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# EBBINGHAUS ILLUSION IN TOUCH AS EVIDENCE FOR THE TWO STREAM PERCEPTION-ACTION HYPOTHESIS

Erin R. Smith
*Northern Michigan University*, erinsmit@nmu.edu

# EBBINGHAUS ILLUSION IN TOUCH AS EVIDENCE FOR THE TWO STREAM PERCEPTION-ACTION HYPOTHESIS

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Erin Smith

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Committee Chair: Date

First Reader: Date

Second Reader (if required): Date

Department Head: Date

Dr. Brian D. Cherry Date

Assistant Provost of Graduate Education and Research

ABSTRACT

EBBINGHAUS ILLUSION IN TOUCH AS EVIDENCE FOR THE TWO STREAM PERCEPTION-ACTION HYPOTHESIS

By

Erin Renee Smith

The Ebbinghaus Illusion (also known as Titchener's circles) is a classic visual illusion. The illusion consists of two inner circles of the same size, with one circle surrounded by a group of larger circles, and the other circle surrounded by a group of smaller circles. Due to the context of the surrounding circles, individuals perceive the inner circle surrounded by the smaller outer circles to be larger, when in fact, both inner circles are the same size. This thesis presents the first evidence of the existence of the Ebbinghaus illusion in the tactile modality. Participants underwent various tactile-tactile and tactile-visual conditions to actively explore Ebbinghaus illusion sets. Our results show that participants are more likely to be deceived when the illusory stimulus (the Ebbinghaus set) is present compared to when the control stimulus (no illusion) is present in a tactile perception condition. Further, our results demonstrate that in a visual-tactile condition, the perceptual system is not deceived, even though the illusion deceives participants in both touch and vision alone. These results contribute to the two-stream hypothesis perception-action debate, which states that the pathways for action and perception are separated in the visual system.

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# INTRODUCTION

The Ebbinghaus Illusion (also known as Titchener's circles) is a classic visual illusion. The illusion consists of two inner circles of the same size, with one circle surrounded by a group of larger circles, and the other circle surrounded by a group of smaller circles. Due to the context of the surrounding circles, individuals perceive the inner circle surrounded by the smaller outer circles to be larger, when in fact, both inner circles are the same size.

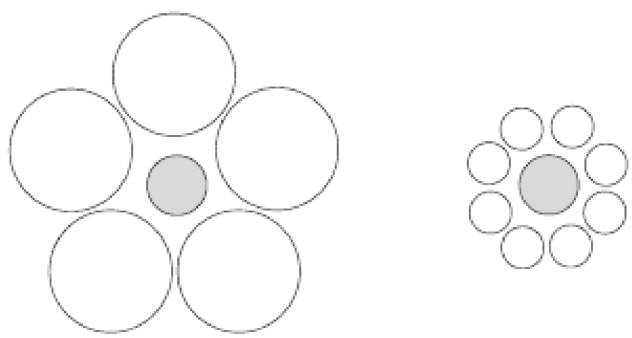

**FIGURE 1: EBBINGHAUS ILLUSION: THE INNER CIRCLE SURROUNDED BY THE LARGER OUTER CIRCLES LOOKS SMALLER THAN THE INNER CIRCLE (OF THE SAME SIZE) SURROUNDED BY SMALLER OUTER CIRCLES**

Although the presence of the Ebbinghaus Illusion has been well-established in vision, its presence in the haptic modality has been a topic of debate. To date, the majority of studies of the Ebbinghaus Illusion in the haptic modality has been on grasping studies. This thesis project presents the first evidence of the existence of the Ebbinghaus illusion in touch through a bimanual tactile (touch) exploration of the Ebbinghaus sets.

Prior experiments using the Ebbinghaus illusion in grasping have contributed to the debate of the two-stream hypothesis in visual perception, which will be expanded upon in chapter 1. Chapter 2 consists of a literature review of grasping studies using the Ebbinghaus illusion. The third chapter is a description of four experiments which investigate the Ebbinghaus in the tactile modality in a unimodal (tactile) and bimodal (visual-tactile) condition. The results of our study support the two perception-action pathways hypothesis in the brain.

# CHAPTER 1: TWO-STREAM HYPOTHESIS

When information from the external world reaches the visual cortex in the form of nerve impulses, it follows two streams for visual perception. This is commonly known as the two-stream hypothesis, which is widely accepted. This theory, proposed by Ungerleider and Mishkin (1982) posits a "*where*" pathway (object localization, dorsal pathway) and a "*what*" pathway (object recognition, ventral pathway). A more recent theory, supported by Milner and Goodale (1991), proposes that the two streams should be action (vision for action, dorsal) and perception (object recognition, ventral). Before discussing evidence that supports either theory, it is important to note how these theories came to be. Ungerleider and Mishkin (1982) based their theory on evidence from lesioning studies in monkeys. Goodale and Milner (1991), however, based their version of the two-stream hypothesis on evidence from neurophysiological studies (see Figure 2).

Ungerleider and Mishkin (1982) formulated their version of the two-stream hypothesis using lesioning studies in monkeys, as previously stated. They noticed that monkeys have high-order visual dysfunction when they have rostral damage to the temporal and parietal lobes. Although both cause visual dysfunction, the type of dysfunction varies depending on whether the damage was to the parietal or temporal lobe. Damage to the temporal cortex produced an impairment in the monkey's visual recognition, and damage to the parietal lobe produced various visual spatial impairments. At the time Ungerleider and Mishkin were developing the two-stream hypothesis, it was widely known that there are two fiber bundles that originate in the occipital cortex and project themselves rostrally in the brain. The inferior longitudinal fasciculus, one of the two bundles, follows a ventral route towards the temporal lobe of the brain, and the other bundle, the superior longitudinal fasciculus has a dorsal pathway. Ungerleider and Mishkin (1982) believed that the ventral pathway was responsible for object perception (object recognition), while the dorsal pathway is responsible for spatial perception (object localization).

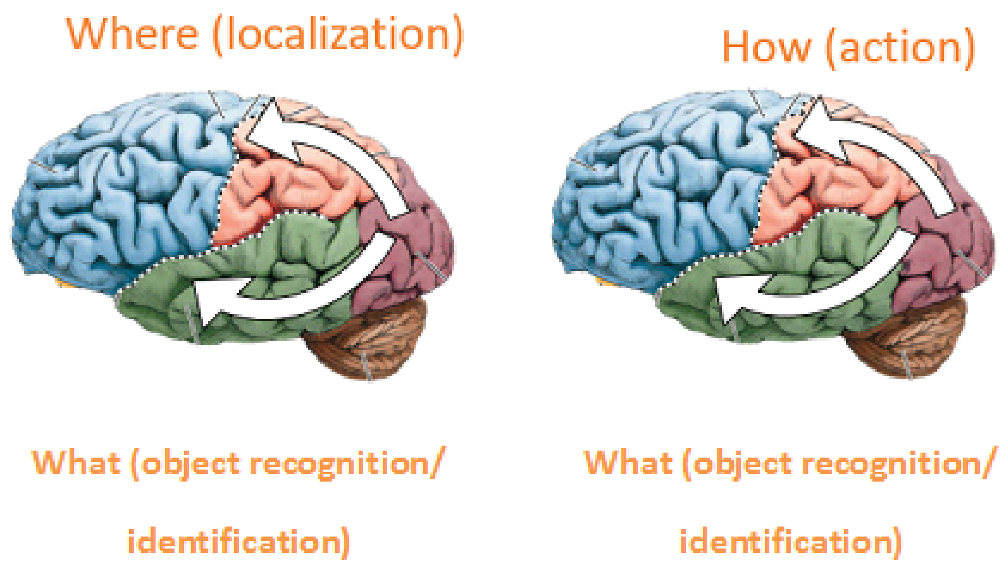


FIGURE 2. THE TWO STREAMS HYPOTHESIS: LEFT: WHERE (LOCALIZATION) AND WHAT (OBJECT RECOGNITION) PATHWAYS; RIGHT: HOW (ACTION) AND WHAT (RECOGNITION) PATHWAYS

Using neurophysiological studies, Goodale and Milner (1991) noticed a double dissociation between perceiving and grasping an object, and consequently re-interpreted the two-stream hypothesis. To support their reinterpretation, they noted that some patients with parietal lobe damage had difficulty reaching visual targets, but these patients did not, however, have difficulty seeing them. On the other hand, they noticed that patients with damage to their primary visual cortices (V1) were able to make saccades or "pointing movements" in the direction of a stimulus located within their "blind" scotoma[1]. Moreover, Goodale and Milner were unsatisfied with the little attention given to visuomotor control in visual disorder patients. Specifically, researchers had not considered how these patients perform complex acts (e.g. manual prehension). In order to grasp a three-dimensional object in space, an individual would need to have knowledge of not only the object location, but other information, such as its orientation, size, and form. To investigate complex acts in neurophysiological patients, Goodale and Milner (1991) conducted a study on patient, D.F., a 35-year-old woman with irreversible brain damage obtained from carbon monoxide poisoning, approximately 15 months after her accident.

Patient D.F. had previously undergone magnetic resonance imaging (MRI), which showed ventral damage to her lateral occipital region and the parasagittal occipitoparietal region. The researchers believed that patient D.F. also sustained damage to her basal ganglia. Through further tests, researchers were also able to demonstrate that patient D.F. suffered from visual agnosia. Further, D.F. had poor perceptual abilities for shape and

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[1] Blind scotoma consists of a blind alteration (similar to a blind spot) in the visual field.

orientation of objects, regardless if this information was derived from color, stereopsis, intensity, motion, continuity, similarity, or proximity. In addition to these difficulties, patient D.F. had significant difficulty perceiving the orientation of objects and being able to execute appropriate reaching movements to these objects in differing orientations (Goodale & Milner, 1991). Goodale and Milner (1991) first tested D.F.'s orientation perception in several ways. For the first task, they presented patient D.F. with four lines (all oriented differently) on a card. Patient D.F. was then instructed to choose which line would match with a large slot in a disk. For the second task, D.F. had to turn a card until it matched with the orientation of the slot. In the third task, D.F. had to verbally indicate to the experimenter the orientation of a block on a table placed in front of her. As Goodale and Milner (1991) point out, even though she had a variety of options in these scenarios, her performance on every task was impaired. Some of her errors included "judging horizontal to be vertical."

