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HAPTIC PERCEPTION OF AFFORDANCES OF A SPORT IMPLEMENT:
CHOOSING HOCKEY STICKS FOR POWER VERSUS PRECISION ACTIONS ON
THE BASIS OF “FEEL”

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Abstract

Hand-held tools vary in their suitability for different tasks. A good hammer may not be a good poker, because what makes a tool a good hammer—having most of its mass concentrated at the distal end—makes the tool hard to control when used as a poker. Research has demonstrated that perceivers can use the haptic perceptual subsystem of dynamic touch to perceive whether a tool is suitable for performing a given task—in other words, to perceive a tool's *affordances* or possibilities for action (Wagman & Carello, 2001, 2003). In four experiments I investigated perception of affordances of hockey sticks for performing power (transferring maximal force) and precision (intercepting a moving object) tasks. I manipulated the sticks' mass distributions to vary the physical properties that made the sticks more or less well suited for power and precision actions (bottom-heavy sticks allow for greater force transfer, but are less controllable, whereas top-heavy sticks are controllable but afford less forceful hitting). Participants wielded the sticks in the absence of vision and haptically gauged the suitability of the sticks for power and precision tasks. The aims of the project were to (1) determine if perceivers could accurately and prospectively (without prior experience or feedback) judge the suitability of differently weighted sticks for power or precision tasks (Experiment I); (2) determine the effects of actually using the sticks to perform power-hitting and precision-interception actions on the same judgments (Experiments II & III); and (3) determine the role of expertise in perceiving affordances of the sticks (Experiment IV). The results supported the notion that people can use dynamic touch to accurately perceive affordances of an object, and also revealed that expertise (Experiment IV-a) and even the very limited experience and feedback obtained when novices

performed the power-hitting task (Experiments II, III, & IVb) elicited sensitivity to unanticipated precision requirements inherent in hitting a hockey puck for power. In sum, the results highlight that perceivers can use dynamic touch to perceive affordances for the prospective control of behaviour and that perceptual sensitivity to action-relevant properties of objects is modifiable with experience.

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Haptic Perception of Affordances of a Sport Implement: Choosing Hockey Sticks for Power Versus Precision Actions on the Basis of “Feel”

CHAPTER I: INTRODUCTION

Traditionally, the role of human factors in designing hand-held devices (e.g., tools, sporting equipment) has been to maximize the fit between an object and a user based on biomechanical and musculoskeletal constraints related to the user's anatomy and physiology (e.g., Cochran & Riley, 1986a; Drillis, 1963; Hedge, 1998; Kroemer, 1986; Sanders & McCormick, 1993). This approach to hand-held device design has contributed to reducing the incidence of occupational injuries associated with tool use, a problem that Mital and Sanghavi (1986) suggested accounts for approximately 10 percent of industrial injuries. From the design of knife handles (e.g., Cochran & Riley, 1986b) to wrenches and screwdrivers (e.g., Mital & Sanghavi, 1986), human factors interventions have improved the efficiency, effectiveness, and safety associated with using hand-held devices (e.g., Hedge, 1998; Smith, 1996).

Optimizing the design of a held device to best suit the biomechanical constraints of the user is but one important consideration, however. In addition to the physical shape and layout of the hand-held object, a user's perceptions of an object's utility may importantly contribute to the user's choice of product and ability to effectively or efficiently use the product (e.g., Kreifeldt & Chuang, 1979; Wagman & Carello, 2001, 2003). Skilled tool users (e.g., skilled carpenters or ice hockey players) effectively employ a piece of equipment (e.g., the hammer or hockey stick) as an extension of their perception-action systems: The equipment extends or augments their capacity to interact

with the environment. This notion suggests that designers should attend to the perceptual properties or “sensory signals” (Macdonald, 1998; Porter & Porter, 1999; Vermeeren, 1999) of tools and hand-held implements in addition to the physical ergonomics of tool design. In fact, there is mounting evidence to suggest that perceivers base their judgments regarding a held object’s utility on information gleaned from wielding or hefting the object (cf. Wagman & Carello, 2001, 2003). Perception via wielding or hefting is achieved using the dynamic touch subsystem of the haptic perceptual system.

Dynamic Touch

In daily life people frequently hold and manipulate objects such as pens, toothbrushes, eating utensils, and sporting implements (e.g., a racket or hockey stick). We can use those kinds of objects successfully even when we do not view them directly, or even in the complete absence of vision. Success at using hand-held objects in the absence of vision implies that the haptic perceptual system is capable of registering information that specifies certain properties of the objects, such as object length or orientation. When perceivers hold an object and use it to perform a given task, they are using muscular effort to overcome and control the object’s inherent resistance to being moved (i.e., its inertia). This type of muscular exertion, in combination with stimulation of the skin and other tissues, is termed *dynamic touch*. J. J. Gibson (1966) differentiated dynamic touch from both *cutaneous* and *haptic* touch. Cutaneous touch involves stimulation of the skin and deeper tissues without joint movements (e.g., an object brushing against the skin), and haptic touch involves stimulation of the skin and deeper tissues with joint movements (e.g., actively feeling the texture of a surface). Muscular

effort (e.g., when an object is grasped and wielded) distinguishes dynamic touch from cutaneous and haptic touch.

A growing body of research has demonstrated that perceptions of a hand-held object via dynamic touch are constrained by the object's mass distribution (Carello & Turvey, 2000, 2004; Turvey, 1996; Turvey & Carello, 1995). Turvey, Shockley, and Carello (1999) noted that the forces and torques generated by a perceiver's muscles as the perceiver holds an object must be tailored to the object's tendency to resist translation and rotation. Those resistances refer to the object's mass and rotational inertia, respectively. The authors suggested that the haptic perceptual system's *proper function* (i.e., that which has warranted reproduction over evolution) is the registration of an object's mass and resistance to rotational acceleration in a manner that enables the individual to tailor the tensile states of the muscles to wield the object in a controlled way.

Affordances

To successfully interact with the environment (e.g., to locomote without stumbling into obstacles), an organism must be able to perceive the ways in which it can interact with the environment. J. J. Gibson (1979/1986) coined the term *affordance* to describe opportunities for action or behaviour presented by the environment to a particular organism; "The *affordances* of the environment are what it *offers* the animal, what it *provides* or *furnishes*, either for good or ill" (p. 127, italics in original). According to J. J. Gibson, information about affordances is specified to the perceiver in structured energy arrays, which, according to J. J. Gibson's theory, means that affordances can be perceived directly (i.e., in the absence of constructive cognitive

mediation). Because ambient energy arrays may be structured multi-modally, affordances may be registered by vision, audition, touch, the chemical sense, or in some combination thereof (cf. Stoffregen & Bardy, 2001).

Researchers have demonstrated that people are remarkably accurate in their ability to perceive various action-relevant properties of the environment. For example, Warren (1984) investigated the variables that might underlie the perceived affordance of stair climbing. Like other forms of locomotor behaviour (e.g., walking, running, passing through an aperture), successfully stepping up on something (e.g., a stair) is contingent both on characteristics of the to-be-stepped-on object (e.g., its height, stability, and surface texture) and how those properties relate to the scale of the organism intent on doing the stepping. Warren presented participants with pictures of modified staircases that varied in riser height and asked them to judge whether the stairs were bipedally “climbable” or not (i.e., climbable, but without resorting to using their hands and knees). The goal of that experiment was to determine whether people were visually sensitive to the critical boundary between climbable and non-climbable riser heights—in other words, whether they could perceive the maximal riser height that would afford climbing. In another experiment, Warren sought to determine whether perceivers could visually identify the riser height that would require a minimum amount of energy expenditure were the participant to actually climb those stairs.¹ The actual maximal and optimal step heights are determined by the relation between a property of the perceiver (leg length) and a property of the environment (riser height). Empirically, maximal step heights correspond to 0.88 leg lengths and optimal step heights corresponded, on average, to 0.26

¹ Minimum energy expenditure was evaluated in a separate experiment by measuring oxygen consumption while stepping on a stairmill (Warren, 1984).

leg lengths. Warren found that participants were capable of very accurately perceiving both maximal and optimal riser heights. The fact that people were able to do so suggests they visually scale the environment by their own body dimensions and hence can visually perceive environmental objects in relation to their action capabilities. Thus, affordances are perceivable and are scaled by the relevant action capabilities of the perceiver.

Mark (1987) extended Warren's (1984) investigation by demonstrating that the visual information specifying the affordances of "sit-on-able" and "step-on-able" are scaled to a perceiver's eyeheight. Participants stood in a corridor at varying distances from a wall and indicated to the experimenter, who was adjusting the location of a suspended weight, when the height of the weight reflected their perceived eyeheight, maximum sitting height, and maximal riser height. Perceived maximal sitting height was compared against actual maximal sitting height with a height-adjustable chair. Maximal "climbable" riser height was computed from Warren's (1984) biomechanical model. Both measures revealed findings consistent with the hypothesis that observers use eyeheight-scaled information about surface height. To further evaluate this hypothesis, Mark attached 10-cm-tall wooden blocks to the feet of the participants and again asked them to make perceptual judgments of maximal sitting height, riser height, and the height of the wood blocks.² The results showed that participants initially underestimated maximal sitting height while wearing blocks, but over the course of six trials, "retuned" their perceptions to reflect actual maximal sitting height. Initially, participants responded as if they were normally proportioned but of a new height, but over subsequent trials

² Participants did not actually see the size of the wood block worn on their feet, but perceived the height of the blocks based on their new combined body-plus-block height while standing.

picked up on the fact that their new body proportions actually increased their maximal sitting height (i.e., a longer lower leg due to the added wood block). Mark postulated that their perceptual retuning was facilitated by the participants' ability to move around between trials while wearing the blocks. This small amount of walking allowed participants to explore how their "new" body proportions affected their ability to interact with the environment. These results, along with those of Warren (1984) and others (e.g., Mark & Vogeley, 1987; Warren & Whang, 1987), suggest that perceivers have direct visual access to information specifying opportunities for behaviour in terms of their own body dimensions.

