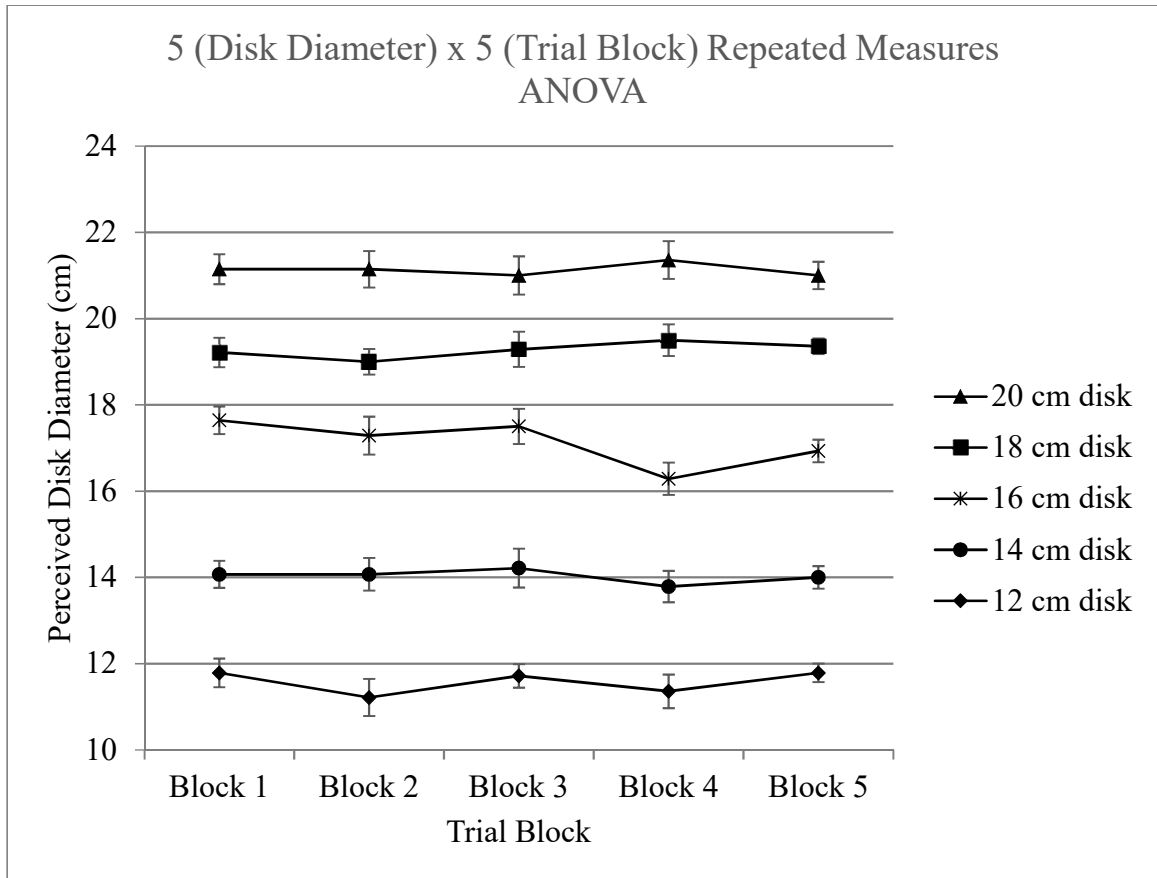


Figure 9. A plot illustrating the significant main effect for disk diameter from the repeated measures ANOVA for Experiment 2. On the *y*-axis are participants' perceived disk diameter judgments in centimeters. On the *x*-axis are the various trial blocks, ranging from one to six. Each separate line represents a different actual disk diameter, ranging from 12 cm to 20 cm by increments of 2 cm. Error bars were calculated using standard error.