Interestingly, despite her poor performance on the perceptual tasks, patient D.F. was easily able to take the card and put it through the slotted disc from the perceptual tasks. In fact, her performance in this task was characterized by Goodale and Milner (1991) to be "excellent." Similar to control participants, patient D.F. began to position the card in the correct orientation as she raised her hand from the starting position (deduced from video records). The same was true when she picked up the block from the perceptual task: she was able to orient her hand appropriately as it raised from the starting position. Further, when the experimenter instructed her to close her eyes and picture a disk slot at different orientations, she was able to correctly orient her hand to the slot orientation she pictured in her head.

Goodale and Milner (1991) deduced that her difficulty stemmed from using her visual information for the tasks listed previously (perceptual and cognitive tasks), as she was able to properly use this information for visuomotor action. How pervasive this dissociation was in patient D.F. surprised Goodale and Milner (1991), and was important in their eventual proposing of their version of the two-stream hypothesis. Goodale and Milner (1991) also noted that the opposite effects occur in patients with optic ataxia. Patients with optic ataxia are able to correctly perceive the orientation of objects, but perform poorly when reaching into an oriented slot (Goodale and Milner, 1991).

From their studies on patient D.F., Goodale and Milner (1991) concluded that a brain-damaged individual can still be capable of calibrating appropriate aiming and prehension movements with respect to the dimensions and the orientation of the objects. This holds true even despite the fact that patient D.F. was unable to indicate (manually or verbally) the visual properties of the objects in the tasks. The dissociation that occurs here proposes that in the healthy brain, at a certain level, the visual processing behind conscious perceptual judgments operate independently from the skilled visuomotor guidance of the hand and/or limbs (Goodale & Milner, 1991).

On the basis of these neurophysiological studies, in contrast to Ungerledier and Mishkin (1982), Goodale and Milner (1991) posited that the function of the dorsal stream in the primate brain is not limited to the localization of objects, but also to guide the manipulation of these objects, which they refer to as the "*how*" pathway. In addition, Goodale and Milner (1991) posited that the ventral stream's function is to perform certain computations that are necessary in order for an individual to consciously recognize an object. These computations do not need to be as quick or precise as the computations for guidance of actions, which need to be fast and accurate. Finally, computations for action also require a short-term memory, because the position of any object can vary moment to moment; while computations for object recognition enable long-lasting representation in the brain.

In summary, based on their hypotheses, Goodale and Milner (1991) came to the conclusion that there are two different visual systems:

- One for guiding motor actions (how pathway)
- One for object recognition and conscious perception (what pathway)

In addition to evidence from neurophysiological studies, evidence which supports Goodale and Milner's hypothesis can be found in grasping studies conducted in humans. The researchers also noted in their original study (Goodale & Milner, 1991) that their theory would be even stronger if they could find evidence of this dissociation in healthy participants, as their original study used only one patient with brain damage, patient D.F., to support their version of the two-stream hypothesis.

# CHAPTER 2: EVIDENCE FROM GRASPING STUDIES

As previously stated, grasping experiments have traditionally been used to study the Ebbinghaus Illusion in the haptic modality which have contributed to the two-stream hypothesis debate. For humans to grasp an object, they must move their hands towards it. While reaching for an object to grasp, the individual's thumb and the index finger open themselves to the maximum aperture. This aperture is directly related to the size of the object the individual is attempting to grasp. It is important to note that the individual forms the maximum aperture *prior* to having any contact to their target object. This reflects how the visual system in the brain transfers the size estimate to the brain's motor system (Jeannerod et al. 1995).

It is widely known that conscious perception can be affected by various size illusions (Coren and Girgus, 1978). Because of this, the question as to whether or not pre-shape aperture will be affected by illusions comes into play. As Franz et al. (2000) points out, there are two possible answers to this question:

1. The system related to motor actions directed toward an object uses the same pathway or internal representation to perceive this same object.

2. The system related to motor actions directed toward an object uses a different pathway or internal representation to perceive this same object.

The second possibility is precisely what Goodale and Milner predict. Specifically, they hold that computations for perception would emphasize the relationship between the object and its surroundings; while for computations for action, the emphasis would be on the relationship between the hand (the effector) and the target object. As Franz et al. (2010) states, due to the fact that visual illusions are typically produced by objects' arrangement, Goodale and Milner expected that these illusions would have a very little, if any, effect on grasping (the motor system).

In grasping experiments, participants are typically instructed to pick up one of the inner circles of the Ebbinghaus Illusion. To date, there have been varying results of these experiments, which are summarized below:

1. The Ebbinghaus Illusion deceives perception and does not affect grasping

2. The Ebbinghaus Illusion deceives perception and affects grasping

If it holds true that the Ebbinghaus Illusion does not affect grasping, the two-stream perception and action hypothesis would be supported. In this case, the perception is deceived, but the grasping aperture is precise. Results that support this notion are typically viewed as supporting Milner and Goodale's (1992) view that there are two parallel visual systems: one for perception and one for visually guided action. The visual system for perception is conscious, and is deceived by the Ebbinghaus Illusion. The visual system for action is unconscious, and the Ebbinghaus Illusion does not deceive it (Franz & Gegenfurtner, 2008). However, Goodale and Milner's 1991 study has been controversial among researchers, as other studies have received opposite results. In contrast, if the Ebbinghaus illusion does affect grasping, it would support the notion that perception and action share the same mechanisms in the brain. Further, it would support that both perception and action are indeed affected by the Ebbinghaus Illusion. Later, Franz and Gegenfurtner, who originally supported the idea of one pathway for perception and action, have recently insisted that these results are not actually contradictory, but that similar effects of the Ebbinghaus Illusion exist in grasping as well (Franz & Gegenfurtner, 2008).

Perhaps the most influential study to date has been that of Aglioti et al. (1995). In this experiment, researchers used three-dimensional “poker-chip” disks for the inner circles in the Ebbinghaus Illusion in a grasping experiment (Aglioti et al. 1995). Participants were instructed to grasp poker-chips with their right index finger and thumb. To record the trajectory of grasping, Aglioti et al. (1995) used cameras which tracked infrared light-emitting diodes attached to the fingers and wrist. The findings from this study supported Goodale and Milner’s theory, as the illusion had a more pronounced effect on perception than on participant’s preshape aperture (motor). However, there were still effects on grasping, as is pointed out by Brenner and Smeets (1996) and Daprati and Gentilucci (1997). Even though the original study by Aglioti et al. (1995) has been regarded as highly influential, several issues in this study have been pointed out. For these reasons, this study has been notably replicated by Haffenden and Goodale (1998) and Franz et al. (2000).

Haffenden and Goodale (1998) addressed the criticisms of Aglioti et al.’s experiment, including that of visual feedback, but also suggested a more rigorous methodology. Because the participants in the original study (Aglioti et al. 1995) were able to see the disc as they reached their hand towards it, it is possible that as their hand got closer to the disc, they adjusted their grip aperture appropriately. Aglioti et al. (1995)

defended their methodology, and argued that previous empirical data had demonstrated that humans need at least 500ms to process information visually about changes in the shape and size of the target, before a new motor command is produced. In the Aglioti et al. (1995) study, maximum grip aperture was reached around 420ms after the participant's grasping movement had already began, which translates to approximately 70% of progress through the reach. Haffenden and Goodale (1998) argued that this demonstrates that the maximum grip aperture actually reflects "early programming" rather than adjustments in grasping movements. Further, Haffenden and Goodale (1998) argue that other grasping studies, such as one by Castiello and Jeannerod (1991) showed that an even shorter amount of time, 320ms, is needed for a participant to adjust when reaching for a rod that changed its size when the participant began their reaching movements. Taken together, Haffenden and Goodale (1998) believed that visual feedback was not an issue in the Aglioti et al. (1995) study and therefore did not affect grasping aperture while participants were reaching for the disc.

To support their argument regarding visual feedback, Haffenden and Goodale (1998) elected to use a slightly different methodology. Two conditions were included in this study: a visuomotor condition and a perceptual condition. In the first visuomotor task, participants were seated in a room with overhead circular light over the stimuli display, and with their thumb and index finger on a "start" button. The participants were able to see both sets of the Ebbinghaus illusion, and were instructed to judge whether the inner circles of the set were the same size, or if they were different. For the first half of participants, if the circles were the same size, the participants were told to pick up the disk on the right. If the inner circles were judged by the participant to be different, they had to pick up the inner circle on the left. The situation was reversed for the second half of participants (i.e. pick up the inner circle on the left if they are the same, the one on the right if they are different). Once the participants had indicated their answer, they had to reach for the inner circle they had selected (this meant they had to remove their thumb and index finger from the start button). Upon removal of the thumb and index finger, the overhead light shut off, leaving the participants in the dark, unable to see their hand or their target circle of the Ebbinghaus set (also known as a visual open loop). The purpose was to remove the influence of vision.

In the second part of the visuomotor task, the participants were given detailed instructions on how to pick up the inner circle of the Ebbinghaus set. Specifically, their thumb and index finger were to be at approximately the 1 o'clock and 7 o'clock positions. Haffenden and Goodale point out that this is the natural grasping position maintained by the majority of participants, so it was utilized in order to maintain consistency across the participants. Once the participant had picked up the disk, they were instructed to place it on the right side of the Ebbinghaus display. Haffenden and Goodale also supported this methodology by suggesting that asking participants to verbally indicate their responses may have influenced their grip and consequent grasping.

In the perceptual (estimation) task, participants were able to view the Ebbinghaus sets for only 1 second. This time period was selected as it was similar to the length of time participants could view the display in the visuomotor task. Consequently, the grip estimation was made while the participants were in the dark. Therefore, in both conditions, participants were in a visual open loop condition. The same instructions were given to the participants as in the reaching task. The key difference was that participants had to estimate their perceived size of the inner Ebbinghaus circle prior to reaching for it. Participants also indicated when their hand adjusted their thumb and index finger to their estimation so the experiments could record their hand posture for approximately 500 milliseconds, without their knowledge. After the 500 milliseconds had passed, a tone cued the participants to begin reaching for the disk. Haffenden and Goodale incorporated this into the perceptual task, as it ensured that participants received an equal amount of haptic feedback as the participants in the visuomotor task.

