Third Joint Eurohaptics Conference and Symposium on Haptic Interfaces
for Virtual Environment and Teleoperator Systems
Salt Lake City, UT, USA, March 18-20, 2009

Evidence for Haptic Memory

Ron Shih[1], Adam Dubrowski[2], Heather Carnahan[3*]
[1]University of Waterloo, Ontario, Canada
[2]Center for Research in Nursing Education, Faculty of Nursing, University of Toronto, Ontario, Canada
[3]Department of Occupational Science and Occupational Therapy,
University of Toronto, Ontario, Canada (*heather.carnahan@utoronto.ca)

Abstract

The purpose of these experiments was to investigate the minimum duration of haptic memory representations. The term haptic memory can be defined as the ability to retain impressions of haptically acquired information after the original stimulus is absent. Participants repeatedly picked up objects of various masses. The time interval between the final practice lift of each object and a test lift was manipulated. In the 0 second delay condition, there was no delay between the release of the object after the final practice lift and the test lift. In the 2 and 10 second delay conditions there was a 2 or 10 second delay, respectively, between the release of the object after the last practice lift, and the test lift. Greater peak grip force was produced for the first lift compared to the subsequent practice lifts. In the 0 second delay condition, the peak grip force used in the test lift was similar to the last practice lift. As the delay increased to 10 seconds, the peak grip forces used were similar to that of the first lift. Even after a 2 second delay the peak grip force was greater than that of the last practice lift. Peak torque also followed these same patterns. The present results suggest that the haptic representation of object mass is short-lived (< 2 s) and has a duration and decay similar to visual iconic memory.

KEYWORDS: Haptic memory, grip force

CR Categories: J.4 [Social and Behavioral Sciences]: Psychology; General Terms: Experimentation

1. INTRODUCTION

In the span of a day, people commonly come into contact with hundreds of familiar and unfamiliar objects. When grasping familiar objects, people tend to use the appropriate amount of force to grip and lift these objects. How is it that the grip and load forces chosen are appropriate to avoid accidental slips and object deformation, while still being scaled appropriately for the object's mass and frictional characteristics [1][2][3]? People pick up common, everyday objects in a way that appears to reflect their experience with the object. If past experience influences action, then how is memory being used to guide these actions? Numerous studies have recognized that previous experiences do create some form of memory that people later use to determine load and grip forces when lifting objects. Gordon, Westling, Cole, and Johansson [4] examined this by measuring the duration of the load phase and the peak load force-rates produced when picking up familiar objects such as books, cans, and cracker boxes. It was found that even before sensory information regarding the objects' weight was registered via the participants' fingertips, participants anticipated the unique physical properties of the object (i.e., object weight) and scaled load force rates and load phase durations appropriately for each object on the first lift.

Furthermore, the load force rates used when grasping these familiar objects were shown to be very consistent. That is, it was demonstrated that over 10 lifts of a familiar item, the first and tenth trials did not differ significantly. In other words, drastic corrections in load force rates were not necessary after the first exposure and therefore indicated that when grasping very familiar objects, appropriate grasping forces were used even at the first exposure.

Gordon et al. [4] also had participants encounter unfamiliar objects possessing unusually high densities (4 kg/l). First attempts of lifting the object resulted in inadequate peak grip and load force-rates reflecting the inappropriate use of size-weight associations to incorrectly anticipate the object's weight. The recorded forces demonstrated the assumption that the novel object's density was expected to be in the range of frequently encountered densities. Within three trials however, participants were able to adapt to the unusual density of the object and to create accurate representations of the weight and thus appropriately modify their grip and load force rates on subsequent trials [4]. After two days of practice lifts of the unusually dense object, it was replaced by a significantly less dense object, whose appearance and dimensions implied that it was the same object as lifted on the previous two days. Participants erroneously programmed for the denser object previously lifted, by grasping the less dense object with the adapted grasping forces produced on the previous two days. Gordon et al. [4] hypothesized that there exists a robust 24 hour haptic memory that is important in anticipatory strategies in grip control.