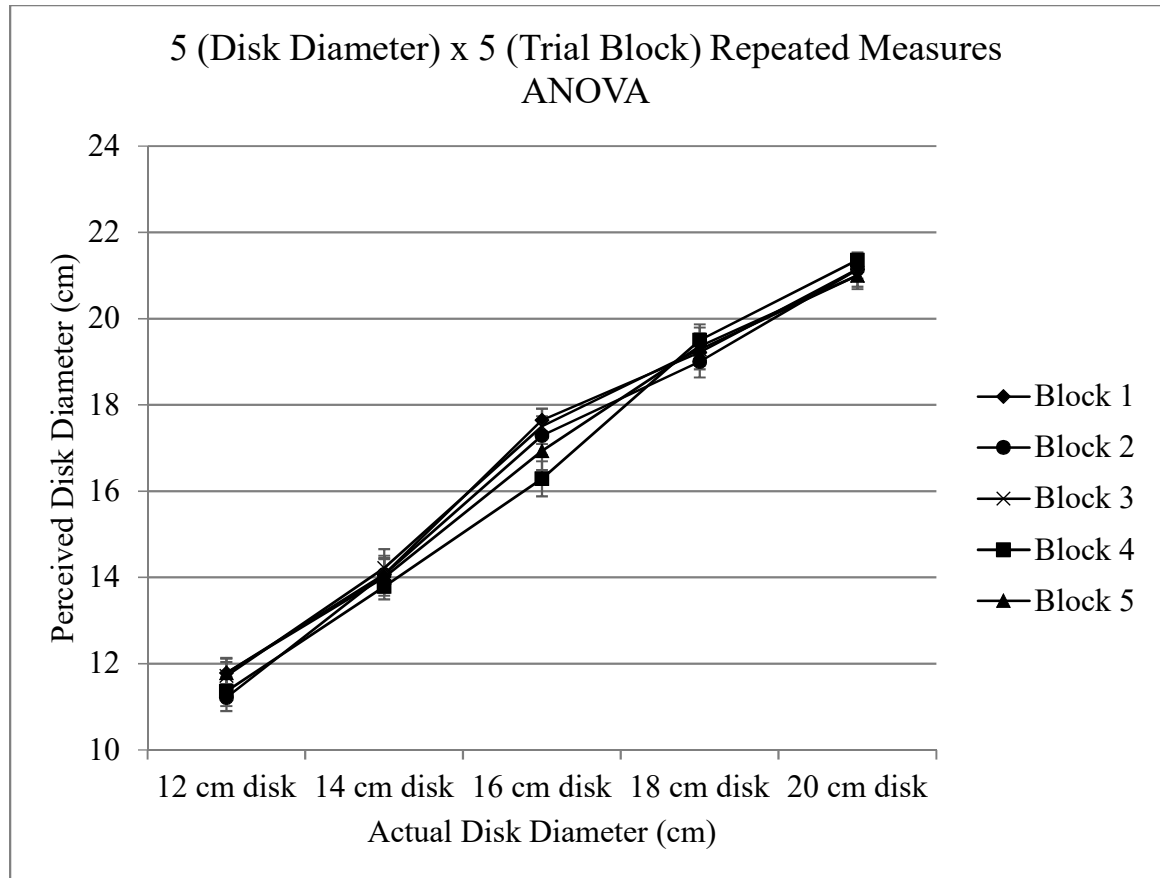


Figure 10. A plot illustrating the nonsignificant main effect for trial block from the repeated measures ANOVA for Experiment 2. On the y -axis are participants' perceived disk diameter judgments in centimeters. On the x -axis are the different actual disk diameters, ranging from 12 cm to 20 cm by increments of 2 cm. Each separate line represents a different trial block, ranging from one to six. Error bars were calculated using standard error.