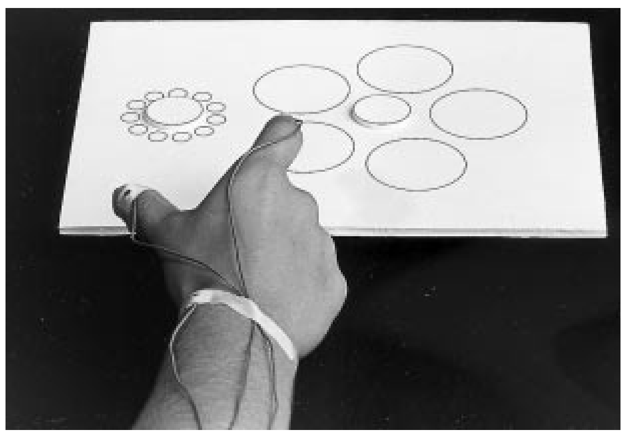

**FIGURE 3: GRASPING TASK (FROM HAFFENDEN & GOODALE, 1998)**

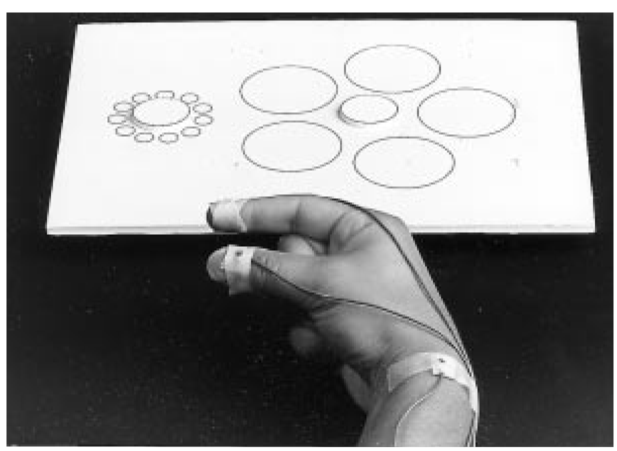

FIGURE 4: MANUAL ESTIMATION TASK (FROM HAFFENDEN & GOODALE, 1998)

The results of Haffenden & Goodale's study demonstrated that the participant's scaling grip aperture had a strong correlation with the actual size of the poker chip disks. However, in the manual estimation task, the estimations of the disk size were biased in the direction of the Ebbinghaus Illusion. Their results also demonstrated that this holds true even when the participant's perception of object size has been modified by the Ebbinghaus Illusion (e.g. grasping aperture reflected actual size and not apparent size). Similar results have also been obtained by other studies using pictorial illusions (e.g. Vishton & Cutting, 1995; Whishaw). Overall, Haffenden & Goodale (1998) had results that support perception and action being separate in the primate brain.

Also attempting to further dispel some of the issues in the original Aglioti et al. (1995) study, Franz et al. (2000), utilized one Ebbinghaus figure at a time. The researchers in this study attempted to justify this by suggesting that only one Ebbinghaus figure would make the perceptual and motor tasks as similar as possible. However, this study has one major flaw: using only one Ebbinghaus figure does not create an illusion. Without the second Ebbinghaus figure, the participants were essentially only presented with a group of circles. Nevertheless, Franz et al. (2000) found no differences between perceptual and grasping tasks. The perceptual task involved adjusting the size of the inner circle on a screen, while the grasping task involved grasping the inner circle of an Ebbinghaus illusion set. The researchers argue that contradictory results obtained from previous studies could be explained by nonadditive effect in the illusion. In other words, if each Ebbinghaus set is compared individually, the error summation (illusion magnitude) would be smaller than the error produced by the Ebbinghaus illusion (the two sets at the same time). However, as previously mentioned, the fact that the illusion is smaller in a one set condition is due to the absence of the illusion. In summary, the nonadditive effect is not surprising, as by definition an illusion would affect perception drastically. Further, Franz et al. (2000) came to the conclusion that the Ebbinghaus illusion does not support a two-stream hypothesis in the primate visual system. As their experiment did not in fact use the complete Ebbinghaus Illusion, the comparison with the original study is minimum. However, their study has the merit in its contribution to the perception-action debate.

Although Haffenden and Goodale (1998) believed their results supported perception and action being separated in the brain, Pavani et al. (1999) believed this was an incorrect interpretation of the results. Pavani et al. (1999) conducted a study to attempt to support an alternative explanation for the results Haffenen and Goodale (1998) received. Regarding Haffenden and Goodale's (1998) study, Pavani et al. (1999) suggest that in grasping tasks, solely the annulus of the surrounding outer circles influenced the participant's results. To test their take on Haffenden and Goodale's (1998) results, Pavani et al. (1999) utilized a task in which participants were instructed to perceptually estimate and grasp the inner disk in the Ebbinghaus Illusion. Pavani et al. (1999) holds that in the perceptual task of Haffenden and Goodale's (1998) study, the participant's judgment was indeed influenced by both sets of Ebbinghaus circles. In contrast, in the grasping experiment, the participants only had to focus on one set of Ebbinghaus circles – the set with the target circle. In the opinion Pavani et al. (1999), due to differences in attention, the illusory effects in the grasping experiment may have been reduced, which could have led to the results obtained by Haffenden and Goodale (1998). Similar to Franz et al. (2000), only a single set of Ebbinghaus circles were present. A circle by itself, which varied in size throughout the trials, served as a reference disk, and was also placed on the table in front of the participants. The results obtained by Pavani et al. (1999) show that grasping as well as perceptual estimation were influenced by the single set of Ebbinghaus circles. Further, they argue that the stronger the illusion, the more grasping was affected in participants. Once again, however, the same criticism arises as in the Franz et al. (2000) study: how could you attribute the results of perception or grasping to the illusion when the actual illusion was never present to begin with? Showing a single Ebbinghaus set with a circle by itself next to it is not the same as the real Ebbinghaus Illusion. Jacob and Jeannerod had a similar argument and criticized the usage of one set of the Ebbinghaus circles (Jacob & Jeannerod, 1999).

Returning to the Ebbinghaus illusion yet again in 2000, Haffenden and Goodale (2000) contemplate the hypothesis that the discrepancy in perception between the two inner circles may be caused by an image-distance equation. In such an equation, Haffenden and Goodale (2000) propose that the outer small circles can be perceived as being more distant in comparison to the outer larger circles (see Coren, 1971). Inherently, Haffenden & Goodale (2000) proposed that the inner circle surrounded by smaller outer circles is perceived as bigger than the other target circle is a potential consequence of the visual system attempting to maintain size constancy.

Haffenden and Goodale furthered their empirical investigation of the Ebbinghaus Illusion in 2001. They used their results from their 2000 study which demonstrated that

2-D pictorial elements may be treated as obstacles to participants to support their methodology for their 2001 study (for our purposes, the obstacles are the outer circles of Ebbinghaus sets). In their 2001 experiment, Haffenden and Goodale manipulated the distance between the surrounding outer circles and the inner circles of an Ebbinghaus illusion set. Three displays were created with various sizes: traditional small and large sets, and an adjusted small set.

Each participant in the 2001 study took part in both a manual estimation as well as a grasping task in a visual open loop. Participants also wore special goggles, where the experimenter could control when they were able to view the stimulus. The setup prevented participants to see their hand, the Ebbinghaus set, or the target (the inner circle of the Ebbinghaus set) unless the experimenter wanted them to. In the beginning of each trial, the participant was able to briefly view the display. As soon as the participant viewed the target, they were instructed to move their hand toward themselves, to allow the experimenter to cover their vision via the goggles. When the goggles were once again opaque, the participant was instructed to manually estimate the size of the target with their thumb and index finger. A single trial lasted 2.5 seconds total. Once the participant had manually estimated the size of the target and the trial was completed, the participant was told to reach out and pick up the target (vision was removed again at this point). Similar to their previous study, Haffenden and Goodale utilized this methodology in order to ensure participants received the same amount of haptic feedback in the manual estimation task as in the grasping task.

The grasping task was created to be similar to the manual estimation task. A start button was placed in front of participants, who rested their thumb and index finger on it. Similar to the manual estimation task, the experimenter controlled the goggles and enabled participants to see the Ebbinghaus set at the beginning of each trial. Participants were instructed to immediately reach out for the target circle. Again, once the participants lifted their thumb and index finger off of the start button, they were unable to see. Therefore, they performed their grasping movements without vision.

The results of their study demonstrated a dissociation between the participants' grasp and perceptual judgments. Supporting their previous studies, Haffenden and Goodale found no evidence that the Ebbinghaus illusion affects grasping. Further, they successfully demonstrated how Franz et al. (2000) was incorrect in suggesting that there is one representation which drives perception and action. Because the sizes of the Ebbinghaus sets were manipulated by Haffenden and Goodale, they were able to show how the illusion's effects on participants' grasping were not directly related to changes in their perceived size. Instead, the critical variable appears to be the distance between the inner circle (the target) and the edge of the outer surrounding circles.

2001 marked the ten year anniversary of the version of the two-stream hypothesis proposed by Goodale and Milner. Since its proposal in 1991, Carey (2001) noted that the majority of studies of the Ebbinghaus Illusion and grasping supported the notion of the independence of motor systems. However, as with all theories, Goodale and Milner's verion of the two-stream hypothesis did not stand without criticism. As Carey (2001) states, one of the main criticism of Goodale and Milner's hypothesis is that it is based off of one patient with visual form agnosia, patient D.F. In Carey's (2001) opinion, this criticism is perhaps "oversimplified." The model of Goodale and Milner (1991) draws on much more than just patient D.F. Neurophysiological and neuropsychological models also heavily influenced Goodale and Milner (1991), although their original study publishes findings based on patient D.F. The criticism has also helped to start two lines of research within neurologically intact participants. The first line of research, which has gained less attention, is the belief that making participants engage in grasping movements in the direction of memorized objects would require the inclusion of the ventral stream and its perceptual mechanisms. This is due to the fact that the dorsal stream's sensorimotor control mechanisms can only maintain the representations of the target for a few seconds maximum.

The second more popular line or research is the idea that motor systems may resist the effects of visual illusions (e.g. the Ebbinghaus illusion). This claim was originally purported by Aglioti et al. (1995). Although a number of earlier studies demonstrated a similar dissociation, Aglioti et al. (1995) remains the most widely cited study on this topic. As discussed previously, some studies have been able to replicate their results, while others haven't. Some studies also fall into a category of "sort of" replicating the original Aglioti et al. (1995) study (Carey, 2001). As Carey posits, it is also possible that many studies that do not replicate the original Aglioti et al. (1995) may not ever be submitted for publication. Although this is a possibility, nothing can be concluded from this claim, as there is no evidence either way to support it.