There is empirical evidence that people are able to perceive affordances other than just stair-climbing and sitting heights. For instance, Oudejans, Michaels, Bakker, and Dolné (1996) considered the spatio-temporal importance of perceiving for acting in a time-dependent situation, such as catching a fly ball in baseball. They demonstrated that stationary observers were not proficient at identifying the "catch-ability" of fly balls. In order to accurately perceive this affordance, participants had to be actively engaged in running at a certain speed with respect to the velocity of the falling ball. This study highlighted the importance of action in the perception-action cycle with regard to accurate affordance perception. The importance of action for perception is also highlighted by the experiments of Mark (1987), in which participants re-tuned their perceptions of their action capabilities after moving around while wearing wooden blocks on their feet.

Affordance research has not been confined to visually perceived opportunities for action. Investigations have revealed that people are capable of accurately perceiving

their ability to perform numerous actions on the basis of haptic perception. For instance, perceivers can identify reachable distance with a held object (Solomon & Turvey, 1988), object throwability (Bingham, Schmidt, & Rosenblum, 1990), and traversability of path gaps perceived haptically using a pole (Burton, 1992). Together these studies illustrate that the perception of an affordance is not limited to any one sensory modality or class of behaviors.

In sum, research on affordance perception has revealed that people are perceptually sensitive to the opportunities for action provided by the environment and objects in the environment. Affordances are apparently accessible to any perceptual modality, alone or in combination. Perception of affordances often depends upon experience and action, as noted by E. J. Gibson and Pick (2000).

Affordances of hand tools

One of the logical extensions of research conducted on haptic perception of affordances involves informing tool or equipment design (e.g., Smets & Overbeeke, 1994). Sporting equipment designers can benefit from an understanding of the psychological and physical variables that affect the perceived utility and functionality of hand-held sporting implements like the hockey stick. This dissertation represents the first study of the perceptual properties of hockey sticks. Other researchers have studied some of the physical variables that influence stick performance. For instance, Pearsall, Montgomery, Rothsching, and Turcotte (1999) conducted an investigation on how the stiffness of the shaft influenced slap-shot speed. Generally, they found that the stick with the lowest shaft stiffness produced the highest peak velocity of the puck. They noted that an area of further study would be to investigate inertial characteristics of a hockey stick

as it relates to stick performance. While the present study does not address stick performance directly, it does address how inertial properties relate to users' prospective and retrospective judgments of stick performance under different action requirements.

Similar issues have been addressed in the context of tennis. For instance, Carello, Thout, Anderson, and Turvey (1999) and Carello, Thout, and Turvey (2000) have shown that participants (both young and old) are sensitive to the location of a racket's center of percussion (sweet spot) simply by means of wielding the racket. In addition, Brody (2000) has shown that proficient tennis players are sensitive to as little as a 2.5% difference in the weight moment of inertia between rackets and that a 5% difference between rackets was necessary to distinguish changes in their polar moments.³

Wagman and Carello (2001, 2003) showed that when a task constraint is action-oriented, the haptic system seems able to “tune into” the relevant physical variables that govern successful task performance. The authors demonstrated that people are sensitive to inertial characteristics of hand-held objects and that specific higher-order inertial properties (i.e., volume [V], symmetry [S], and eigenvector angle [$\mathbf{e}_k$] of the inertial ellipsoid; see Appendix) constrain the haptic perception of an object's affordances. They also demonstrated that people are able to choose a hand-held object (or identify where to grasp an object) to maximize its prospective utility for a given task. Wagman and Carello (2001) had participants rate the degree to which hand-held objects afforded either hammering or poking. The participants could wield the objects, but were not privy to seeing what they were holding. According to participant reports, the best hammers had the lowest V ; the mass concentration was farthest from the point of grasp. The opposite

³ The swing weight moment and polar moment are both second moments of inertia that vary depending on the axis used to measure distance of the masses from the hand.

relation for V held for the poking task. The best poker had the highest V or the mass concentration closest to the point of grasp of the object. The authors concluded that people are sensitive to how the inertial ellipsoid is informative about an object's utility.

In another investigation, Wagman and Carello (2003) demonstrated that participants tailored their choice of grasp position according to how they would have to use the held object. The experimenters asked the participants to grasp weighted rods at a location along the shaft that felt like the best place to grasp in order to perform either a hammering or a poking action. Wagman and Carello found that when power movements were emphasized (implicitly or explicitly) over precision control, regardless of the specific task performed, participants grasped an object to minimize V and S without regard to $\mathbf{e}_k$. When precision was emphasized, grasp positions were chosen that maximized V and S while minimizing $\mathbf{e}_k$.

Perceiving affordances of hockey sticks through dynamic touch: A preview of the present experiments

From an occupational and health standpoint, a common goal for product designers has been to reduce the number of injuries associated with improper or extended use of hand-held tools (e.g., Mital & Sanghavi, 1986). Relatedly, well-designed tools should improve “feel” and performance. Kreifeldt and Chuang (1979) noted that an object's moment of inertia, or its resistance to rotational acceleration, is a relevant contributor to the “feel” of a held object. Similarly, Wagman and Carello (2001, 2003) demonstrated that a held object's resistance to rotational acceleration may inform the perceiver about the object's affordances. The present set of experiments was designed to expound the relation between an object's inertial configuration and its perceived affordances.

Participants engaged in exploratory perception-action in order to determine the perceived functionality of a hand-held tool for either a *power* task (transferring maximal force to an object) or a *precision* task (precisely controlling the stick to intercept a moving object). The game of ice hockey served as a context for addressing those issues. The first aim for the project was to determine whether perceivers could produce accurate prospective judgments of the suitability of differently weighted hockey sticks for power or precision tasks; a related aim was to determine whether the perceived suitability of the sticks would depend on the sticks' mass distribution (Experiment I). The second aim was to determine the effects of actually using the sticks to perform the relevant actions (a power-hitting task and a precision interception task) on the perceived suitability of the differently weighted hockey sticks (Experiments II & III). The third aim was to determine how hockey expertise affected perceptual sensitivity to the suitability of the differently weighted hockey sticks for power and precision tasks (Experiment IV). While the outcome of this research may have practical consequences for the design of hockey sticks, the main goal for this project was to further assess the utility of the concept of affordances as formulated by J. J. Gibson (1986) and quantified by Turvey (1992) and others (e.g., Chemero, 2003; Jones, 2003; Michaels, 2003; Stoffregen, 2003).

CHAPTER II: GENERAL METHOD

Participants

Undergraduate students from the University of Cincinnati (Experiments I, II, III) and Miami University (Experiment IV-b) received course credit for participating in this research. Members of the Miami Redhawks men's varsity ice hockey team, who were paid \$15, participated in Experiment IV-a. Sample sizes were determined during pilot studies for all but Experiment IV-a, for which sample size was limited by the number of available hockey players. Participants were excluded if they reported any history of disease or malfunction of their neuromuscular, vestibular, or skeletal system, or if they had experienced any recent injuries to their arms or hands. Participants in Experiments I, II, III, and IV-b did not have any league-level hockey experience.

Apparatus

Hockey Sticks. In each of the experiments, participants held and wielded three differently weighted, right-handed *Nike Quest 2* wooden hockey sticks. The sticks were 162 cm long and were composed of fiberglass-wrapped solid aspen. Two 100 g metal weights were attached to the shaft of each stick at one of three locations, yielding three unique mass-distribution conditions. To mask the weight location, low-density foam blocks were taped around all three potential weight locations (regardless of the actual weight location, so that the sticks were visually identical). See Figure 1 for a depiction of the sticks.

Figure 1. The top-, middle-, and bottom-weighted sticks used in all experiments. 200 g was attached to the shaft of the stick at the locations depicted (open circles) and represents a 10.5 cm shift in the center of percussion (CP) between sticks. Weight location was 41 cm, 111 cm, and 137 cm for the top, middle, and bottom stick, respectively. Masking foam cubes over the weight locations (hatched outline) were used in Experiment II-IV.