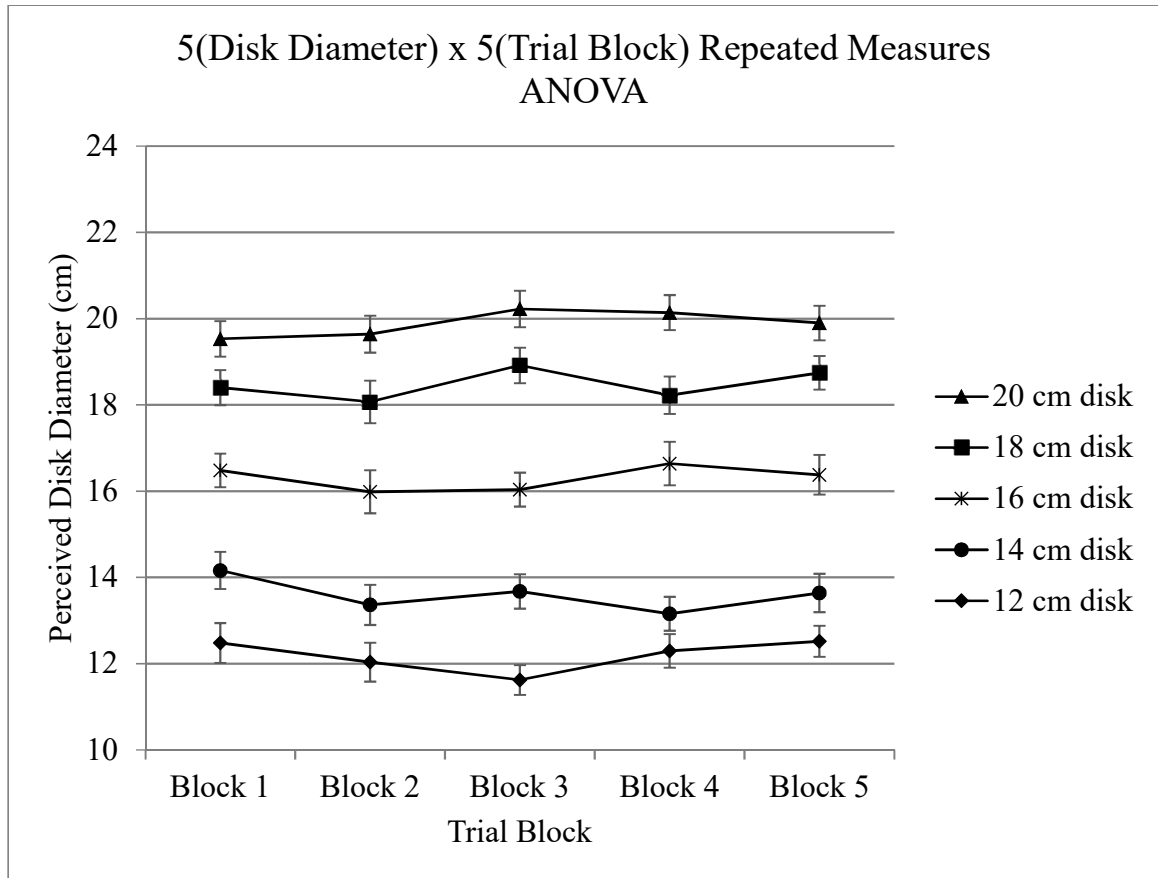


Figure 11. A plot illustrating the significant main effect for disk diameter from the repeated measures ANOVA for Experiment 3. On the y -axis are participants' perceived disk diameter judgments in centimeters. On the x -axis are the various trial blocks, ranging from one to six. Each separate line represents a different actual disk diameter, ranging from 12 cm to 20 cm by increments of 2 cm. Error bars were calculated using standard error.