In his review of the Ebbinghaus illusion in grasping studies, Carey (2001) notes that a visual occlusion issue arises when studying the illusion in grasping. Brought to the attention of researchers by Mon-Williams and Bull (2000), they argued that while reaching for the target stimulus (Mon-Williams and Bull used the Judd illusion; in our case it would be the inner circle of the Ebbinghaus Illusion), the participant's hand could actually occlude a portion of the stimulus. Because the participant would, hypothetically, not be able to view the entire Ebbinghaus Illusion stimulus, it is possible that the effects of the illusion on grasping would be decreased. Mon-Williams and Bull's argument is also of use for criticisms regarding task differences when the participant's hand is visible.

Concluding his review of the literature of the Ebbinghaus illusion in grasping studies, Carey (2001) posits that the research will begin a new phase: one where researchers will have to think intently about control conditions in their experiments as well as statistical analysis.

In 2003a, Franz et al. returned to repudiate some of the criticisms of their previous studies. Franz et al. compared manual size estimation with the method of adjustment, which is a classic psychophysical technique. He noted that the differences in results between the two methods could be due to the method used. According to Franz, the manual size estimation results are larger than the adjustment method, mainly because the manual estimation size is sensitive to the physical size of the stimulus (inner circle). The peak aperture was also was also larger with the manual estimation size as opposed to grasping task or the method of adjustment. To explain his results, Franz et al. (2003a) argued that differences between responses and size-scaling functions are of the utmost importance when attempting to explain the effects of the Ebbinghaus Illusion (and illusions in general). To further support his position, Franz et al. (2003a) also suggested that researchers correct for the absolute effect of the Ebbinghaus Illusion by dividing this absolute effect by the slope of the size-scaling function. Franz et al. (2003a) also demonstrated that when this correction is performed, the results of the 1998 Haffenden and Goodale study actually shows equal effects for size estimation and grasping in the Ebbinghaus Illusion.

Unlike the studies explained previously, Doherty et al. (2010) took a different approach to studying the Ebbinghaus Illusion. As previously discussed, sensitivity to size perception in context is used to support the dissociation between vision for action and perception. As Doherty et al. (2010) also notes, the effects of a stimuli's context on an individual's size perception has been one of the central themes in the two-stream hypothesis. Specifically, it has been widely debated in which conditions the effects may occur in, and how researchers should interpret them (e.g. Franz et al. 2000). Because the Ebbinghaus Illusion depends on the context (the surrounding outer circles and comparison to the other Ebbinghaus set), it is an appropriate stimulus to use for sensitivity to size perception to context. Instead of focusing on the more popular aspects of context on size perception, such as size constancy and size contrast, Doherty et al. (2010) elected to investigate local contour interactions. Local contour interactions depend on the target and its surrounds. As Roberts et al. (2005) found, when the surroundings stimuli are close to the target, their size is overestimated, as opposed to surrounding stimuli that are relatively far from the target, which would make it look smaller. This idea corroborated by Haffenden et al.'s findings which demonstrated that the separation between the targets and their surrounds in the Ebbinghaus Illusion has an effect on participant's grasp.

Although not a grasping study, the results of Doherty et al. (2010) are still relevant to the Two-Stream Hypothesis debate as it focuses on the effects of context on size perception. In their study, Doherty et al. (2010) found that children younger than seven and ten years old were not as affected by the context, and therefore were not deceived by the Ebbinghaus Illusion in comparison to older adults. This study is relevant to our purposes for various reasons. First, it suggest that the ventral pathway in the human brain does not have a "built-in property" for size contrast at birth which subserves an individual's vision for perception. Rather, there is a development of sensitivity to size perception to context throughout development that occurs sometime after ten years old. For these reasons, results obtained from age groups across the lifespan could demonstrate differences in the effects of context on size perception.

Although Westwood and Goodale (2011) considered Franz et al.'s (2003a) findings to be "substantial," they were quick to point out a few areas that require further consideration before accepting the conclusions of Franz et al. (2003a). To begin, Westwood and Goodale (2011) question whether or not it is necessary to perform the correction for the absolute effect of the Ebbinghaus illusion that Franz proposed. In addition, they cite a claim made by Gregory (1997), which states the majority of pictorial illusions affect size perception because of their unusual size-constancy mechanisms. If true, the claim by Gregory (1997) would support the idea that the effects of illusions on perceived object size is caused by a mechanism other than physical change, which was suggested by Franz et al. (2003a). Westwood and Goodale (2011) posit that it is more likely that other mechanisms, such as inappropriate size-constancy scaling, would be more appropriate than veridical change in this scenario. Westwood and Goodale (2011) also state that because the various mechanisms affect the response through different scaling functions, it "might not be appropriate to 'calibrate' one effect (the illusion) based on the scaling function for another effect (veridical size)." A size-scaling correction may be even more inappropriate for tasks such as grasping, as grip aperture is affected by many other factors than veridical size alone (Westwood & Goodale, 2011). Due to the previous issues, Westwood and Goodale (2011) questioned whether it is would even be valuable to interpret the correction and concluded that correcting for the absolute effect of the Ebbinghaus illusion is premature at best.

Since proposing their version of the two-stream hypothesis based off of patient D.F., many studies were conducted on healthy subjects. Westwood and Goodale (2011) note that many of these studies were still in line with their original findings from their 1991 study, although an active debate ensued as to whether or not the Ebbinghaus illusion affects grasping as well as perception. However, no studies were conducted using active touch in the Ebbinghaus illusion. As an investigation using active touch could have important implications for the perception-action debate, which is why we elected to use active touch in our experiment.

# CHAPTER 3: EBBINGHAUS ILLUSION IN TOUCH

## 1. INTRODUCTION

As previously discussed, the majority of research on the two-stream hypothesis debate using Ebbinghaus Illusion have required participants to engage in grasping tasks. Typically, participants are instructed to grasp or pick up one of the inner circles in an Ebbinghaus Illusion set. Contrary to these studies, we elected to use active touch in our experiment instead of grasping. Using tactile exploration instead of grasping offers a variety of benefits. First, touch requires the *active* exploration of the Ebbinghaus Illusion sets with the participant's hands. As the participants in the study were also blindfolded, none of their actions were visually-guided. In contrast, in grasping, a participant's actions are visually-guided (i.e. participants viewed the inner circle of the Ebbinghaus Illusion they were about to grasp). This is not a new procedure, as blindfolding experiments have been used to investigate the dissociation in perception and action through blind-walking studies as well as walkable illusion studies (Loomis et al., 1992; Wraga et al., 2000). Many of these studies (e.g. Thomson, 1980) demonstrate that blindfolded participants are able to accurately walk towards a previously seen target, and even navigate around obstacles. Moreover, in Haffenden and Goodale (2000, 2001), the stimulus and participants' hand disappeared temporarily from the view in both manual estimation and grasping tasks. In our situation, participants were exposed to the stimuli before the experiment started, but they were not relying on a visual memory of the stimulus. Their answers were based only on tactile exploration based on a previous knowledge of the stimulus nature during the tactile-tactile experiments.

As Hayward (2008) describes, various visual illusions also exist within the tactile modality. Typically, they are incorporated into touch by using raised line drawings. Similar to our experiment, participants were instructed to explore the stimuli using active touch with their hands while blindfolded. To date, some of the visual geometrical illusions that have been used in touch include the Müller-Lyer, Oppel-Kundt, vertical-horizontal, Bourdon, Ponzo, Zöllner, Poggendorf, and Delboeuf illusions (Hayward, 2008; Suzuki & Arashida, 1992; Heller & Joyner, 1979). Evidence from a study conducted by Gentaz & Hatwell (2004) has demonstrated that the strongest illusion in touch is the Müller-Lyer illusion, while the weakest is Delboeuf illusion.

As Gentaz and Hatwell (2008) posit, results not demonstrating the existence of a visual illusion in touch would support the idea of specific haptic perceptual mechanisms, while results demonstrating the existence of a visual illusion in touch supports the notion of similar haptic and visual perceptual mechanisms. Although results may support the existence of a visual illusion in touch, it is difficult to deduce whether or not the error is caused by similar perceptual processes in vision and touch.

As noted, studies involving blindfolding participants are used to solve this dilemma. In previous studies, participants have also included early and late blind individuals to be compared to normal-sighted participants. This can cause some methodological issues, however, as normal-sighted blindfolded participants have an advantage over early blind participants due to their vision and mental images that they were able to generate (Hatwell, 1966). However, congenitally blind participants may actually have an advantage, as they have had more practice using tactile perception to navigate. Finally, late blind individuals have the greatest advantage, as they have had extensive tactile practice as well as spatial visual representations. Due to these differences, it has been suggested that if an illusion is present in the late blind but not in the early blind that visual experience is responsible (Gentaz & Hatwell, 2008). If the visual illusion also exists in the early blind, non-visual explanations must be used to explain the phenomenon. As Gentaz & Hatwell (2008) point out, the causes may exist in both modalities, or they may be specific to vision and touch. The final consideration for comparing normal-sighted and early- and late-blind individuals is to investigate whether tactile and visual perceptual processes share the same pathways. Further, the results of studies investigating visual illusions in touch may be influenced on which part(s) of the hand are used. For example, some tasks require participants to use their whole hand, their index finger, or both hands.

As previously mentioned, the Müller-Lyer illusion is the strongest illusion in touch (Gentaz & Hatwell 2004). In this classic visual illusion, the perceived size of the horizontal lines are altered by the arrows on both ends of the line (Figure 5). The line with the arrowheads pointing in (image B) is perceived to be longer than the line in which the arrowheads are pointing out (image A) and the line without arrowheads.

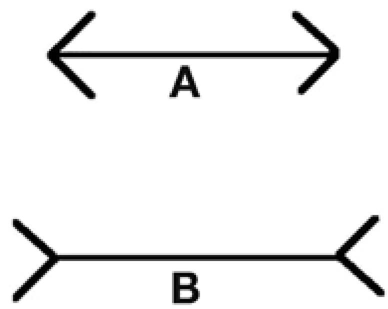


FIGURE 5: MÜLLER-LYER ILLUSION (FROM GENTAZ & HATWELL, 2008)

Previous studies have shown that the Müller-Lyer illusion exists in normal-sighted, early blind, and late-blind participants (Millar & Al-Attar, 2002; Wong, 1975). Because it is present in all of these populations, it can be inferred that the Müller-Lyer illusion is independent from visual experience. Gentaz & Hatwell (2008) also posit that perceptual learning is present in the tactile modality as it is in the visual modality. For example, participants' performance typically improves as they complete more trials, even without feedback on their performance. Millar and Al-Attar (2002) have also demonstrated that by using experimental manipulations, the effects of the illusion in both touch and vision are reduced. Specifically, they instructed participants to avoid the arrowheads at the end of each horizontal line of the Müller-Lyer illusion. For this reason, in our study in experiments 3 and 4, participants were instructed to feel the entire Ebbinghaus set, and not just focus on the inner target circles of the set.