Westling and Johansson [5] have also observed the influence of texture in the formation of the memorial representation used to determine grip and load force. It was noted that the texture condition (sandpaper, suede, and silk) from the previous trial influenced the grip forces used during the static hold phase of the subsequent trial. For example, the safety margin (difference between static grip force and the minimum grip force used to hold an object) increased for trials with sandpaper grasping surface that were preceded by trials that involved a more slippery grasping surface, like silk or suede rather than sandpaper. As well, it was found that object mass played a significant role in anticipatory control during prehension [5]. When object masses were presented in a pseudorandom order, participants erroneously programmed grip and load forces on the basis of the previous mass lifted. When the previous mass was heavier, a visible overshoot in grip force was seen. The overshoot was proportional to the difference in masses between the previous and current trials. A trial that was preceded by a trial involving a lighter mass showed grip force developments matching the previous lighter weight. Participants assumed that the current weight was the light weight of the previous trial, but when haptic input revealed the error in planning, a slower, discontinuous increase in grip and load force ensued. These data support the notion that a shorter term memory system for haptic information exists. The term haptic memory can be defined as the ability to retain impressions of haptically acquired information after the original stimulus is absent. However, when dealing with the haptic system, it is difficult to isolate the memory of the percept with motor memory. Movements are involved in interacting with objects; thus it is unclear if haptic percepts, or the associated exploratory movements are remembered.

The characteristics and minimum duration of the haptic memory system are not clear. While there is some evidence supporting the notion of a long term (24 hour) haptic memory system, what are the characteristics of the shorter term haptic memory system? Is it similar to the visual iconic memory system which only lasts approximately 2 seconds [6]. Visual iconic memory is a short-lived visual representation of the movement environment that can be used to accurately guide movement without vision. Elliott and Madalena [6] conducted an experiment involving a visually guided aiming task. Participants were required to use a stylus to aim at various targets. There were four vision conditions. The first condition used full-vision. In the remaining conditions, subjects moved to the target without vision after a 0, 2, 5, or 10 second delay. As expected, it was found that performance with vision was more accurate than without vision. What was more interesting however, was that performance was seen to differ between the various delay conditions with significant declines in aiming accuracy occurring with delays of 2 seconds or greater. These initial findings indicated that there existed a visual iconic memory system that can last up to 2 seconds after which time it starts to deteriorate. The existence of a visual iconic memory has since been replicated many times [7][8].

Our goal was to determine if haptic memory behaves like the visual memory system and to see if it has a similar rate of decay. Following the paradigm established by Elliott and Madalena [6] to explore visual memory, masses with common densities [4] were randomly presented in three different delay conditions (0 s, 2 s, 10 s). This experiment aimed at determining what happens to haptic memory after a delay following exposure to an object. It is expected that like visual memory, haptic memory will show a rapid rate of decay resembling that of the visual iconic system. A decay in haptic memory would be represented in the peak grip force that is used to lift an object. That is, on the first lift of a novel object, participants will produce more grip force than necessary. However, after several more lifts, the amount of grip force produced will decrease. If the memorial representation for haptic information decays in a manner similar to visual information, after a delay (2 s or 10 s) the amount of grip force produced will resemble that produced on the first lift of an object. However, if the haptic memorial representation is very robust, then even after a 2 or a 10 second delay, the amount of grip force produced will resemble that of a lift of a familiar object. That is, the appropriate grip force will be produced. It is expected that load force will resemble the same pattern as that seen for grip force.

2. METHOD

2.1 Subjects

Twelve students from the University of Waterloo, with a mean age of 24.2 years (range = 22 to 28 years) participated in this experiment.

2.2 Apparatus and Procedure

The object to be grasped was a six-axis force-torque sensor (Nano F/T transducer; ATI Industrial Automation, Garner, NC) with two exchangeable polyethylene plastic cylindrical ends with flat grasping surfaces, secured to either side of the sensor. The cylinder had a diameter of 3.5 cm and a length of 5.5 cm. The cylinder was mounted on a containment unit in which masses could be placed. The base of the containment unit was 7 cm x 3 cm. When mounted to the containment unit, the center of the grasping surface was located 8.0 cm above the tabletop. The total mass of the apparatus was 200 g, 300 g or 400 g.