Previous research on dynamic touch has shown that people are able to identify the center of percussion (CP) of an object by wielding alone (e.g., Carello et al., 1999, 2000). This ability is rooted in the haptic system's sensitivity to rotational dynamics, as specified by the relative ease or difficulty with which an object can be moved by muscular effort. A key factor in determining the necessary direction and mean force required to move a held object is the object's mass distribution. A mass distribution may be quantified in terms of *moments of inertia*, or the tendency to produce or resist rotation around an axis (Jewett, 1994). A growing body of evidence has demonstrated that dynamic touch's exteroceptive capabilities are related by power functions to the mass distributions of

hand-held objects (e.g., Turvey & Carello, 1995). For instance, nonvisible perception of hand-held object lengths has been shown to scale as the second moment of the mass distribution (Carello et al., 1999). Additionally, the first or static moment has been implicated when an object is held but not wielded (e.g., Burton & Turvey, 1990). The CP is defined as the ratio of the first and second moments of inertia and has been shown to constrain perception of the “sweet spot”—the preferred location on the implement in question for hitting another object (e.g., Carello et al., 1999, 2000). The present tasks were similar in that they required the identification of the implement for optimal hitting with power or precision. Varying the CP was, therefore, selected as the means for physically differentiating the three hockey sticks.

In order to demarcate grasp location on the sticks, two pieces of Velcro were adhered to each stick at a position 5.5 cm (left hand) and 59.0 cm (right hand) from the top end of the stick (i.e., the non-bladed end). The soft, “loop” side of Velcro was used.

Action-Phase Materials. For the power action tasks, participants used the sticks to strike a street-hockey puck (111.9 g, 8 cm diameter $\times$ 2.2 cm tall) into a block of foam padding (142 cm wide $\times$ 181 cm tall). The foam pad was located approximately 125 cm in front of the puck and served to absorb the puck’s impact after a shot. For the precision action tasks, participants had to intercept an object attached to a pendulum. The pendulum consisted of a pulley wheel that was fixed to a small board and bolted to the laboratory ceiling. The swinging arm of the pendulum was a rigid wood dowel (174 cm long) that was attached to the center groove of the pulley wheel and adjusted in length to hang 73 cm from the ground when at its vertical hanging position. A small rubber ball (4 cm in diameter) was attached to the end of the dowel and constituted the target to be

intercepted with the center of the blade of the hockey stick. See Figure 2 for a depiction of the pendulum and its motion.

Figure 2. The swinging pendulum used in the precision-action phase of Experiments II-IV. The top of the pendulum was attached to the laboratory ceiling. The path length of the swinging arm from start to intercept point was approximately 342 cm.

Procedure

All experiments were conducted in a large open room that was of sufficient size to allow participants to freely swing a hockey stick. Experiments I, II, and III were conducted at the University of Cincinnati and Experiment IV was conducted at Miami University. All experiments except Experiment I consisted of three phases: A prospective rating phase, an action phase, and a post-action rating phase. Experiment I did not include the action and post-action phases. Participants wielded and rated each stick for its suitability for power or precision action in the pre- and post-action phases of

the experiment with their eyes closed. However, their eyes were open during the action phase because the action tasks required visual guidance. Before the start of the first trial in all of the experiments, the experimenter told the participants that part of the experiment (or all trials in Experiment I) would be conducted with their eyes closed. The Velcro strips indicated the grasp location for the right and left hands and provided the tactile feedback necessary to locate the correct grip position without the use of vision. Participants were instructed to keep their eyes closed for all non-action phases in Experiments II-IV and for the entirety of Experiment I. Handedness was not assessed although some participants volunteered that they were left-handed when asked to hold the right-handed sticks. Post-hoc inspection of the self-proclaimed left-handers' data indicated a similar pattern of responding as the other participants, suggesting that handedness did not influence the results of the study.

Perceptual Rating Tasks. In two experimental conditions (*power* and *precision*), participants were asked to make perceptual judgments about the functionality of three differently weighted hockey sticks. Participants closed their eyes, wielded a given stick for as long as they deemed necessary, and then verbally rated the stick using a 7-point scale (1: "not at all suited to the task"; 7: "ideally suited to the task"; c.f. Wagman & Carello, 2003). The experimenter recorded the ratings for later analysis. Participants were instructed to consider how the stick they were currently wielding compared to the other two sticks. In other words, they were to consider the three sticks in relation to each other. They were encouraged to employ the full range of the rating scale to accurately reflect their perceived differences in utility among the sticks for the given task.

In the *power* condition participants were asked to make prospective judgments of the suitability of each of the three modified hockey sticks for transferring power to a struck object. That is, they were asked to rate the sticks on the degree to which they could swing the stick to generate the most force.

For the *precision* rating task, participants were asked to rate each of the three sticks on the degree to which they could accurately maneuver the sticks. They were asked to consider maneuverability when using the stick's blade to intercept an object flying past them, and to rate the degree of ease with which they could maneuver or position the stick's blade to make a quick and accurate interception.

In Experiment I and in the *pre-action* phases of remaining experiments the ratings were prospective in that participants did not come into contact with another object while wielding the sticks prior to stating their rating. Participants did not rate the sticks during the action-phase of Experiments II-IV. The post-action phase of Experiments II-IV followed the same procedures as the pre-action phase to obtain retrospective ratings of the sticks.

Action-Phase Tasks. The action phase of the *power* condition involved hitting the street hockey puck with each of the modified hockey sticks. The participant's task was to hit the puck, which was positioned 96 cm in front of their left foot, into the large foam pad. Foot placement for the hitting task was specified with tape markings on the floor; the left and right feet were spaced 45 cm apart. These dimensions for foot and puck placement represented a comfortable stance for conducting a slap shot⁴ based on the stick

⁴ A slap shot in hockey involves taking a full swing with the stick and transferring a high-velocity impact to the puck. Skilled players can propel a puck at velocities of up to 110 km/h (e.g., Pearsall, Montgomery, Rothsching, & Turcotte, 1999).

length and grip position used in these experiments. Participants stood facing in the direction of the puck, oriented so as to hit the puck into the foam pad.

The action-phase of the *precision* condition involved maneuvering a hockey stick to intercept a ball at the end of a swinging pendulum. Participants faced the pendulum, whose path followed a perpendicular trajectory 115 cm in front of them. The pendulum trajectory followed a path starting from the right to the left side of the standing participant. At the start of each trial, the experimenter held the pendulum 114 cm from its vertical hanging position before letting it fall and swing. Participants watched the pendulum swing from their right side, pass through its full range of motion (i.e., a half cycle), and reverse direction to swing back toward the participant and the starting position. Participants were instructed to intercept the ball when the pendulum arm was at its vertical position during the second (return) half-cycle. In other words, they were to intercept the ball when the pendulum had completed $3/4$ of one full movement cycle. Participants stood with their feet 30 cm apart while holding one of the three modified hockey sticks. At the beginning of each trial, participants rested the blade on the floor 70 cm to the right of the right foot. A piece of tape on the floor indicated where to rest the blade.

Design and data analysis

Rating condition (power vs. precision) order was blocked and counterbalanced across participants. The order in which participants wielded the sticks was randomized within blocks. There were two rating conditions (power and precision) and three mass distribution conditions (mass at the top, middle, or bottom of the hockey stick), yielding six total conditions. Four repetitions per condition yielded 24 trials in Experiment I.

Because the action phase substantially lengthened the experiment duration, only two trials per condition (12 rating trials) were conducted in Experiments II-IV. In addition to the pre- and post-action trials during which participants rated the utility of the sticks, there were five action-phase trials per condition (power and precision) in Experiments II-IV ($2 \text{ task conditions} \times 3 \text{ mass distribution conditions} \times 5 \text{ repetitions} = 30 \text{ action-phase trials}$). No performance or rating data were collected during the action phase trials: the only purpose of the trials was to give participants experience using the hockey sticks to perform actions relevant to the rating tasks. Stick condition was blocked within action-phase trials, and the order in which participants received the sticks to perform action-phase trials was counterbalanced across participants.

Stick ratings were averaged across repeated trials in each condition for each participant. The two rating conditions (power and precision) were assessed separately using repeated-measures analysis of variance (ANOVA) supplemented with follow-up tests and Bonferonni/Dunn post-hoc comparisons where appropriate. For all within-subjects analyses reported below, the ordinary degrees of freedom are reported, but the probability level shown was calculated using the Huhyn-Feldt epsilon-adjusted degrees of freedom. This adjustment was applied to control for inflated Type I error rates associated with violations of the assumption of compound symmetry.⁵ Additionally, the Cohen's *d* estimate of effect size accompanies all statistically significant pair-wise comparisons.

Aims of the research

This set of experiments was designed to expound the relation between an object's inertial configuration and the perceived affordances of the object. Participants engaged

⁵ If compound symmetry holds, all variances of difference scores will be equal (Myers & Wells, 1995).

in exploratory perception-action in order to determine the perceived functionality of a hockey stick for either a *power* task (transferring maximal force to an object) or a *precision* task (precisely controlling the stick to intercept a moving object). The first aim for the project was to determine whether participants were perceptually sensitive to how manipulations of the sticks' mass distributions affected the sticks' suitability for power or precision tasks (Experiment I). The second aim was to determine the effects of actually using the sticks to perform the relevant actions (a power-hitting task and a precision-interception task) on the perceived suitability of the differently weighted hockey sticks (Experiments II and III). The third aim was to determine the effects of extensive hockey experience on the same perceived suitability of the sticks (Experiment IV).