Taken together, the results of the previous studies investigating the Müller-Lyer illusion in vision and touch suggested the involvement of similar processes in both modalities. As noted, the Müller-Lyer illusion is the strongest visual illusion to exist in touch. This could be also attributed to the fact that it is one of the most widely studied visual illusions in touch.

Another visual illusion that has been studied in touch is the vertical-horizontal illusion (Figure 6). In this illusion, participants overestimate the vertical line segment compared to the horizontal line. Previous studies have found the vertical-horizontal illusion to exist in normal-sighted, and in the early and late blind (Suzuki & Arashida, 1992) when incorporated into the tactile modality. Specifically, Suzuki & Arashida (1992) found the vertical line bisecting the horizontal line (image A of Figure 6) is perceived to be approximately 1.2 times larger than the horizontal line segment in the same image.

Studies investigating the vertical-horizontal illusion have suggested that the factors responsible for the effects of the illusion are similar in both touch and vision. In both modalities, participants overestimate the length of the vertical line segment in images A and C compared to in image B when the vertical line does not bisect the horizontal line. This seems to suggest the role of the bisection is important in both vision and touch.

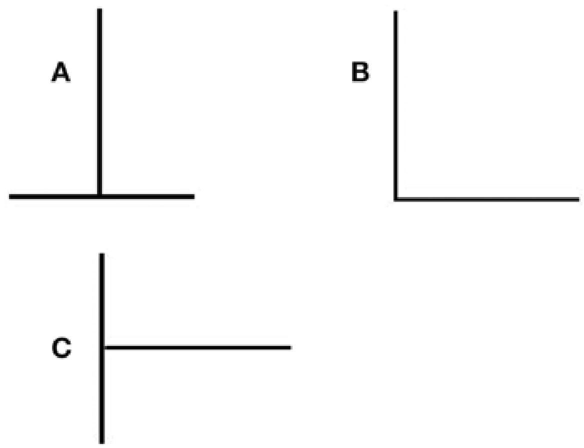


**FIGURE 6: THE VERTICAL-HORIZON ILLUSION (FROM GENTAZ & HATWELL, 2008)**

In 2000, Millar investigated the magnitude of image A (Figure 6) in normal-sighted blindfolded adults. In their task, two groups of participants used active tactile perception. One group was restricted to using their right index finger, while their other group used both hands and also were able to use reference cues (a rigid frame surrounding the illusory stimulus). Millar (2000) found a clear reduction in errors in the second group which explored the vertical-horizontal illusion with both hands. They attributed these results to the reference cues (the frame surrounding the illusory stimulus) that was available to them. In aggregate, these results suggest that the role of bisection in the vertical-horizontal illusion share similar processes in both vision and touch.

Unlike in the Müller-Lyer illusion, there appears to be differences in the mechanisms for the vertical-horizontal illusion in touch and in vision. For example, it has been proposed that in vision, the error is caused by anisotropy in the visual field

(Künnapas, 1955). In the tactile modality, however, active tactile exploration seems to play an important role.

The Delboeuf illusion is another famous visual illusion that has been studied in touch. As previously mentioned, Hayward (2008) stated that the Delboeuf illusion is the weakest visual illusion in the tactile modality (with the Müller-Lyer illusion being the strongest). In this illusion, the circle surrounded by an outer circle appears larger than the other circle, which is by itself (Figure 7). The Delboeuf illusion is of particular importance for our purposes, as it has been proposed that the visual processes that cause this illusion may also cause the Ebbinghaus illusion (Roberts et al. 2005).

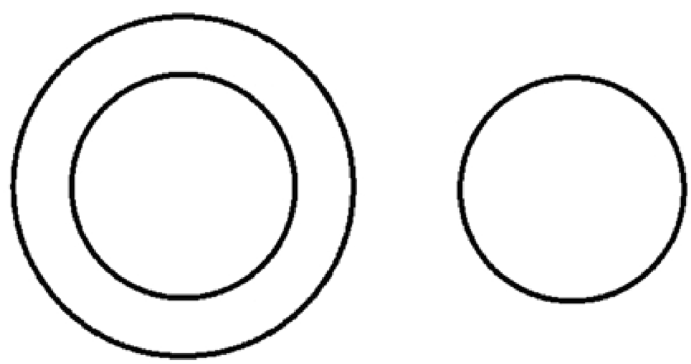

**FIGURE 7: DELBOEUF ILLUSION (FROM GENTAZ & HATWELL, 2008)**

In a previous study, Hatwell (1960) used a bimanual exploration task to explore the Delboeuf illusion. Hatwell (1960) found that this illusion is not present in children who are blind (early and late). This held true even when the illusion was increased (equivalent to the maximum condition in vision). Another team of researchers, Suzuki and Arashida (1992) used normal-sighted adults to study the Delboeuf illusion in touch.

Their results were similar to that of Hatwell's: the illusion is present in vision, but not in the tactile modality. In an interesting twist, participants actually underestimated the outer surrounding circle in both vision and touch.

Various researchers have proposed reasons why the Delboeuf illusion is absent in touch. Hatwell (1960) proposed that its absence in touch could be attributed to exploratory hand movements (e.g. active touch), as they may reduce the context effects. As Gentaz and Hatwell (2008) note, this is plausible, but has some gaps. First, it does not explain why the illusion occurs in touch for the exterior circle. Another reason this illusion may not be present in touch is that participants are able to isolate one of the sets and compare it to the other. For these reasons, participants are not as easily deceived. Based on the results of this study, participants in our experiment were touching both sets of the Ebbinghaus illusion at the same time, to ensure they were not isolating one of the sets which could lessen the effects of the context.

For the scope of this thesis, we performed four different experiments. Experiment 1 tested the threshold of comfort detection, which consisted of determining the optimum difference between two circles that could be easily compared tactilely. Experiment 3 consisted of testing whether the Ebbinghaus illusion exists within the tactile modality. Experiments 2 and 4 explored the visual-tactile interaction for the inner circles of the Ebbinghaus illusion alone (without the outer circles present), and and the full set Ebbinghaus circles (with both the inner and outer circles present).

# EXPERIMENT 1

## 1.1. PARTICIPANTS

All participants were students at Northern Michigan University, and received a course credit for their participation in the study. Thirty participants participated in this experiment, and all participants were right-handed. The institutional review board (IRB) approved the experimental procedures, and all participants gave their informed consent to the experimenter prior to participation in the study.

## 1.2. APPARATUS AND STIMULUS

Laser-cut 3mm thick sticky foam circles were used as the stimuli. The results of experiment 1 determined the size of the foam circles to be used. In this experiment, there were 5 sizes for each group. Group 1 used a size range of 17.49-23.81mm with a 1.58mm step, group 2 used a size range of 20-28mm with a 2mm step, and group 3 used a size range of 24-35mm with a 3mm step.

## 1.3. PROCEDURE

The first experiment was a preliminary study, with the goal of determining the optimal sizes for the inner circles (no outer circles were present) for the Ebbinghaus Illusion experiment. By determining the step threshold, it could be determined which sizes participants can easily distinguish. Participants were randomly assigned to each of the three groups. For each group, five different sizes of circles were used. Participants were divided into three groups and were instructed to bimanually explore the sticky foam circles while comfortably seated in a chair. Participants were blindfolded and stimuli were presented on a table directly in front of them, where they could reach the stimuli with each hand without difficulty. The circles were glued onto letter size sheets, which were attached to the table via Velcro (to ensure the sheets did not move during tactile exploration). The participants were instructed by the experimenter to tactilely explore the two sheets simultaneously (one with each hand), and verbally indicate to the experimenter if the circles were the same size or different. If the participant indicated different, they verbally indicated to the experimenter which circle they perceived to be larger. There were a total of 50 equally randomized trials (5 sizes x same vs. different).

### 1.4. Data Analysis

A one-way analysis of variance (ANOVA) was conducted to see if differences existed among groups 1, 2, and 3 with a significance level set at $p>0.05$. A Tukey posthoc analysis was also performed to determine differences between groups.

### 1.5. Results

Results are displayed in Figure 2. The assumption of homogeneity of variance has been met (Levene's test > 0.05) and the one-way ANOVA showed a significant effect of the group factor on the percentage of correct answers, $F(2,29) = 6.46$, $p = 0.005$. Tukey posthoc tests revealed a significant different between G1 and G3 ($p=0.004$), but not difference between G2 and G3, and G1 and G2. As shown in Figure 2, the performance of participants in group 3 was higher than both groups 1 and 2. Even though all of the groups did perform above chance level, the purpose of this preliminary experiment was to ensure all participants could easily discriminate between the different sizes of circles without the presence of the outer circles. This was important, as that served as the baseline for comparison. Based on the results of this experiment, and the results of previous grasping experiments, we elected to use a range of sizes between 28-27mm with a 3mm step, which also served as the sizes used for experiments 2, 3, and 4.