Each participant was seated in front of a table with the hand resting on the table top. The target object was located immediately in front of the participant's hand. All participants wore liquid crystal goggles that when closed prevented the use of vision during lifting [9]. In this experiment we aimed to isolate the haptic system and eliminate the contributions of vision to haptic memory.

Participants grasped the apparatus between the index finger and thumb, lifted it up 10 cm, set it down, and then released the object, four consecutive times at a tempo of one lift every two seconds. The were called the practice lifts. Using a ruler as a visual guide before the trials began, participants were informed that all lifts should be approximately 10 cm in height. Upon replacing the object on the tabletop after the final practice lift, an electronic timer was initiated. After a 0 second, 2 second, or 10 second time period, a sound cue informed participants to pick up and hold the object for approximately 2 seconds, for a fifth time. This was labelled the test lift. Thus five lifts (4 practice, and 1 test lift) comprised one trial (see Figure 1).

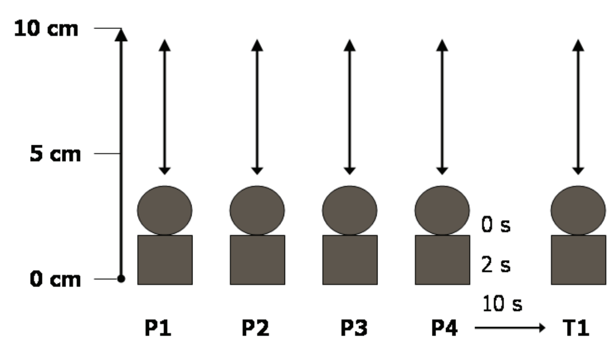

Figure 1. Depiction of experimental trial consisting of five consecutive lifts.

During each lift, grip forces were measured along the line connecting the centers of the two grasping surfaces. This defined the grip axis. Load forces were recorded and calculated as the resultant of the forces tangential to the grasping surfaces in the direction of the lift and perpendicular to the lift direction. Torque in the x, y, and z-planes were measured and the resultant of these torques was calculated. The forces and torques were collected at 200 Hz with a resolution of 0.025 N and .05 Nmm respectively.

Eight trials were collected for each of the three masses in each of the three delay conditions. Thus, a total of 72 trials were collected, each consisting of five lifts (4 practice, and 1 test lift). For each participant, masses were randomly presented for each of the three delay conditions, which were blocked. The delay order was blocked within a participant, and the order of these blocks was randomly assigned across participants.

Means were calculated from the eight trials of each mass and delay condition. The mean of peak torque, load force and grip force, and the time to reach these variables, were analyzed in separate 3 test mass (200 g, 300 g, 400 g) x 3 delay condition (0 s, 2 s, 10 s) x 5 lift number (4 practice lifts, and 1 test lift) repeated measures analyses of variance (ANOVAs). ANOVA differences significant at $p<0.05$ were further investigated using a Tukey HSD method for post hoc comparison of means.

To monitor if the moisture of the finger (i.e., sweating) had any influence on the results of this study, after the collection of the experimental trials, slip trials were collected to measure the static coefficient of friction between the fingers and the object grasped. For each slip trial, the 300 g mass was held between the index finger and thumb and was slowly released until it dropped. Three slip trials were performed both prior to, and following the three delays. That is, they were performed prior to the practice lifts and following either a 0, 2, or 10 second delay. The data were analyzed in a 2 time of test (practice lifts, after delay) x 3 delay condition (0 s, 2 s, 10 s) repeated measures ANOVA. The grip forces at the moment the object began to slip between the fingers represented the minimum amount of force required to hold the object. The static coefficient of friction was estimated by dividing the load force by grip force at the moment of object slip [1].

3. RESULTS

3.1 Grip Force

As seen in Figure 2, the delay and lift number interaction showed that for each delay condition the greatest peak grip force was reached during the first practice lift when compared to the other practice lifts, $F(8, 88) = 9.93$, $p < 0.01$. All practice lifts within each delay condition were statistically equal. The test lift for the 0 second delay condition was not different than the practice lifts, while the test lift in the 2 second delay condition was significantly greater than the second and third practice lifts. For the 10 second delay condition, the test lift was statistically similar in magnitude to the first practice lift and was significantly greater than all the other practice lifts. Typical curves are seen in Figure 5.