CHAPTER III: EXPERIMENT I

Prospective ratings for *power* vs. *precision* tasks

Previous research has suggested that a held object's perceived affordances for *hammering* and *poking* are influenced by its mass distribution (e.g., Wagman & Carello, 2001, 2003). Those authors found that a *poking* action was best served by an object whose mass was concentrated nearest the point of grasp. In contrast, the best *hammer* was characterized by a mass concentration farthest from the point of grasp. Experiment I concerned whether perceptions of the prospective functionality of a hockey stick would depend on the stick's mass distribution. Participants rated the hockey sticks, which were weighted at different points along their lengths, for their suitability for performing either a forceful movement (*power* condition) or precision movement (*precision* condition). The power-hitting and precision-interception rating conditions were designed to parallel the hammering and poking conditions employed by Wagman and Carello, in that both hammering and power hitting emphasize the transfer of power and both poking and precision interceptions require fine control over the object. As such, it was hypothesized that the bottom-weighted stick would be preferred for exerting force while the top-weighted stick would be perceived as being most suitable for conducting highly controlled or precision movements.

Method

Participants

Twelve men and one woman participated in this experiment. They were all University of Cincinnati undergraduate students in Introductory Psychology who fulfilled a course requirement by participating. They ranged in age from 18 to 27 years ($M = 20$,

mode = 18, median = 19) and averaged 179 cm in height ($SD = 8$ cm). None reported extensive competitive hockey experience (defined as more than a year of organized, league hockey).

Procedure

There were 12 trials in both the power- and precision-rating conditions. Rating conditions were blocked, and block order was counterbalanced across participants. Trials were conducted in blocks of three trials, one trial with each hockey stick (mass distribution condition). The order of mass distribution conditions within those blocks was randomized. Participants were instructed that they would be given different hockey sticks to hold, wield, and rate, and that this experiment would be conducted with their eyes closed. However, they could turn away from the experimenter and the sticks between blocks of trials should they need to take a rest break and open their eyes. This procedure was followed so as to assure that the ratings were not unduly influenced by visual confirmation of the location of the weights added along the stick shafts, even though the foam pads masked the actual weight location.

Results

Power

The mean (M) and standard deviation (SD) of the ratings of suitability for the top, middle, and bottom mass location conditions were $M (SD) = 3.22 (1.33)$, $5.06 (0.89)$, and $5.39 (1.43)$, respectively. A repeated-measures ANOVA revealed a statistically significant main effect of mass location, $F(2, 24) = 9.05$, $p < .01$, epsilon = 0.685. Follow-up Bonferonni/Dunn comparisons indicated that there were statistically

significant differences between the top- vs. bottom-weighted stick ($p < .001$; $d = 0.84^6$) and the top- vs. middle-weighted stick ($p < .01$; $d = 0.99$). While the ratings of the middle- and bottom-weighted sticks were not significantly different ($p > .05$), the overall pattern of results pointed towards a clear trend for participants to favor bottom-heavy sticks (see Figure 3).

Figure 3. Mean hockey stick ratings (error bars indicate 1 standard error) for the *power* condition in Experiment I.

Precision

The mean and standard deviation of the stick ratings for the top, middle, and bottom mass location conditions were, respectively, $M (SD) = 6.28 (0.70)$, $4.03 (1.42)$, $3.12 (1.20)$. A repeated-measures ANOVA revealed a significant main effect of mass

⁶ Effect size was estimated using Cohen's d . Cohen (1977) recommended that values around 0.2 can be considered small, values around 0.5 can be considered medium, and values above 0.8 can be considered as indicating large effects.

location, $F(2,24) = 82.18$, $p < .001$, $\epsilon = 0.923$. Participants tended to prefer the top-weighted stick when asked to prospectively rate the sticks for a task that required precise control over the stick's movement (see Figure 4). Bonferonni/Dunn post-hoc tests revealed that all pair-wise comparisons were significant (top vs. bottom, $d = 3.50$; top vs. middle, $d = 2.05$; middle vs. bottom, $d = 1.29$) at $p < .001$.

Figure 4. Mean hockey stick ratings (error bars indicate 1 standard error) for the *precision* condition in Experiment I.

Discussion

The results of Experiment I were consistent with the hypothesis that was based on the findings of Wagman and Carello (2003). In that research and in this study, participants preferred an object whose mass was concentrated farther away from the point of grasp when prospectively determining the object's usefulness for exerting force. In contrast, participants preferred sticks whose mass distribution was concentrated nearest

the point of grasp when prospectively rating the object's usefulness for a precision control task. Of course, the present experiment differed from that of Wagman and Carello (2001, 2003) in terms of the domain of activity in which the prospective judgments took place. Wagman and Carello examined ratings of weighted sticks for hammering and poking, whereas the present study investigated hockey sticks for power (e.g., slap-shot) and precision (e.g., puck interception), both ice-hockey tasks; nevertheless, similar outcomes were observed. Moreover, even though participants in the present investigation did not have ice-hockey-playing experience, they were able to identify the mass distribution that would function best under both task conditions. In contrast, most participants in Wagman and Carello's studies were likely to have had experience with objects used for hammering or poking.

The similarity of results between the studies is based on the underlying similarity of the constraints of the tasks for which the objects were rated. Both Wagman and Carello's (2001, 2003) hammering condition and the power condition of the present experiment reflect tasks that maximize the transfer of force using a held object or tool. The poking and precision conditions both reflect tasks constrained by the directed, precise application of force with a held tool. Both studies demonstrate people's ability to haptically discriminate objects with reference to the force and precision control requirements of different tasks, based on variations in the objects' mass distributions.

There were many other procedural differences between the present study and the experiment of Wagman and Carello (2001). However, both studies indicate that an object's resistance to rotation, which depends directly upon the object's mass distribution (which, in turn, is the material variable that determines the object's actual suitability for

performing different kinds of actions) is an informative variable on which to base perceptions of the object's utility for different behaviors. In other words, perceptions of a hand-held object's affordances may be based on how the object resists the exploratory wielding actions that perceivers undertake during dynamic touch (e.g., Carello & Turvey, 2004; Turvey & Carello, 1995; Turvey, 1996).

Whereas participants in the present experiment were able to prospectively identify which mass distribution would function best under the power and precision conditions, they were not given the opportunity to actually perform those actions with the hockey sticks—they wielded the sticks, but did not engage them in an actual task-relevant action. Doing so may serve to fine tune their ratings. Experiment II was designed to assess whether performing a task-relevant action would influence perceivers' sensitivity to the sticks' suitability for power and precision tasks.

CHAPTER IV: EXPERIMENT II

Power vs. precision ratings with an action component:**Hitting a puck for power vs. intercepting a small ball**

The rating task of Experiment I demonstrated that participants were able to prospectively perceive a hockey stick's functionality by virtue of wielding the stick. However, the very nature of a prospective action task is not without its limitations. Because both perceiving and acting are intimately related components of human movement (e.g., Bernstein, 1967; J. J. Gibson, 1966; Kugler & Turvey, 1987), a prospective action task is limited in how well it represents goal-directed human movement as a whole. In other words, goal-directed activity may rely on the successful integration of both perceiving and acting (cf. Oudejans, Michaels, Bakker, & Dolné, 1996). Experimental paradigms that solely investigate prospective action tasks are limited in that they decouple this perception-action cycle (e.g., Kugler & Turvey, 1987; Shaw & Kinsella-Shaw, 1988; Turvey, Carello, & Kim, 1990) by focusing only on the perception component. In Experiment I, participants were asked to consider how well a given stick *would* function for a certain task, without actually performing the action. While it is useful to examine what factors govern the intended use of an object or tool (cf. Turvey, 1992), allowing participants to fully engage in the perception-action cycle should offer a more complete picture of how perception informs action, and action, in turn, constrains perception.

It can be argued that perceiving-via-wielding alone represents a fulfillment of the perception-action cycle, because successful perceiving-via-wielding consists of an active movement of the object during the perceptual process. However, a perception-action

cycle does not completely encompass the behaviourally complex actions encountered in the game of ice hockey: It is one of many “local” perception-action cycles nested within more global or macroscopic perception-action cycles that characterize the game of ice hockey. The more relevant perception-action cycle with respect to the present experiment is that of perceiving the stick’s affordances, using the stick to perform the intended action, and then using feedback from that action to fine-tune the perception of the stick’s affordances. This more macro-level consideration of how perception is influenced by action should be informative about whether performing an action-relevant task influences perceptions of a stick’s affordances. As illustrated, perception-action cycles are nested variables that can be addressed at differing levels of analysis. By incorporating an action component into the design of Experiment I, the macro-level perception-action cycle that emerges enables the experimenter to evaluate the extent that an action task informs affordance perception. In Experiment II, participants were given an opportunity to use the modified sticks to perform power and precision action-tasks.