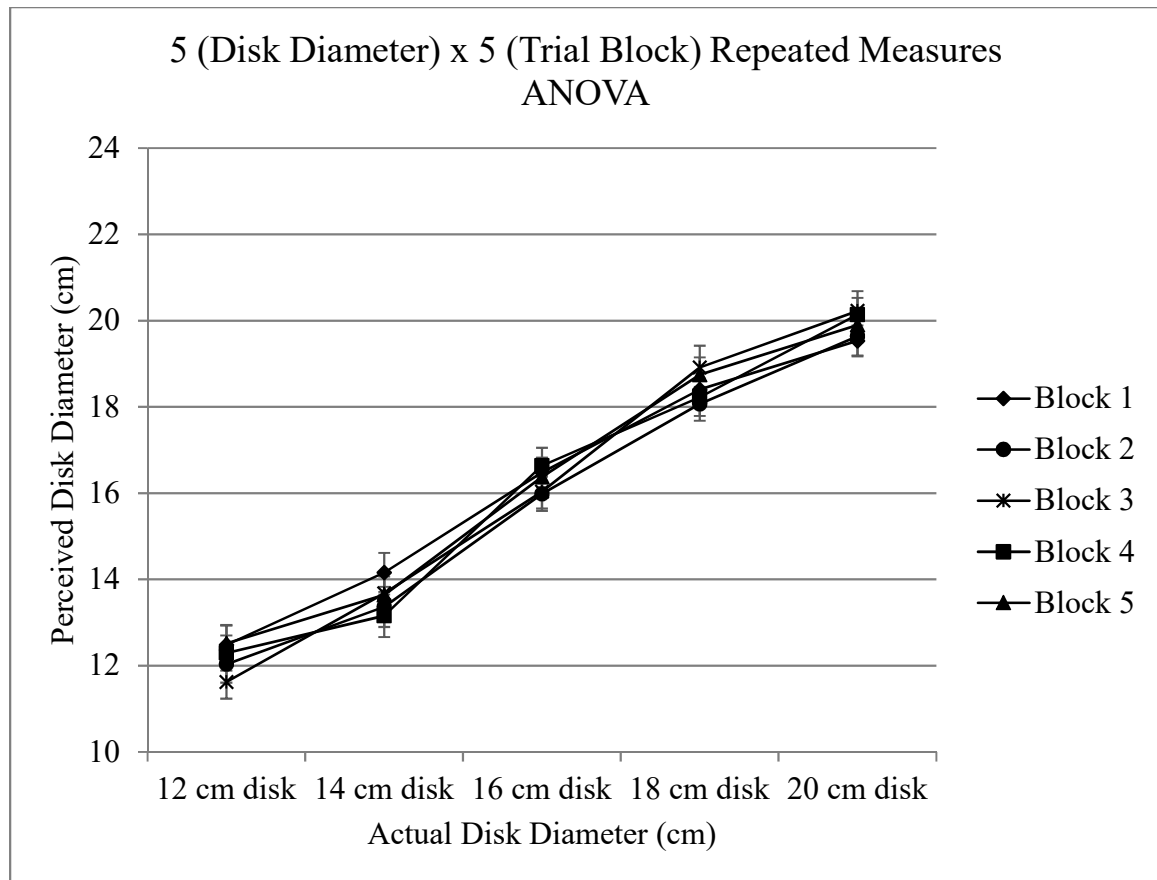


Figure 12. A plot illustrating the nonsignificant main effect for trial block from the repeated measures ANOVA for Experiment 3. On the y -axis are participants' perceived disk diameter judgments in centimeters. On the x -axis are the different actual disk diameters, ranging from 12 cm to 20 cm by increments of 2 cm. Each separate line represents a different trial block, ranging from one to six. Error bars were calculated using standard error.

Appendix A

IRB Approval

STUDY #: 16-0206

STUDY TITLE: Perception of Disk Diameter from Moment of Inertia

Submission Type: Renewal

Expedited Category: (7) Research on Group Characteristics or Behavior, or Surveys, Interviews, etc.

Renewal Date: 4/20/2017

Expiration Date of Approval: 4/19/2018

Appendix B

Consent to Participate in Research

*Information to Consider About this Research***Muscle Sense Information Study**

Principal Investigator: Kenneth M. Steele

Department: Psychology

Contact Information: steelekm@appstate.edu

You are being invited to take part in a research study about using information from your ability to manipulate an object to identify the size of an object. If you take part in this study, you will be one of about 20 people to do so. By doing this study we hope to learn what kinds of muscle sense information people can use to identify an object.

The research procedures will be conducted at Room 201, Smith-Wright Hall.

You will be asked to spin a disk that is hidden from your view using your fingers. You may spin the disk as quickly or as slowly as you want. The disk can be spun both clockwise and counter-clockwise. Once you have decided that you have enough information then you will be asked to identify the size of the disk from a set of examples. We will use several disks and you will have practice with the task.

You should not participate if you have an upper-body neuromuscular disorder.

What are possible harms or discomforts that I might experience during the research?

To the best of our knowledge, the risk of harm for participating in this research study is no more than you would experience in everyday life.

What are the possible benefits of this research?

There may be no personal benefit from your participation but the information gained by doing this research may help others in the future by identifying the information that can be used in object identification when sight is unavailable.

Will I be paid for taking part in the research?

We will not pay you for the time you volunteer while being in this study. The SONA recruitment system will record your participation and you will receive 1 ELC for participation.

How will you keep my private information confidential?

This study is anonymous. That means that no one, not even members of the research team, will know that the information you gave came from you.

Who can I contact if I have questions?

The people conducting this study will be available to answer any questions concerning this research, now or in the future. You may contact the Principal Investigator at steelekm@appstate.edu. If you have questions about your rights as someone taking part in research, contact the Appalachian Institutional Review Board Administrator at 828-262-2692 (days), through email at irb@appstate.edu or at Appalachian State University, Office of Research and Sponsored Programs, IRB Administrator, Boone, NC 28608.

Do I have to participate? What else should I know?

Your participation in this research is completely voluntary. If you choose not to volunteer, there will be no penalty and you will not lose any benefits or rights you would normally have. If you decide to take part in the study you still have the right to decide at any time that you no longer want to continue. There will be no penalty and no loss of benefits or rights if you decide at any time to stop participating in the study. If you decide to participate in this study, let the research personnel know. A copy of this consent form is yours to keep.

This research project has been approved by the Institutional Review Board (IRB) at Appalachian State University.

This study was approved on:

This approval will expire on 4/19/2018 unless the IRB renews the approval of this research

Vita

Corey Michael Magaldino was born in Dover, NJ, to Joe and Geri-Beth Magaldino. He graduated from Topsail High School in May, 2008. Following his high school graduation, he enrolled at North Carolina State University, where he was awarded a Bachelor of Arts degree in Sociology in May, 2013. The following year, he enrolled at University of North Carolina Wilmington and was awarded a Bachelor of Arts degree in Psychology in December, 2014. In the autumn of 2016, he pursued a Masters of Arts degree in Experimental Psychology at Appalachian State University. The Master of Arts in Psychology was awarded in August, 2018. In August, 2018, Mr. Magaldino began education toward a Ph.D. in Psychology at Arizona State University, specializing in Cognitive Science.