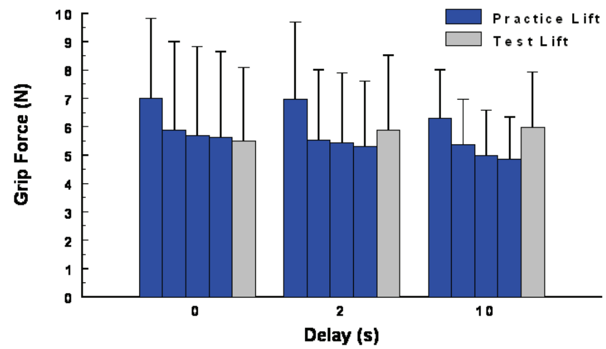

Figure 2. Means and standard deviations for peak grip force as a function of trials for the three delay conditions.

3.2 Load Force

Peak load force was greatest in the 400 g condition (M = 3.92 N, SD = 0.94 N), intermediate in the 300 g condition (M = 3.09 N, SD = 0.72 N) and smallest in the 200 g condition (M = 2.17 N, SD = 0.52 N), $F(2, 22) = 123.17$, $p < 0.01$. Also, as seen in Figure 3, ($F(8, 88) = 3.40$, $p < 0.01$), for the 0 second delay and 2 second delay conditions the greatest peak load force was reached during the first practice lift and then significantly declined for the remaining practice lifts, which did not differ from each other. In the 10 second delay condition, however, the first practice lift did not differ statistically from the other practice lifts. The test lifts for the 0 second delay condition had a smaller peak load force than the test lifts for the 2 second and 10 second delay conditions, which did not differ. As well, the test lift in the 10 second delay condition showed a higher peak load force compared to the practice lifts for this condition. The test lifts for the 0 and 2 second delay conditions, however, did not differ from their respective practice lifts. Typical curves are seen in Figure 5.

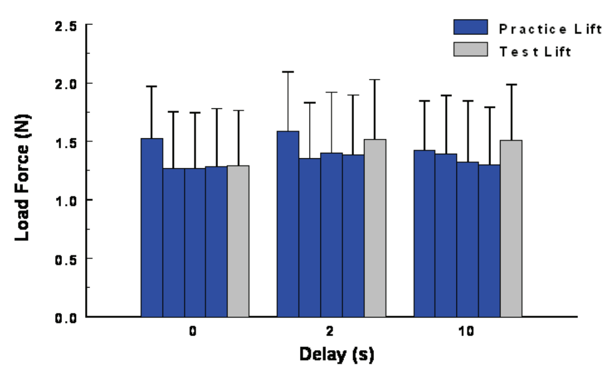

Figure 3. Peak load force as a function of trials for the three delay conditions.

3.3 Torque

The peak torque values were found to significantly increase as the object mass increased (200 g, M = 33.56 Nmm, SD = 11.55

Nmm; 300 g, M = 47.38 Nmm, SD = 13.11 Nmm; 400 g = 59.74 Nmm, SD = 15.36 Nmm), $F(2, 22) = 211.57$, $p < 0.01$. Peak torque was greater for the first practice lift in comparison to all other practice lifts for each delay condition. As well, for all delay conditions there was a trend for peak torque to decrease across the three practice lifts, however these differences were only statistically significant for the 10 second delay condition. Finally, the test lift statistically differed from the practice lifts only for the 10 second delay condition, $F(8, 88) = 3.79$, $p < 0.01$(refer to Figure 4).

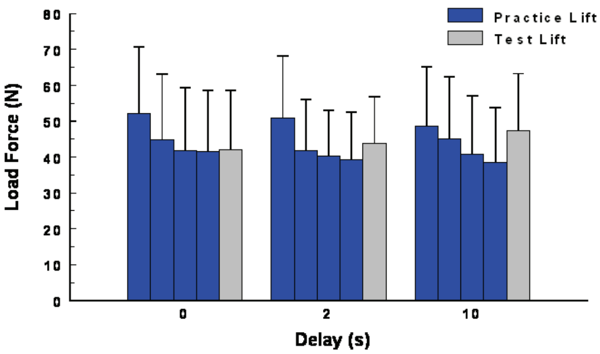

Figure 4. Peak load force as a function of trials for the three delay (s) conditions.