The results of Experiment I were concordant with the findings of Wagman and Carello (2001, 2003) in that participants tended to prefer the bottom-weighted stick for a task that was constrained by a force-exerting action component. Further, participants tended to prefer the top-weighted stick when prospectively rating the sticks for performing a precision maneuverability action. Participants in Wagman and Carello’s study were able to accurately identify the appropriate mass distribution without actually engaging in a task-representative action. However, unlike Wagman and Carello’s hammering and poking tasks (with which most people have had some experience), participants unfamiliar with ice hockey might have difficulty identifying which hockey

stick mass distribution would be ideally suited for performing power-hitting and precision-interception tasks. Nevertheless, in Experiment I participants were able to prospectively identify the mass distributions best suited for performing such actions. Despite the participants' lack of familiarity with hockey sticks, and lack of experience playing any form of hockey, the results of Experiment I seem to indicate that participants did not require the added insight potentially offered by engaging in an action with the sticks. However, that is not to say that they *could not* benefit from experience performing task-relevant actions with the sticks. Perhaps such experience could serve to fine tune their responses. That is, their perceptual experience could be enriched by the opportunity to perform an action with the sticks, and thus lead to a different pattern of post-action responding when compared to pre-action ratings. Thus, using the sticks to perform interactive actions with the environment might enrich the participant's ability to identify the best mass distribution for each of the power and precision tasks, leading to a more pronounced preference for the bottom- and top-weighted sticks for those respective tasks than was seen in Experiment I. In that experiment, there was no significant post-hoc difference between the bottom- and middle-weighted sticks. A significant post-action difference between those two sticks was anticipated in Experiment II.

Method

Participants

Nine undergraduate men and 11 undergraduate women at the University of Cincinnati participated in this experiment in exchange for course credit. Their ages ranged between 18 and 32 years ($M = 19$, mode = 18, and median = 18 years). They averaged 173 cm in height ($SD = 11$ cm).

Procedure

Participants in Experiment II engaged in three separate experimental phases for each of the two experimental conditions: *Pre-action* ratings, the action phase, and *post-action* ratings. As in Experiment I, participants were instructed in the *pre-* and *post-action* phases to wield each of the hockey sticks with their eyes closed and to verbally report their ratings on the same 1-7 scale after wielding each of the individual sticks. Because the action phase required visual guidance, participants completed it with the eyes open.

Condition order (power vs. precision task) was blocked across participants so that half of the participants started with the power condition, and half started with the precision condition. The *pre-* and *post-action* phases of Experiment II were procedurally identical to Experiment I. That is, participants were instructed to rate each of the sticks according to its suitability for power or precision actions. For the action phase, participants used each of the sticks to hit a puck (power condition) or intercept the ball swinging on the pendulum (precision condition) five times with each stick. All five repetitions with a given stick were performed in a single block of trials. Block order was counterbalanced across participants.

Results

Power

The mean (M) and standard deviation (SD) of the ratings in the *pre-action* phase of the power condition for the top-, middle-, and bottom-weight locations, respectively, were $M (SD) = 3.40 (1.98)$, $5.05 (1.30)$, and $5.58 (1.51)$. The *post-action* ratings for those same respective conditions were $4.68 (2.16)$, $5.08 (1.28)$, and $4.65 (1.90)$. Figure 5

depicts the mean rating results. A repeated-measures ANOVA showed that there was a significant interaction between mass location and experiment phase (*pre-* vs. *post-action*), $F(2,38) = 4.80, p < .05$, epsilon = 0.913. Follow-up ANOVAs indicated that there was a significant main effect of mass location in the *pre-action* phase of the experiment, $F(2, 38) = 8.85, p < .001$, epsilon = 0.723, but not in the *post-action* phase ($p > .05$).

Bonferonni/Dunn comparisons indicated significant *pre-action* differences between the top and middle locations, $d = 0.81$, and between the top and bottom locations, $d = 0.70$, (both $p < .01$). Because the pattern of responses differed between the *pre-* and *post-action* phases, the results indicate that the *post-rating* phase of the experiment was influenced by performing the power-shot action. Performing the action phase seems to have informed participants about each stick's suitability for transferring force, and seems to have informed participants differently than did prospectively wielding the sticks.

Figure 5. Mean hockey stick ratings (error bars indicate 1 standard error) for the *power* condition in the pre- and post- action phases of Experiment II.

Paired *t*-tests were used to assess whether the ratings of each stick differed significantly across the *pre-* and *post-action* phases. The *t*-test comparing ratings for the top mass location across *pre-* and *post-action* phases indicated a significant increase in that stick's mean rating, $t(19) = -2.74, p < .05, d = 0.61$. However, the *t*-tests for the middle and bottom mass locations across *pre-* and *post-action* phases were not significantly different (both $p > .05$). Overall, the results indicate that there was a *post-action* trend toward favoring the top-weighted stick for conducting a *power* action.

Precision

The *pre-action* mean (M) and standard deviation (SD) of the ratings for the top, middle, and bottom mass locations, respectively, were $M(SD) = 6.20(0.91)$, $3.83(1.65)$, and $3.15(1.81)$. The *post-action* ratings for those respective conditions were $5.98(1.14)$, $4.05(1.60)$, and $3.40(1.85)$. Figure 6 depicts these results. A repeated-measures ANOVA indicated a main effect of mass location, $F(2, 38) = 30.11$, $p < .001$, epsilon = 0.715 , but no main effect of experimental phase or interaction between phase and mass-position ($F_s < 1$; ratings for precision did not differ across *pre-* and *post-action* phases). Bonferonni/Dunn comparisons indicated that there were significant differences between the top and middle locations, $d = 1.35$, and between the top and bottom locations, $d = 1.30$ (both $p < .001$).

Figure 6. Mean hockey stick ratings (error bars indicate 1 standard error) for the *precision* condition in the pre- and post- action phases of Experiment II.

Discussion

In both the power and precision conditions of Experiment II, participants provided both prospective as well as retrospective ratings on their suitability for either transferring force or being maximally maneuverable. Results for the precision condition were remarkably similar across *pre-* and *post-action* phases. Participants rated the top-weighted stick most suitable for performing the interception task both prospectively and after they had an opportunity to perform the intercepting action. It was predicted that experience gleaned from actually performing the action component of the experiment would enrich participants' perceptions regarding each stick's suitability for performing the precision interception task. Because the *pre-* and *post-action* ratings were so similar,

it appears that participants were able to accurately identify the best mass distribution for performing the interception action before ever engaging in the behavior, based solely on information obtained from wielding each of the three sticks. The added experience and feedback obtained from the action phase did not affect participants' ratings.

Unlike the precision condition, the results of the power condition demonstrated a marked change in how participants judged the suitability of the hockey sticks before and after the action phase. The *pre-action* ratings for the power condition in Experiment II and those of Experiment I were quite consistent: participants tended to prefer the bottom-weighted stick when making prospective judgments about suitability for forcefully striking an object. However, in Experiment II, *post-action* ratings for the power condition exhibited a clear difference when compared to the *pre-action ratings*. In the *pre-action* phase, participants preferred the bottom-weighted stick, but in the *post-action* phase no longer exhibited a preference for any one stick. While there were no statistically significant differences between the top, middle, and bottom-weighted sticks in the *post-action* ratings, participants no longer clearly favored the bottom-weighted mass distribution as they did in the prospective *pre-action* rating phase. Moreover, ratings of the top-weighted stick for the power task were significantly higher in the *post-action* phase than in the *pre-action* phase. That was an unexpected result: Preference for the bottom-weighted stick was expected to be enhanced in the *post-action* phase. That prediction was motivated by the fact that, from a physical perspective, a bottom-weighted object is optimal for exerting force via striking. For instance, a sledge hammer's mass distribution makes it optimal for pounding a fence post. As an object's center of mass is

located farther from the point of grasp, it becomes a more effective tool for transferring force to a struck object.

A possible explanation for that unanticipated finding is that participants (who had no or very little hockey experience) may have found that making contact with a puck required a considerable degree of aiming, or precision control over the stick's movement. To swing a hockey stick from approximately waist height and make contact with the small puck (7.6 cm diameter $\times$ 2.5 cm tall) was perhaps novel and difficult enough to influence stick ratings. Once participants gained actual action-relevant experience using each of the hockey sticks to strike a puck, they modified their ratings during the *post-action* phase to reflect the precision constraints of the hitting task. The pattern of *post-action* ratings suggests that the hitting task may have required an unexpected degree of precision control for accurate task performance. Even though the experimenter expressly instructed the participants to evaluate the effectiveness of each stick's mass distribution for transferring force, there appears to have been an intervening effect of task difficulty and precision on the ratings. Before being able to hit the puck hard, the actor must be able to aim and maneuver the stick to make contact with the puck. This aiming and maneuvering is presumed to have influenced how these novice participants rated the hitting task over and above considerations for hitting the puck with a maximal amount of force. While the direction of change in the *post-action* ratings was not anticipated, the results clearly demonstrated that participants' perceptions were affected by the action phase of the experiment. Experiment III was designed to address the issue of whether the unexpected pattern of responding in the *post-action* phase power condition was attributable to the precision requirements of hitting a hockey puck.

CHAPTER V: EXPERIMENT III

Power vs. precision ratings with an action component:**Hitting a large ball vs. intercepting a small ball**

In Experiment II, participants with little or no hockey experience rated the sticks both prior to and after performing a relevant action with the sticks. Participants hit a puck in the power condition, and intercepted a small ball swinging from a pendulum in the precision condition. As predicted, participants in Experiment II rated the bottom-weighted stick least favorably and preferred the top-weighted stick for intercepting a ball. There was a roughly linear trend for preferring the top-weighted, followed by the middle and then the bottom-weighted sticks. *Post-action* ratings were consistent with *pre-action* ratings, which was interpreted as indicating that participants were accurate in their initial prospective ratings. That is, experience performing the interception task validated their *pre-action* ratings, rather than provided discordant information that would have led to their changing the ratings.