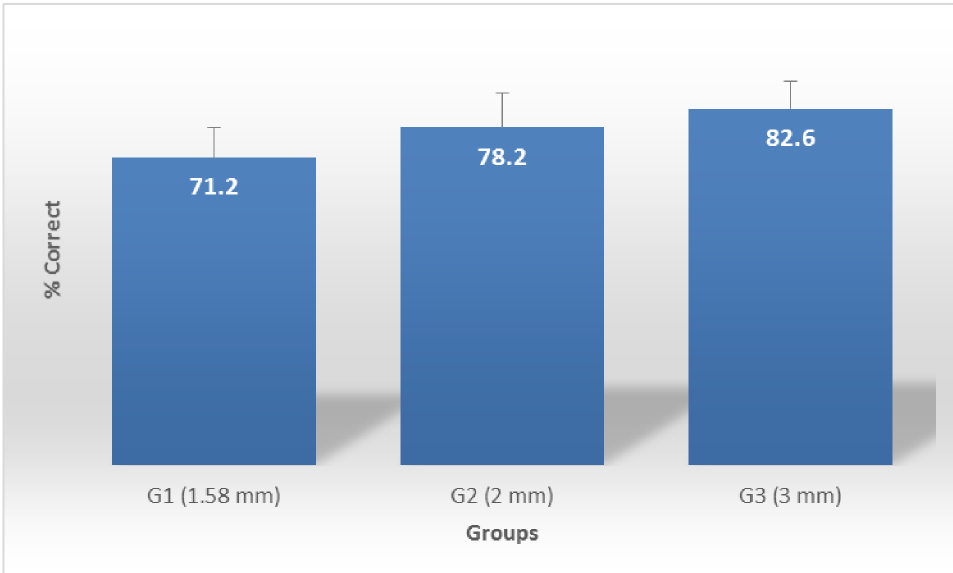


FIGURE 8: PERCENTAGE OF CORRECT ANSWERS PER GROUP OF PARTICIPANTS

## 2. EXPERIMENT 2

### 2.1. PARTICIPANTS

All participants were students at Northern Michigan University, and received a course credit for their participation in the study. Of the thirty participants, twenty-five of them were right-handed, 3 were left-handed, and 2 were ambidextrous. The mean age of participants was 24.6. The institutional review board (IRB) approved the experimental procedures, and all participants gave their informed consent to the experimenter prior to participation in the study.

### 2.2. Procedure

The goal of experiment 2 was to identify the cross-modal tactile-visual versus unimodal tactile-tactile interaction for size estimation of the inner circles alone. In this experiment, participants were randomly assigned to two groups: group one was in the tactile-visual condition and group two was in the tactile-tactile condition. Participants in group 1 were instructed to touch a sticky foam circle with their dominant hand hidden behind a screen, and compare its size to three sticky foam circles visually during the tactile exploration. The three circles used as visual stimuli were always of different sizes. The size of the circles were determined by the results of experiment 1: 28-37mm with a 3mm step. One of the visual stimuli was identical to the tactile stimuli for each trial. Participants in group 2 had a similar task to participants in group 1 from experiment 1 (e.g. touching and comparing the sizes of two circles while blindfolded).

### 2.3. Data Analysis

A one-way analysis of variance (ANOVA) was conducted to see if differences existed between the tactile-tactile and visual-tactile groups with a significance level set at $p>0.05$. A Tukey posthoc analysis was also performed to determine differences between groups.

### 2.4. Results

The results of experiment 2 can be found in Figure 9. The assumption of homogeneity of variance has not been violated and the one-way ANOVA showed a significant difference between crossmodal and unimodal conditions, $F(1, 28) = 12.005$, $p = 0.002$. Participants' performances were higher for the tactile-tactile condition as opposed to the tactile-visual condition. Selective attention could be an explanation for these results, as suggested by Martino et al. (2000), where cross-modal interaction of vision and touch showed similar results when participants were exposed to vibrotactile and a visual stimuli. As our task was not as cognitively demanding as the one used by Martino et al. (2000), where the participants had to pay attention to one sensory modality or another, these results are particularly surprising. Further, no conflict has been introduced in the visual-tactile matching case, as is such in the case of Heller et al. (1993).

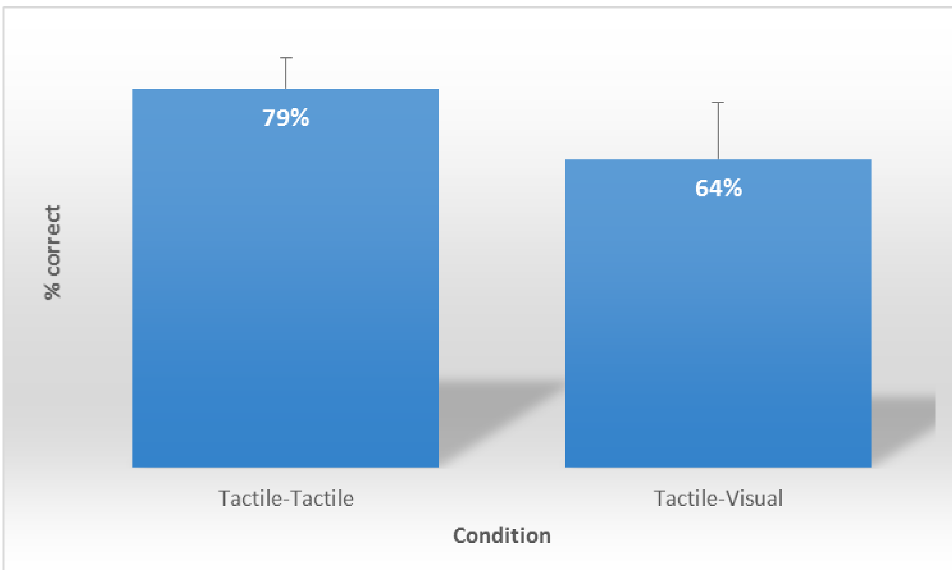


**FIGURE 9: PERCENTAGE OF CORRECT ANSWERS FOR CROSS-MODAL (VISUAL-TACTILE) AND UNIMODAL CONDITION (TACTILE-VISUAL).**

## 3. EXPERIMENT 3

### 3.1. PARTICIPANTS

All participants were students at Northern Michigan University, and received a course credit for their participation in the study. Thirty participants participated in this experiment. Two participants were left-handed, and 20 participants were right-handed. The mean age of participants was 23.1. The institutional review board (IRB) approved the experimental procedures, and all participants gave their informed consent to the experimenter prior to participation in the study.

## 3.2. PROCEDURE

For the Ebbinghaus sheets, the same sticky foam circles of 3mm thickness were used. The circles were glued on letter size sheets, and the sheets were attached to the table using Velcro. The size range of the circles was from 28-37mm with a 3mm step. The larger outer circles were of 50mm in diameter, and the smaller outer circles were of 10m in diameter. The distance between the center of the outer circle and the center of the inner circle was 100mm, and the distance between the center of the inner circle and the center of any small outer circle was 50mm. The inner circles were either surrounded by 11 small circles or five larger circles (Figure 10). The Ebbinghaus Illusion circles were glued on a letter size sheet, and could have three possible layouts, as described in .

Table 1.

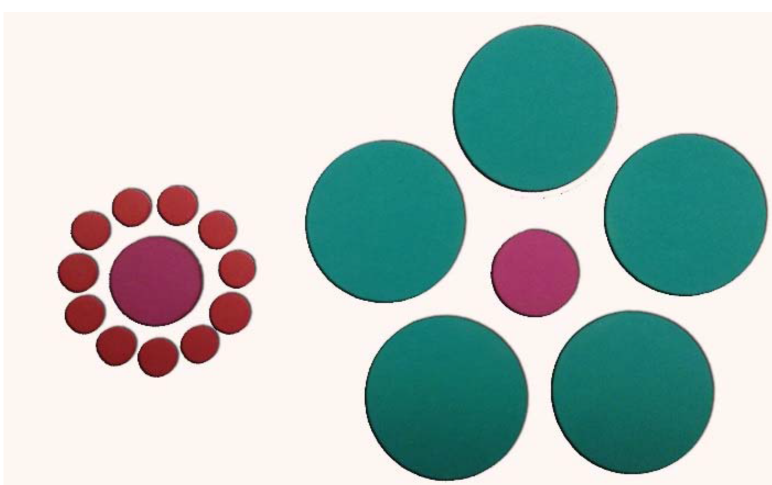

**FIGURE 10: EBBINGHAUS ILLUSION STIMULUS FROM EXPERIMENT 3**

The tactile-tactile group from experiment 2 was used as a control for this experiment. Whereas experiment 2 only used the inner circles by themselves, experiment 3 used the Ebbinghaus Illusion sheets. Again, the participants were asked to bimanually explore tactilely the sets of circles on the table in front of them while blindfolded. In order to avoid the participants solely focusing on the inner circle, they were instructed to feel the entire set of circles. The participants were asked to verbally indicate to the experimenter if the inner circles were the same size or if they were different. If the participant indicated the inner circles were different, they had to verbally tell the experimenter which inner circle was larger or smaller.

**TABLE 1. POSSIBLE LAYOUTS OF THE EBBINGHAUS CIRCLES**

| Outer circle sizes | Inner circle sizes |
|---|---|
| Large vs. large | Same or different |
| Small vs. small | Same or different |
| Small vs. large | Same of different |

There were a total of 72 equally randomized trials (4 sizes x 3 layouts x same vs. different). The participants were faced with a variety of scenarios. When the surrounding outer circles were of the same size (either both small or both large), the Ebbinghaus Illusion is not present. When the surrounding outer circles were different sizes (e.g. one small one large), there are three potential scenarios:

1. The inner circles are the same size (Ebbinghaus Illusion is present).

2. The Ebbinghaus Illusion is reduced when the inner circle surrounded by large outer circles is smaller than the inner circle surrounded by smaller outer circles. The illusory effect is reduced in this condition, as this particular set-up increases participant accuracy.

3. The Ebbinghaus Illusion is increased when the size of the inner circle surrounded by larger outer circles is larger than the inner circle surrounded by smaller circles.

## 3.3. Data Analysis

Signal detection theory (SDT) was used to analyze the data for this experiment, as we were primarily interested in the responses related to the illusion in the tactile modality. SDT is a psychophysical method which is utilized to assess the perceptual judgments of participants as well as their decision criteria. In addition, SDT can be used to determine the participant's sensitivity, their ability to make decisions in circumstances with fuzzy conditions, and their decision making style.

When using SDT, a signal is present in some of the trials in the experiment. In other trials, there is no signal (the "noise"). In this case, however, the presence of the Ebbinghaus Illusion was used as the signal, and the absence of the signal was considered to be the "noise." In the experiment, participants will respond "yes" if they perceive the signal, and "no" if they do not perceive the signal. The responses of participants can be placed into four distinct categories (Table 2).