3.4 Static coefficient of friction

There were no differences in coefficient of friction across the three delay conditions or between the test of coefficient of friction that occurred before and after the delay ($p > 0.05$). That is, the coefficient of friction did not change as a function of the delay (0 s 2 s, 10 s) between slip trials. Thus, the effects of delay (0 s, 2 s, 10 s) in this study are not related to sweating.

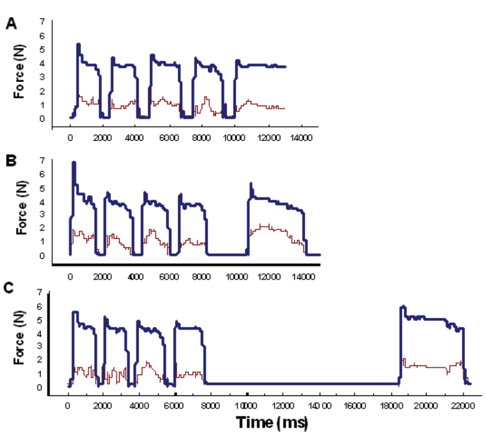

Figure 5. Typical trials showing grip force (thick line) and load force profiles (thin line), for a single participant in the 300 g mass condition in Experiment 1. Each of the 5 lifts per trial (4 practice, 1 test lift) are presented for A) the 0 second delay condition B) the 2 second delay condition and C) the 10 second delay condition.

4. DISCUSSION

The results of this experiment have indicated that, like the visual iconic system, the rate of decay for haptic memory is subject to a rapid decay after only 2 seconds. The decay in haptic memory was evident from the two delay conditions (2 second and 10 second) in the dependent measures of peak grip force, peak load force, and peak torque. That is, there were larger grip and load forces produced on first attempts of lifting the object. After lifting the object four consecutive times during practice, the grip and load forces were scaled more accurately to the mass of the object. For the fifth lift (test lift) of the object, for the 0 second delay condition, participants produced grip and load force values similar to those reached on the fourth lift of the same object. For the 2 and 10 second delay conditions, participants produced grip and load forces more similar to those produced during the first practice lift attempts suggesting that there was decay of the memorial representation for mass. The patterns seen in force measures were mirrored closely by peak torque. Thus, these patterns indicated that after only several seconds, there was decay in the memorial representation that was used to guide grasping.

The precise nature of the contents of the memorial representation are unclear. The possibility was considered that the increase in peak grip force for the test lifts in the 10 second delay condition may not have been due to a decay in haptic memory for object weight, but instead a decay for finger positioning on the object surface. Since vision was not used to guide hand movements to the object, a 10 second delay may have caused participants to forget the location of the centers of the grasping surfaces [7]. If the fingers were offset from the center of the target, then tangential torques about the grip axis would have been created. Several studies have shown that when tangential torques are present the grip force applied in a grasp increases to prevent the rotation of an object between the fingers [10]. That is, if an object is not grasped exactly along the axis of the centre of mass, there is a tendency for the object to rotate because of the torques that are present. To prevent this rotation, people will produce more grip force. The torque patterns observed in this study, mirrored those observed for peak grip force. These torques, that were created by the object being grasped slightly off center could conceivably have been responsible for the grip force patterns. That is, with each grasp during practice, the finger placement may have been slightly altered to achieve a position closer to the center of mass which would be apparent by a decrease in torque with practice. However, with the delay, the optimal finger placement may have been forgotten and torques would increase. Thus the question still remains as to what kind of information is being forgotten. Is the change in force output due to a decay in the haptic memorial representation for mass? Or alternatively is the memorial representation that guides the finger position on to the grasping surfaces subject to decay?

5. CONCLUSION

The main findings from this Experiment showed that, as the time delay increased after a period of practice, the grip force used to grasp a particular mass increased to a magnitude similar to that used in the grasp of a novel mass. However, the analysis of peak load force showed a similar pattern to that of grip. Flanagan and Tresilian [11] have shown that grip and load forces are usually correlated and vary together when transporting an object.