Unexpected results occurred in the *post-action* phase for the power task in Experiment II. Experience gained from hitting the puck in the action phase apparently informed participants that having the mass distribution farthest from the point of grasp was not the ideal condition for hitting a puck, contrary to their *pre-action* power ratings indicating a preference for the bottom-weighted stick. A possible reason for the pattern of *post-action* responding was that inexperienced participants found it difficult to make contact with the small hockey puck. The pattern of *post-action* results may reflect an unanticipated degree of precision requirements for what was intended to be a power task. To test that hypothesis, in Experiment III the puck was replaced with a large inflatable

ball of sufficient size (21.6 cm diameter; 105.4 g) to have eliminated most of the precision aiming required to make contact with the blade of the hockey stick. In that case, participants were expected to rate the bottom-weighted mass distribution as being most favorable for transferring power to the ball, in both the *pre-* and *post-action* phases. As in Experiment II, participants again gave *pre-* and (after performing the intervening precision interception task) *post-action* ratings of the sticks' suitability for a precision task.

Method

Participants

Nine men and six women between the ages of 18 to 40 years participated in this experiment ($M = 21$, mode = 18, median = 19 years). Participants, averaging 175 cm in height ($SD = 9$ cm), were University of Cincinnati undergraduates, who received course credit in exchange for their service.

Procedure

The procedure was identical to that of Experiment II, with the exception that instead of making contact with a hockey puck, participants hit the inflated ball during the power-condition action phase.

Results

Power

The mean (M) and standard deviation (SD) of ratings for the top, middle, and bottom mass locations were $M (SD) = 3.90 (1.86)$, $5.20 (1.15)$, and $5.33 (1.32)$, respectively, in the *pre-action* phase and $3.73 (1.77)$, $5.00 (1.45)$, and $5.27 (1.41)$, respectively, in the *post-action* phase (see Figure 7). There was a significant main effect

of mass location in a repeated-measures ANOVA, $F(2, 28) = 5.07$, $p < .05$, epsilon = 0.728, but no effect of experimental phase nor an interaction between phase and mass-position ($F_s < 1$). Experimental phase Bonferonni/Dunn post-hoc comparisons indicated that only the mean ratings for the top and bottom locations, $d = 0.42$, were significantly different, $p < .01$, from each other.

Figure 7. Mean hockey stick ratings (error bars indicate 1 standard error) for the *power* condition in the pre- and post- action phases of Experiment III.

Precision

The mean (M) and standard deviation (SD) of ratings for the top, middle, and bottom mass locations were $M (SD) = 6.17 (1.52)$, $4.43 (1.02)$, and $3.60 (1.55)$ respectively, in the *pre-action* phase and $6.10 (1.31)$, $4.63 (1.59)$, and $3.07 (1.80)$, respectively, in the *post-action* phase (see Figure 8). A repeated-measures ANOVA

indicated a significant main effect of mass location, $F(2,28) = 23.26$, $p < .001$, epsilon = 1.0, but no effect of experimental phase nor an interaction between phase and mass-position ($F_s < 1$). Bonferonni/Dunn comparisons indicated that all pair-wise contrasts were significantly different (top vs. bottom, $d = 1.84$; top vs. middle, $d = 0.98$; middle vs. bottom; $d = 0.81$; all $p < .001$).

Figure 8. Mean hockey stick ratings (error bars indicate 1 standard error) for the *precision* condition in the pre- and post- action phases of Experiment III.

Discussion

There was a marked similarity in participants' *pre-* and *post-action* ratings of the sticks in Experiment III. That was true for both power and precision conditions. As predicted, in the power condition participants rated the bottom-weighted stick highest both before and after hitting the ball with the sticks during the action phase. That result stands in contrast to the *post-action* ratings obtained after Experiment II's puck-hitting

task, which reinforces the suggestion that hitting a puck does involve a degree of precision to which participants become attuned after attempting to hit the puck. The pattern of ratings in Experiment III indicates that participants were able to accurately identify which mass distribution would function best for transferring force to the ball before actually using the hockey sticks to perform this action. Once given the opportunity to engage the sticks in the power action, participants' initial pattern of responding was confirmed, though not enhanced.

The *pre-* and *post-*action phase ratings for the precision condition in Experiment III were very similar to those of Experiment II. Participants in the *pre-action* phase rated the top-, middle-, and bottom-weighted sticks as being most favored, average, and least favored, respectively. As in Experiment II, *post-action* ratings in Experiment III did not differ greatly from the *pre-action* ratings. This result suggests that actual experience intercepting the ball on the pendulum did not provide participants with any information that may have served to counter their initial perceptions regarding the optimal suitability of the three sticks for precision control tasks.

The finding that participants with little or no hockey-playing experience responded differently depending on the size of the object they were asked to strike and on the opportunity to perform the power-hitting task suggested that level of experience with the game of hockey may have influenced the results of Experiments I-III. The results obtained from inexperienced participants in Experiment II suggested that their initial perceptions regarding which stick was best suited for transferring power changed once the participants discovered the difficulty associated with hitting the small puck. To address the role of actual hockey-playing experience on ratings of the sticks' suitability

for power and precision tasks, Experiment IV examined ratings obtained from an expert group of hockey players.

CHAPTER VI: EXPERIMENT IV-A AND IV-B

Power vs. precision ratings from expert (IV-a) and novice (IV-b) participants

The results of the first three experiments have shown that participants with little or no hockey experience are able to accurately and reliably identify, by non-visual wielding alone, the optimal stick (i.e., mass distribution) for intercepting a ball moving through the air (i.e., the precision condition). That result points to the ability of the haptic perceptual system to inform the perceiver about how a held object can be used (cf. Turvey & Carello, 1995). In the power condition of Experiment II, participants gave different ratings of the sticks in the *post-action* phase relative to the *pre-action* phase. The change in ratings in Experiment II seems to reflect the participants' inexperience with hitting pucks, which are quite small. The results of Experiment III, in which participants struck the large ball during the action phase and did not show a discrepancy between *pre-* and *post-action* ratings, are consistent with the interpretation that in Experiment II experience hitting the small puck led participants to acknowledge (perhaps implicitly) a precision requirement for the puck-hitting task. Another, more direct, way to address the effect that level of experience has on perceiving hockey stick affordances for power and precision tasks is to obtain ratings from a group of expert hockey players. If experience hitting pucks plays a role in judging a stick's effectiveness for a power shot, there should be no difference between *pre-* and *post-action* ratings obtained from such experts—their *pre-action* ratings should reflect attunement to precision demands of hitting pucks. Experiment IV-a was designed to address that issue. Members of the men's varsity ice hockey team at Miami University (Oxford, Ohio) served as the group of expert hockey players. To rule out the possibility that the change in student population and

experiment location was responsible for any unique findings in Experiment IV-a, a replication of that experiment using Miami University undergraduates with no hockey experience was conducted in Experiment IV-b.

For Experiment IV-a, expert varsity-level hockey players were recruited to participate. They were exposed to the same experimental conditions as in Experiment II. It was expected that in the power condition, the hockey players would prefer the top-weighted stick, followed linearly by the middle and then bottom-weighted stick for both *pre-* and *post-action* ratings. Results of Experiment IV-b were expected to mirror those of Experiment II since undergraduates at the University of Cincinnati and Miami University were not expected to respond differently from one another.

Method

Participants

Four men between the ages of 20 to 21 years participated in Experiment IV-a ($M = 21$, mode = 21, median = 21 years). They averaged 180 cm in height ($SD = 2$ cm). Participants were members of the Miami Redhawks varsity men's NCAA Division-I ice-hockey team which was ranked in the top ten nationally during the 2003-2004 season. Participants averaged 17 years of experience playing hockey. They were compensated \$15 for their participation.

In Experiment IV-b, 9 men and 2 women between the ages of 18 to 20 years participated ($M = 19$, mode = 19, median = 19 years). They averaged 179 cm in height ($SD = 9$ cm). All were undergraduate students at Miami University with no hockey experience and received course credit in exchange for their participation.

Procedure

For both Experiments IV-a and IV-b the same experimental procedure as in Experiment II was employed, with the exception that these experiments were conducted in a laboratory in the Department of Psychology at Miami University. The pendulum apparatus used in Experiments I-III was transported to Miami University and re-assembled in that laboratory. In addition, after Experiment IV-a was completed, the experimenter asked the hockey players to identify the physical attributes of an ideal hockey stick and to describe their own stick that they currently favor.

Results

Power

In Experiment IV-a, the mean (M) and standard deviation (SD) of the *pre-action* ratings for the top, middle, and bottom mass locations were, respectively, $M (SD) = 5.25 (1.71)$, $3.75 (1.50)$, and $2.88 (1.44)$, and of the *post-action* ratings in those respective conditions were $6.00 (1.41)$, $4.25 (0.65)$, and $3.13 (0.85)$ (see Figure 9). A repeated-measures ANOVA revealed a significant main effect of mass location, $F(2,6) = 8.15$, $p < .05$, $\epsilon = 1.0$, but no effect of experimental phase or significant interaction between phase and mass-position ($F_s < 1$). Bonferroni/Dunn comparisons revealed significant differences between the top and bottom locations, $d = 1.55$, $p < .01$.

Figure 9. Mean hockey stick ratings (error bars indicate 1 standard error) for the *power* condition in the pre- and post- action phases of Experiment IV-a.