1. A "yes" answer after the Ebbinghaus Illusion is presented is a HIT

2. A “yes” answer in the absence of the Ebbinghaus Illusion is a false alarm (FA)

3. A “no” answer after the Ebbinghaus Illusion is presented is a miss

4. A “no” answer in the absence of the Ebbinghaus Illusion is a correct rejection (CR).

TABLE 2. SIGNAL DETECTION THEORY: THE MATRIX OF THE FOUR CATEGORIES. THE HIT RATE IS THE CATEGORY THAT IS RELEVANT FOR THIS EXPERIMENT (ILLUSION IS PERCEIVED).

| | Respond “illusion” | Respond “no illusion” |
|---|---|---|
| Stimulus present (illusion effect) | HIT | MISS |
| Signal absent (no illusion effect) | FA | CR |

## 3.4. RESULTS

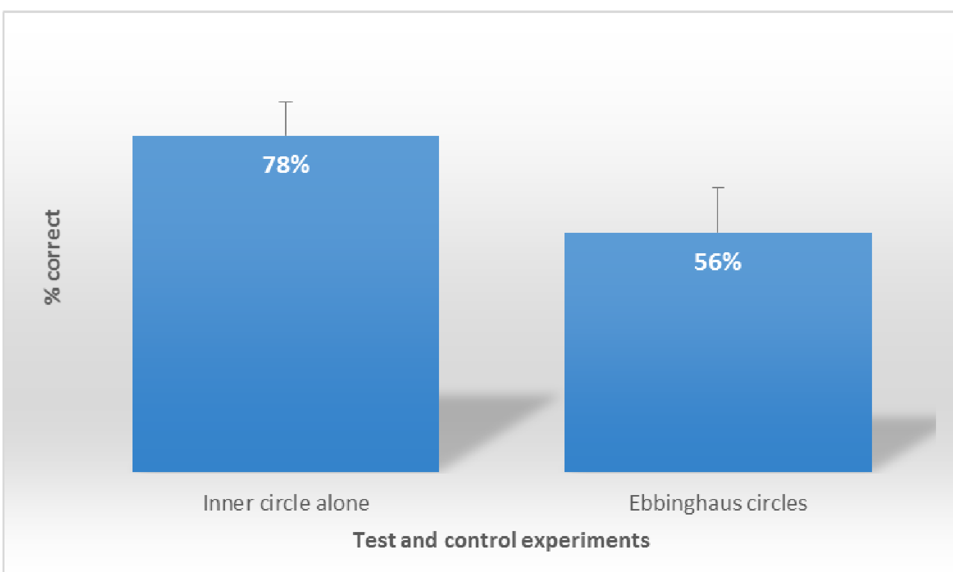

**FIGURE 11: PERCENTAGE OF CORRECT ANSWERS FOR THE TEST AND THE CONTROL EXPERIMENTS**

First, the percentage of correct answers was compared to the participants' answers in the control conditions. A one-way ANOVA was performed after verifying that the assumption of homogeneity of variance had been met. The ANOVA showed a significant difference between the test and control experiment, $F(3, 29) = 16.069$, $p < 0.001$. Indeed, the results show that the performance for circles in context (with outer circles) is lower than when the circles are alone (Figure 11). This suggests that the participants were sensitive to the context, and therefore based their answers by taking the outer circles into consideration.

Second, we tested the participants' sensitivity (d') as showed by the ROC curve (Figure 12). Seven participants were excluded for random responses throughout the experiment (d'=0, which is equivalent to random responses).

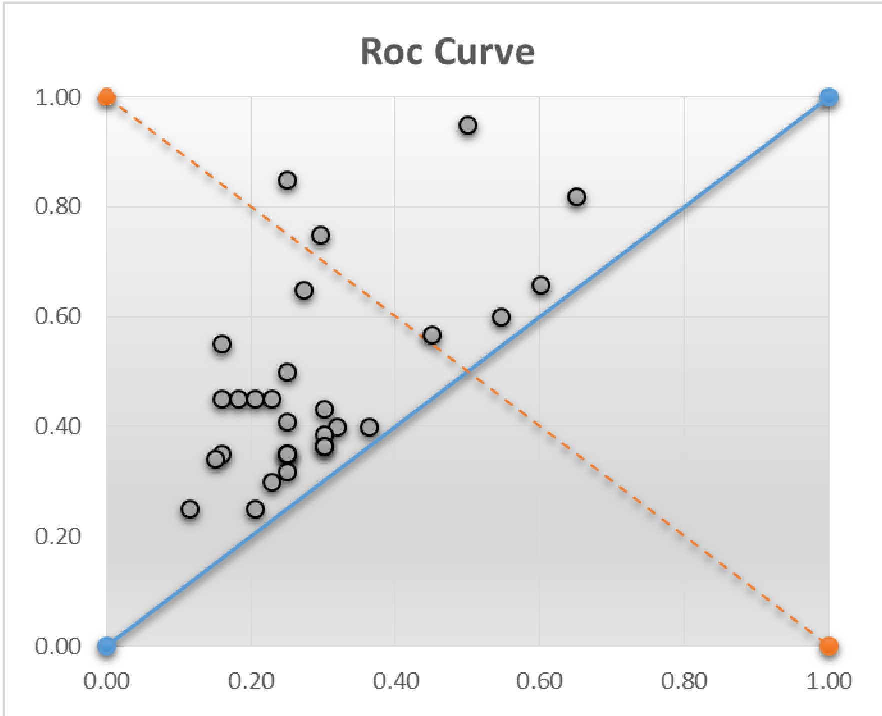


FIGURE 12: ROC CURVE SHOWING PARTICIPANTS' ANSWERS. THE DATA OF SEVEN PARTICIPANTS (VALUE ON THE LINE, I.E. D'=0) WERE REMOVED. THE OTHER VALUES ARE BETWEEN 0.1 AND 1.71. THE CURVE WAS OBTAINED BY PLOTTING SPECIFICITY AGAINST SENSITIVITY (OR HIT RATE ON THE Y-AXIS AGAINST THE FA RATE ON THE X-AXIS).

A one-way ANOVA for repeated measures showed a significant effect of the factor category, $F(3, 39) = 21.40$, $p < 0.001$. Pairwise comparisons showed the number of CRs was significantly different from hits ($p<0.001$), misses ($p<0.04$), and FAs ($p<0.001$). Indeed, Figure 13 shows that the percentage of CR is significantly higher relatively to the other categories. This suggests that when no illusion was present, the participants were able to determine the correct size of the inner circles despite the presence of the outer circles. There were no difference between the number of misses (correct rejection of the illusion) and the number of hits (illusion is perceived). As shown in Figure 13, participants made more errors (number of MISS not significantly different comparing to HITS) when the illusion was present. This suggests that the illusory stimulus indeed deceived the participants. This is corroborated by the significant difference between HIT and FA ($p<0.04$), which states that there are more errors when an illusory stimulus is presented, comparing to conditions where the non-illusory stimulus is presented, and the significance difference between MISS and FA, ($p<0.01$), which validates the fact participants are less deceived by the noise (answer no to a non-illusory stimulus) than by the signal (answer no to an illusory stimulus). In summary, these results support evidence for the existence of the Ebbinghaus illusion in the tactile modality.

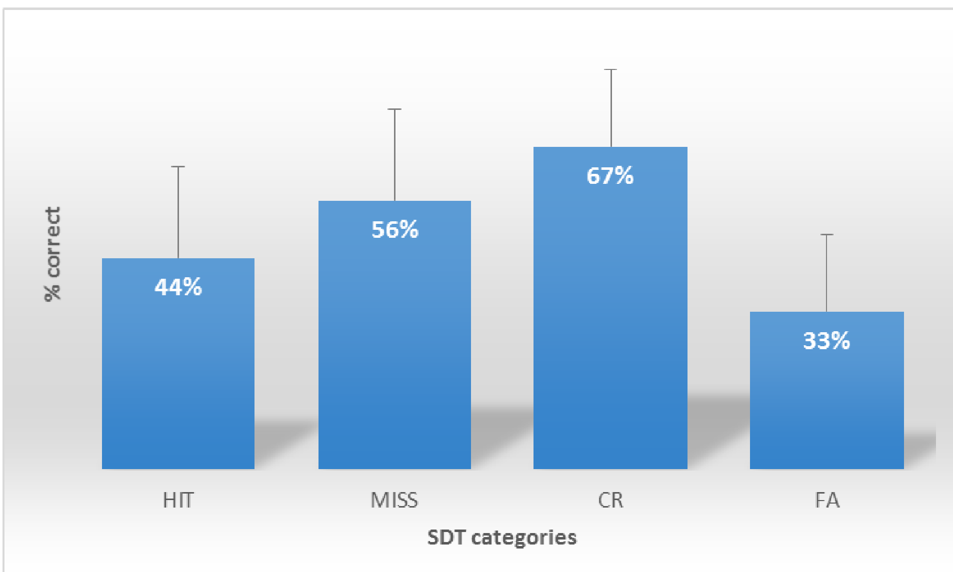


**FIGURE 13: PERCENTAGE OF CORRECT ANSWERS FOR THE FOUR CATEGORIES: HIT, (FALSE ALARM) FA, (CORRECT REJECTION) CR, AND MISS**

# 4. EXPERIMENT 4

## 4.1. PARTICIPANTS

Sixteen participants participated in this condition. Five participants were males, 16 were females. Thirteen of the participants were right-handed, and 3 of the participants were left-handed. The participants had an age range of 18-20 years old (mean age of 19.06 and a standard deviation of .65).

## 4.2. PROCEDURE

Participants were instructed to touch an Ebbinghaus Illusion sheet (constructed with foam circles) with their dominant hand hidden behind a screen, and compare its size to three Ebbinghaus Illusion sheets visually during the tactile exploration. Halfway through the trials (after the first 32 trials), participants were instructed to use their opposite hand for the tactile exploration. The size of the three inner circles used as visual stimuli were always of different sizes, determined by the results of experiment 1 (28-37mm with a 3mm step). One of the inner circles in the visual Ebbinghaus stimuli was identical to the tactile stimuli for each trial.

## 4.3. DATA ANALYSIS

The data analysis procedure from experiment 3 was also followed for experiment 4 (signal detection theory).

## 4.4. RESULTS

We tested the participants' sensitivity (d') as showed by the ROC curve (Figure 14). Four participants were excluded for random responses throughout the experiment (d'=0, which is equivalent to random responses).