The conclusions of the present study could be interpreted as being inconsistent with those of Gordon et al. [4]. While it is suggested here, that haptic memory is short lived and lasts for less than 2 seconds, Gordon et al. [4], propose that haptic memory is very long lived and can last up to 24 hours or longer. However, Gordon et al. [4] were examining a different memory system than was studied in the present series of experiments. While the present study examined a short duration memory system for haptics, Gordon et al. [4] were looking at a longer term 24 hour memory system. In spite of the evidence that the memorial representation decays relatively quickly, this does not negate that existence of a long term memory store. Many of us have experienced the situation where we lift an empty milk carton left in the refrigerator and slam the carton into the top of the shelf. We anticipate the force required to accomplish this task based on previous experiences lifting milk cartons. We seldom encounter an empty milk carton in a refrigerator and therefore there is no anticipation of such a light carton. This error in anticipation of force could only be accomplished with some sort of long term storage of information regarding the mass of objects. It is possible to conceptualize a model of haptic memory in which the long term memory is able to get the force production into the "ballpark", but the short term store is required for a precise haptic representation. However, the precise nature of what aspects of the haptic/motor experience are being represented is unclear and could be quite varied depending on the complexity of the associated objects being explored or manipulated [12,13]. While the present findings are of theoretical interest, they also have practical implications for design of hapticons (defined as small, programmed force patterns that can be used to communicate a basic notion in a similar manner as ordinary icons are used in graphical user interfaces) for blind computer users.

ACKNOWLEDGEMENTS

This work was supported by the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

[1] G. Cadoret and A.M. Smith. Friction, not texture, dictates grip forces used during object manipulation. *Journal of Neurophysiology*, 75:1963-1969, 1996.

[2] R.S. Johansson and K.J. Cole. Grasp stability during manipulative actions. *Canadian Journal of Physiological Pharmacology*, 72:511-524, 1994.

[3] R.S. Johansson. Sensory control of dexterous manipulation in humans. In A.M. Wing, P. Haggard, and J.R. Flanagan editors, *Hand and brain: The neurophysiology and psychology of hand movements*, pages 381-414. Academic Press: Toronto, 1996.

[4] A.M. Gordon, G. Westling,, K. Cole, and R.S. Johansson. Memory representations underlying motor commands used during manipulation of common and novel objects. *Journal of Neurophysiology*, 69:1789-1796, 1993.

[5] G., Westling, and R.S., Johansson. Factor influencing the force control during precision grip, *Experimental Brain Research*, 53:277-284, 1984.

[6] D. Elliott, and J. Madalena, The influence of premovement visual information on manual aiming. *The Quarterly Journal of Experimental Psychology*, 39A:541-559, 1987.

[7] D. Elliott. Intermittent visual pickup and goal directed movement: A review. *Human Movement Science*, 9:531-548, 1990.

[8] D. Elliott, Intermittent versus continuous control of manual aiming movements. In L. Proteau and D. Elliott editors, *Advances in psychology: Vision and motor control,* pages 33-48. North-Holland: Amsterdam, 1992.

[9] P. Milgram, A spectacle-mounted liquid-crystal tachistoscope. *Behavior Research Methods, Instruments and Computers*, 19:449-456, 1987.

[10] H. Kinoshita, L. Backstrom, J.R. Flanagan, and R.S. Johansson, R.S. Tangential torque effects on the control of the grip forces when holding objects with a precision grip. *Journal of Neurophysiology*, 87:1619-1630, 1997.

[11] J.R. Flanagan, and J.R. Tresilian. Grip-load force coupling: A general control strategy for transporting objects. *Journal of Experimental Psychology: Human Perception and Performance*, 20: 944-957, 1994.

[12] A.M. Wing and S.J. Lederman. Anticipating load torques produced by voluntary movements. *Journal of Experimental Psychology: Human Perception and Performance*, 24: 1571-1581, 1998.

[13] S.J. Lederman and A.M. Wing, A.M. Perceptual judgement, grasp point selection and object symmetry. *Experimental Brain Research*, 152: 156-165, 2003.