In Experiment IV-b the mean (M) and standard deviation (SD) of the pre-action ratings for the top, middle, and bottom mass locations, respectively, were $M (SD) = 2.77 (1.46)$, $5.14 (1.23)$, and $6.36 (0.78)$; M and SD of the post-action ratings were $3.96 (2.20)$, $5.14 (1.05)$, and $5.18 (1.94)$ (see Figure 10). A repeated-measures ANOVA revealed a main effect of mass location in the *power* condition, $F(2,20) = 9.11, p < .01$, epsilon = 0.664 , but that main effect was subsumed by a significant interaction between mass location and rating phase, $F(2, 20) = 4.81, p < .05$, epsilon = 0.834 . Follow-up ANOVAs on the *pre-action* ratings revealed a significant effect of mass location, $F(2, 20) = 25.83, p < .001$, epsilon = 1.0 . Bonferonni/Dunn comparisons showed significant *pre-action* differences between the top and middle, $d = 1.41$, and between the top and bottom, $d = 1.94$, mass locations (both $p < .001$). Follow-up ANOVAs for the *post-action* phase did not reveal a significant effect of mass location ($p > .05$). These analyses indicate that the

effect of mass location was limited to the *pre-action* phase. Paired *t*-tests comparing each stick across the *pre-* and *post-action* phases for the *power* condition indicated that the bottom-weighted stick was rated significantly lower in the *post-* than in the *pre-action* phase, $t(10) = 2.80, p < .05, d = 0.84$. The decrease in the rating of the top-weighted stick was not significant, and there was no difference in the mean ratings for the middle-weighted stick.

Figure 10. Mean hockey stick ratings (error bars indicate 1 standard error) for the *precision* condition in the pre- and post- action phases of Experiment IV-a.

Precision

In Experiment IV-a the mean (*M*) and standard deviation (*SD*) of the *pre-action* ratings for the top, middle, and bottom mass locations were, respectively, $M (SD) = 6.38 (0.63)$, $3.75 (1.26)$, and $2.50 (0.58)$; *M* and *SD* of the *post-action* ratings in those respective conditions were $5.63 (1.11)$, $3.63 (1.11)$, $2.25 (0.50)$ (see Figure 11).

Repeated-measures ANOVA showed a statistically significant main effect of mass location, $F(2,6) = 24.80$, $p < .001$, epsilon = 0.943, but not for experimental phase or interaction effects ($F_s < 1$). Bonferonni/Dunn comparisons revealed significant differences between the top and middle locations, $d = 3.52$, and between the top and bottom locations, $d = 3.59$ (both $p < .01$).

Figure 11. Mean hockey stick ratings (error bars indicate 1 standard error) for the *power* condition in the pre- and post- action phases of Experiment IV-b.

In Experiment IV-b the mean (M) and standard deviation (SD) of the ratings for the top, middle, and bottom mass locations, respectively, were in the *pre-action* phase M (SD) = 6.36 (1.00), 3.82 (1.40), and 2.86 (0.81), and were in the *post-action* phase 6.46 (0.69), 3.96 (1.29), and 2.09 (1.24) (see Figure 12). A repeated-measures ANOVA revealed a significant main effect of mass location, $F(2, 20) = 105.38$, $p < .001$, epsilon =

1.0. The interaction between experimental phase and mass-position was not significant, nor was there a main effect of phase ($F_s < 1$). All possible Bonferonni/Dunn pair-wise comparisons (top vs. bottom, $d = 4.65$; top vs. middle, $d = 2.55$; middle vs. bottom, $d = 1.58$) were significant, $p < .001$.

Figure 12. Mean hockey stick ratings (error bars indicate 1 standard error) for the *precision* condition in the pre- and post- action phases of Experiment IV-b.

Discussion

For both *pre-* and *post-action* ratings for both the power and precision conditions, the hockey players preferred the top-weighted mass distribution, followed by the middle- and then bottom-weighted distributions. The hockey players were remarkably consistent in how they rated the three experimental sticks and were generally uninfluenced by the action task. In the *pre-action* ratings of the sticks for the power task, the hockey players seemed to have been influenced by how the stick's mass distribution would function for

hitting a puck, rather than considering more abstractly which mass distribution would yield a maximal transfer of force to a struck object in the absence of a precision requirement. Their reasons for preferring the top-weighted mass distribution became apparent once they were asked to clarify their opinion of what makes for an ideal hockey stick. They unanimously described their preference for a “light” stick, stating their top consideration was in terms of being able to control or “stick handle” the puck. Participants reported afterwards that the flex of the stick shaft, rather than absolute “bottom-heaviness” of the stick, affected their perceived ability to maximally transfer force or power. To this end, the hockey players expressed that their “ideal” stick would be very light-weight.

Perception of an object’s weight has been shown to be tied to the object’s mass distribution (i.e., inertia), rather than simply to the object’s mass, per se (e.g., Shockley, Grocki, Carello, & Turvey, 2001; Turvey, Shockley, & Carello, 1999). Because the top-weighted sticks had the lowest moment of inertia of the three sticks, it may have felt lighter. Therefore, participants may have based their ratings on their bias toward preferring light sticks rather than on the constraints of hockey, per se. To address that concern, I introduced an additional task for the hockey players. After they had participated in all experimental trials, the players were again asked to close their eyes and were subsequently given each of the three sticks to wield. The experimenter asked them to rank order the sticks in terms of suitability for pounding a tent peg into the ground. That is, they were asked to consider the sticks in a context completely removed from the game of hockey. All four participants ranked the bottom-weighted stick as being most suitable to the hammering task, followed by the middle- and then the top-weighted

distribution. Those results, while somewhat informal, suggest that their responses for the *power* condition in Experiment IV-a reflected hockey-specific task demands, rather than an outright bias for “light-weight” sticks or an inability to determine which stick was best suited for absolute force transfer.

The hockey players’ *precision* condition ratings were consistent with the ratings offered by novices. As in the previous two experiments, participants’ prospective ratings of the sticks’ suitability for intercepting a ball were accurate. Actually intercepting the ball on the pendulum did not substantially alter how the participants rated each mass distribution’s suitability for being maneuverable.

To summarize, the hockey players rated the sticks in the *power* condition in a manner that suggests an influence of expertise within the domain of hockey. Experiment IV-b was designed to control for the possibility that because this experiment was conducted at Miami University (i.e., not at the University of Cincinnati, like the previous three experiments), the novel setting of both the laboratory and university may have been a confound. The results of Experiment IV-b were largely consistent with those of Experiment II, which suggests there was no confound due to location.

CHAPTER VII: GENERAL DISCUSSION

In four experiments, the nature of the relation between an object's mass distribution and its perceived affordances was investigated. As a whole, the results support the notion that people can use the haptic perceptual subsystem of dynamic touch to perceive how a held object may be used (i.e., its affordances; see also Shockley, Grocki, Carello, & Turvey, 2001; Wagman & Carello, 2001, 2003). The first experiment, with University of Cincinnati undergraduates, demonstrated that variations in mass distribution sufficiently differentiated hockey sticks in terms of their prospectively perceived functionality. The second experiment, with University of Cincinnati students, sought to determine whether engaging in an action task might further constrain perception of which mass configuration might function best for power and for precision actions. The participants who had experienced the action task were influenced by it, but not as anticipated. Pre-action ratings in Experiment II indicated that participants felt the bottom-weighted stick would, as expected, function best for the power task. However, after having performed the task, those participants apparently realized that contact with the puck required a considerable degree of precise control and aiming of the stick. Thus, to transfer absolute maximum power to the puck, it was first necessary to precisely aim the stick in order to make contact with the small puck, an action task best afforded by the top-weighted stick.

This unanticipated result guided the design of Experiment III, which was an attempt to resolve the shift in how participants responded in the post-puck-hitting phase. A large inflatable ball replaced the puck of Experiment II. The larger surface area of the ball was anticipated to vastly reduce precision aiming requirements and result in a true

power-transferring task for which participants would rate the bottom-weighted stick as optimal. The result was consistent with the hypothesis that the small size of the puck was responsible for the unexpected post-action ratings in Experiment II: In Experiment III participants, again University of Cincinnati students, preferred the bottom-weighted stick for transferring force during both the pre- and post-action phases. Experiment IV employed varsity-level hockey players from Miami University as participants to evaluate the role of hockey-playing experience. The hockey players preferred the top-weighted mass distribution for both tasks during both pre- and post-action phases. A replication of Experiment II with Miami University undergraduates (Experiment IV-b) demonstrated similar results as those obtained from the University of Cincinnati undergraduates, providing evidence that the distinctive pattern of responses from the expert hockey players was not an artifact of collecting data at a different university and in a different laboratory space.

In sum, the results of the present experiments highlight two notable characteristics of haptic perception using the subsystem of dynamic touch: (1) perceivers can use dynamic touch to detect affordances for the prospective control of behavior, and (2) haptic sensitivity to action-relevant properties of objects is modifiable by experience. These experiments demonstrated that people are prospectively able to judge, with reasonable success, how variations in the mass distribution of hockey sticks would affect their ability to utilize the sticks to perform distinct tasks. The action phase of the experiments and subsequent post-action ratings provided evidence of participants' ability to modify their perceptions based on unanticipated behavioural constraints encountered during exploratory perception-action.