A one-way ANOVA for repeated measures showed a significant effect of the factor category, $F(3, 15) = 15.359$, $p < 0.001$. Pairwise comparisons showed the number of hits was significantly different from the number of misses ($p<0.001$), and the number of correct rejections ($p<0.002$), as can be seen in Figure 15. The number of misses and the number of false alarms were also significantly different ($p<0.001$). These results between the hit (illusion is perceived) and miss (correct rejection of the illusion) categories demonstrate that when the illusion was present, participants were able to correctly reject it (miss) as opposed to being deceived by it (hit). Because the percentage of misses and the percentage of false alarms were significantly different, we can deduce that participants were able to correctly reject the illusion when it was present more than they were deceived by the non-illusory stimulus.

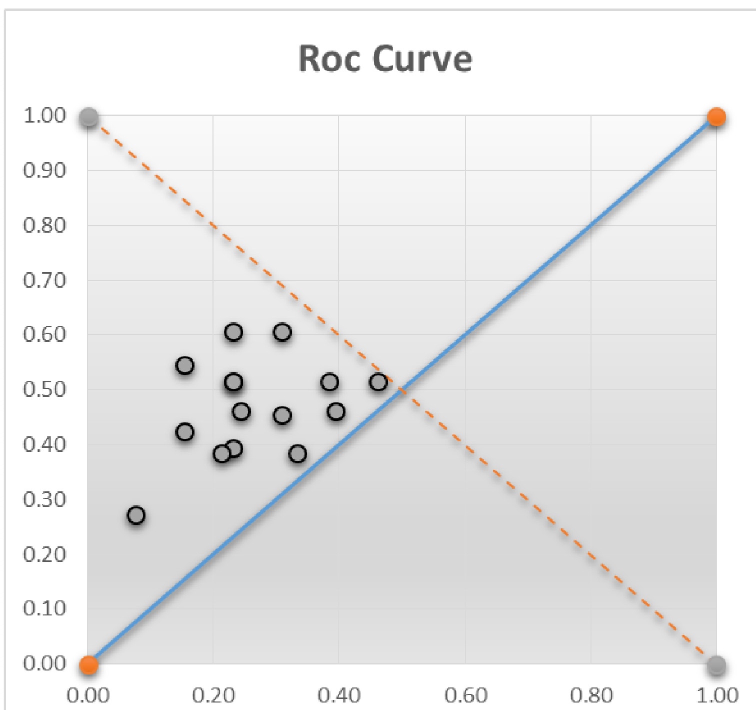

FIGURE 14: ROC CURVE SHOWING PARTICIPANTS' ANSWERS. THE DATA OF FOUR PARTICIPANTS (VALUE ON THE LINE, I.E. D'=0) WERE REMOVED. THE OTHER VALUES ARE BETWEEN 0.13 AND1.13. THE CURVE WAS OBTAINED BY PLOTTING SPECIFICITY AGAINST SENSITIVITY (OR HIT RATE ON THE Y-AXIS AGAINST THE FA RATE ON THE X-AXIS).

The significant differences between the number of correct rejections and the number of hits show that when the illusion was not present, participants were accurately able to deduce this, even with the presence of the outer circles of the Ebbinghaus illusion.

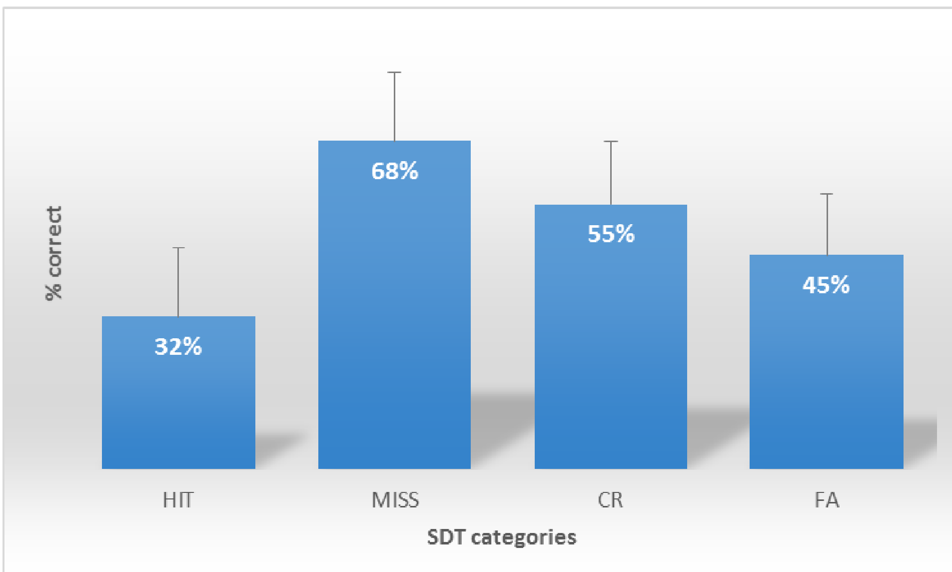


FIGURE 15: PERCENTAGE OF CORRECT ANSWERS FOR THE FOUR CATEGORIES: HIT, (FALSE ALARM) FA, (CORRECT REJECTION) CR, AND MISS

Further, we noted that the percentage correct for the four SDT categories from experiment 3 and experiment 4 are different, as shown in Figure 16. As can be deduced from the graph, the trends are reversed. For example, in experiment 3, the number of

HITS was lower than in experiment 4. This trend was significantly different as shown by the t-test scores (Table 3).

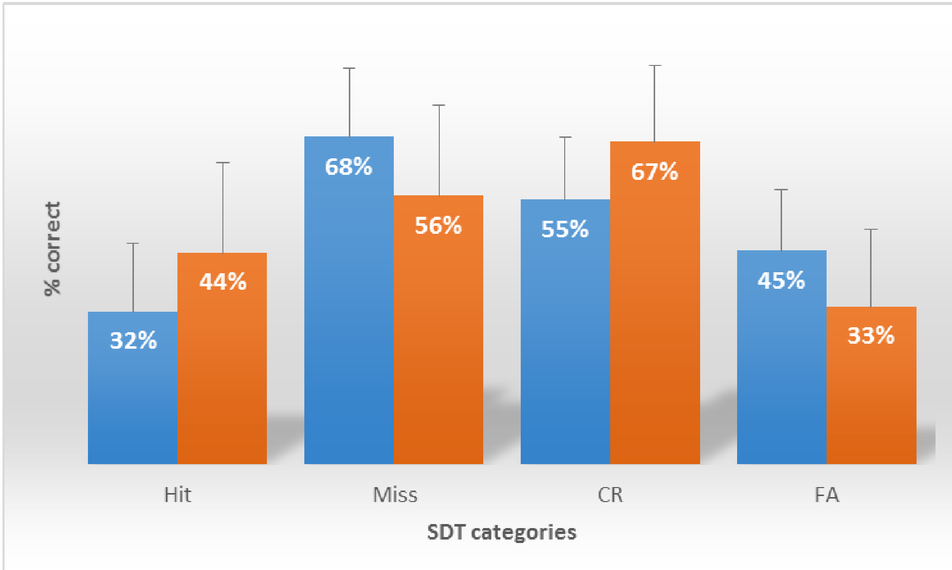


FIGURE 16: COMPARISON OF PERCENTAGE CORRECT IN THE FOUR SDT CATEGORIES FOR EXPERIMENTS 3 AND 4

TABLE 3: INDEPENDENT SAMPLES T-TEST COMPARISONS OF PERCENTAGE CORRECT IN THE FOUR SDT CATEGORIES FOR EXPERIMENTS 3 AND 4

| CATEGORY | T-VALUES | SIGNIFICANCE |
|---|---|---|
| HIT | 2.283 | P<0.05 |
| MISS | -2.283 | P<0.05 |
| CR | 2.565 | P<0.05 |
| FA | -2.510 | P<0.05 |

# GENERAL DISCUSSION AND CONCLUSION

The results from this study support the existence of the Ebbinghaus illusion in the tactile modality, as well as Goodale and Milner's (1991) version of the Two-Stream Hypothesis.

In experiment 3, our results demonstrated that participants were more likely to be deceived when an illusory stimulus (the Ebbinghaus illusion) was present, versus when a non-illusory stimulus was present. Further, participants were able to accurately respond "no illusion" when the signal was absent (approximately 33% correct). In addition, our results demonstrate that participants performed better with the inner circles by themselves (78% correct) than when the Ebbinghaus sets were used (56% correct). Because participants in this experiment were blindfolded and vision was not present, these results support the existence of the Ebbinghaus illusion in the tactile modality.

Further, the results of experiment 3 could aid in explaining the divergence of results obtained from grasping studies (see chapter 2). As the participants in the experiment were unable to view the stimuli, vision could not have affected our results. In contrast, in the grasping studies, participants were at least able to briefly see the stimuli, albeit only for a second in some previous studies. If the stimuli were being constantly viewed by the participants, they would be able to adjust their perceptions and actions accordingly, and not be affected by the illusion. Taken together, the results from our third experiment support Goodale and Milner's (1991) version of the two-stream hypothesis.

Experiment 4 had slightly different results from experiment 3. In this experiment, the pairwise comparisons showed a significant difference between the number of hits (respond "illusion" when the signal is present) and the number of misses (respond "no illusion" when the signal is present). The number of misses was higher (68% correct) compared to the number of hits (32% correct), which suggests that the illusion did deceive the participants. The number of hits and the number of correct rejections (respond "no illusion" when the signal absent) was also significantly different. Finally, the number of misses and the number of false alarms (respond "illusion" when the signal is absent) were also significantly different. This suggests that when both modalities are present to estimate the illusion (e.g. vision and touch), the perceptual system is not deceived, while participants are deceived when touch and vision are presented alone.

At first, we could posit that because the visual and tactile conditions do not resist the Ebbinghaus illusion, that they must share the same perceptual mechanism in the brain. If this was the case, using both systems (vision and touch) simultaneously would have resulted in stronger illusion effect, which was not supported in our study. Because participants were exploring with one hand and basing their responses on visual information, the notion that they were using the action pathway and the perception pathway simultaneously is supported. If, however, both action and perception shared the same mechanism, we would have obtained the same results. The results obtained from experiment 4 reinforced the idea that action and perception pathways are indeed separated in the brain.

Although the Ebbinghaus illusion has been widely studied in grasping, and has now been introduced in touch, there is still much to be investigated. As previously described, whether or not the same perceptual processes in vision and touch are used in the Ebbinghaus illusion has yet to be answered. A further understanding of both of these processes could potentially aid in explaining our results. As this is also the first study using active tactile exploration and cross-modal interaction in the Ebbinghaus illusion, further studies should be conducted to see if our results are supported.

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