The role of experience: Expert vs. novice hockey players

For the power condition, the expert hockey players' responses were inconsistent with the novices' pre-action tendency to prefer bottom-weighted sticks. The experts quickly and reliably identified the top-weighted stick as being the optimal mass configuration for performing both the power and precision actions. However, the novices' post-action ratings began to align with the hockey players' ratings once the novices had experienced the hockey-relevant action phase in Experiments II and IVb. By virtue of their experience hitting the pucks, the novices seem to have perceptually "tuned-in" to the same action constraints as those governing the experts' ratings.

The process by which experience in exploring how a tool may be used to augment or change a person's action capabilities may be viewed as an instance of perceptual learning. E. J. Gibson and Pick (2000) noted that perceptual learning is a process of perceptual refinement and differentiation that characterizes human development throughout the lifespan. In this case, interacting with the sticks in the action phase of the power condition was the exploratory activity necessary for the novices to begin tuning their perceptions to the task of effectively hitting a puck. From this perspective, the novices' pattern of responding during the initial rating trials may have reflected their lack of experience utilizing this specialized equipment for carrying out the puck-hitting task. Although there were only 15 puck-hitting trials for each experimental condition, this small amount of exploratory activity apparently was meaningfully informative for guiding perception in the service of action. Lockman (2000) suggested that the process of discovering the information that specifies an affordance characterizes tool use and development. From this perspective, the novel tool-using situation encountered by the

novices during the puck-hitting phase of the experiments was necessary for identifying the appropriate physical and perceptual variables that specified the relevant affordances.

Affordances in action

Bongers, Smitsman, and Michaels (2003) noted that for an expert tool user, the perceiver and the tool function as an integrated whole. The body-plus-tool system must be considered holistically as altering the realm of action possibilities available to the individual (while employing the tool). Until the tool is paired with a purposeful and goal-directed organism, however, the tool is nothing more than an object that may present different affordances for different organisms, under varying circumstances. In a sense, the tool alone is nothing more than unrealized potential. Once a person purposefully grasps the tool, the person's effective relation with the environment changes. The body-plus-tool system is therefore a dynamic and integrated whole. From an affordance perspective, tools and users must be paired as the unit of analysis in much the same way as an organism must be considered in relation to its broader environment. Effective tool use is a combination of intentionality on the part of the user and ergonomic and functional fit on the part of the tool.

Bongers et al. (2003) manipulated a held rod's mass distribution (as well as length and material composition) to investigate whether the affordances for "poking" would require behavioural (postural) adaptations for successful task performance. Participants in their study held a rod in one hand and walked towards a table that held a target object to be poked with the rod. They were to stop walking and extend their rod towards the target object when they felt they were in a suitable position to do so. The results indicated that participants actively adjusted the position and joint angles of their arms to

accommodate the varying mass distributions of the held rods to make contact with the target object. The authors interpreted this postural adjustment to the varying mass distributions of the rods as indicating that the participants were haptically sensitive to the changing affordances of the rods. The results of the present investigation complement Bongers et al.'s findings. In their study, participants used information obtained haptically to actively tailor their behaviour to accommodate physical differences in their held tools; in the present study, participants indicated haptic perceptual sensitivity to physical differences in the sticks by giving verbal reports. Considering the present investigation along with the results of Bongers et al. (2003), Shockley et al. (2000), and Wagman and Carello (2001, 2003), there is converging evidence, obtained using distinct experimental tasks and methodologies, that perceivers capitalize on action-relevant information available in structured haptic (mechanical energy) arrays to perceive the affordances of hand-held tools via dynamic touch.

Implications for hockey stick design

In the present investigation, the game of ice hockey served as the framework for addressing the relation between a held object's mass distribution and the perceived affordances of the object for conducting either a forceful or a precision action. The motivation for using the game of ice hockey as a framework for addressing these issues stemmed, in part, from a desire to inform the design of hand-held sporting equipment. By combining haptics and affordance research, experimenters can investigate how the haptic perceptual system registers information and how information gleaned through dynamic touch can inform the perceiver about an object's perceived functionality.

Currently, there are numerous ways to customize a hockey stick according to individual preference. For instance, sticks vary in terms of composition, weight, shaft flexibility (both absolute degree of flex as well as location of flex points), curve and lie of the blade, and shaft length. As players develop their skills, they may discover stick configurations that work best for their style of play, own body size and weight, and position they play. I propose that, in addition to those customizable features just mentioned, the mass distribution of a stick could be modified to offer an additional measure of personalization. The present research findings suggest that manipulating the inertial properties of hockey sticks may influence consumers' perceptions of and preferences for hockey sticks.

As this research demonstrated, the top-weighted stick (i.e., the one with the lowest moment of inertia) was consistently identified by the expert hockey players as being the mass configuration best suited to the requirements of the game of ice hockey. The expert hockey players, unlike the novice participants in Experiment I and during the pre-action phases in Experiments II-IV, were tuned in to the agility or maneuverability requirement inherent to the game of ice hockey. Because hockey is such a fast-paced game, and because hockey pucks are quite small, maneuverability and precision appear to be more important behavioural constraints than absolute force generation. It may therefore prove beneficial to manipulate the density of materials of the stick's shaft or to place small weights inside the shaft of the stick to achieve an optimum "maneuverable feel" to the stick. The result should be the creation of a hockey stick that capitalizes on the sensitivity of the player's haptic system to identify action-relevant properties of held objects.

Future research

While there are numerous ways in which a mass-distribution manipulation can be introduced into the marketplace, further research is needed to address whether expert hockey players are able to differentiate between mass configurations other than those used in the present study. That is, it has yet to be determined whether there might be one optimal mass configuration, or whether people are sensitive enough to perceptually differentiate a greater number of configurations than those used in the present studies. Modern hockey sticks may be composed of various lightweight and composite materials, yielding sticks as light as 445 g. One of the potential extensions of the present research would be to modify some of these higher-end composite sticks to evaluate whether smaller variations in the stick's mass distribution would be salient to the perceiver. A psychophysical investigation of the ability to identify small differences in a stick's mass distribution (e.g., at a threshold level) would help identify how sensitive the haptic system is to these types of manipulations. Determining those psychophysical thresholds and incorporating the relevant inertial manipulations in tool and sporting equipment design may increase the subjective "feel" (the user's sense of comfort or liking) of the product as well as its usability (cf. Kriefeldt & Chuang, 1979).

Anecdotally, when the experimenter asked the expert hockey players to describe their ideal hockey stick, they unanimously identified a lightweight stick with a balanced shaft (i.e., a uniform mass distribution) as being best suited to their performance needs. However, when given the opportunity to choose between three sticks of approximately equal mass, they consistently preferred the stick with the mass concentrated nearest their point of grasp. Further research could be conducted to assess whether hockey players

truly prefer lighter sticks (as revealed anecdotally in Experiment IVa) or whether a top-heavy mass distribution might be preferred over a uniformly distributed or bottom-heavy, but lighter, stick. That study would help inform whether a stick with a higher moment of inertia (i.e., top-heavy) would be perceived as being more maneuverable and controllable than the conventional stick design. If perceivers exhibit high sensitivity to that manipulation, it should be possible to manufacture and market different sticks based on, perhaps, style of play (e.g., offensive vs. defensive).

The novice hockey players in the power condition started to align their post-action ratings with those of the expert players. One line of future research could investigate whether additional opportunities to experience the action phase of the power condition might further align the novices' ratings with those of the experts. Alternatively, a study could be conducted with people who are just starting to play hockey (e.g., a children's introductory league) to see if they have yet to tune in to the specified mass distribution requirements identified by the expert population in this study.

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Appendix

The Inertial Ellipsoid

When an object is held and rotated about an axis (say, at the wrist), the amount of force required to rotate and translate that object can be expressed as an array of quantities representing magnitude and direction. This quantification is called an inertia tensor.

Now imagine that the held object is intersected by a three dimensional coordinate system, with x, y, and z axes running orthogonally through the object's length, width, and depth.

When the three axes are arranged in such a manner that the object's mass is evenly distributed about the three axes, they are said to be symmetrical. The inertia tensor and the symmetry axes may be used to depict a geometric representation of the object that roughly approximates its mass distribution (i.e., the inertial ellipsoid; see Figure A1).

Figure A1. Inertial ellipsoid. $\mathbf{e}_1$, $\mathbf{e}_2$, and $\mathbf{e}_3$ are the inertial eigenvectors or symmetry axes. I_1 , I_2 , and I_3 are moments of inertia about those symmetry axes.

The symmetry axes ($\mathbf{e}_1$, $\mathbf{e}_2$, and $\mathbf{e}_3$) govern the ellipse's orientation, while its depth in each direction comes from the moments of inertia about each of these axes (I_1 , I_2 , and I_3) (Carello & Turvey, 2004). The three symmetry axes are the principal directions of the ellipsoid. The size and shape of the ellipsoid are specified, respectively, by its volume ($V = 4\pi/3 [I_1 \times I_2 \times I_3]$) and symmetry ($S = 2 \times I_3 / (I_1 + I_2)$). V and S , as Wagman and Carello (2001, 2003) have demonstrated, are haptically meaningful variables that may constrain affordance perception. V and S respectively specify the level and patterning of muscular forces necessary to control a held object (e.g., Shockley et al., 2001).