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Psychophysical Test for the Independence of Perception and Action

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Research has suggested that perception and action are independent (see M. A. Goodale & A. Haffenden, 1998). The authors used the Ebbinghaus illusion to test this hypothesis in 2 experiments. Verbal reports of perceived size were compared with maximum grip aperture during grasping (Experiment 1) and manual reports of perceived size (Experiment 2). A multidimensional signal detection analysis was used to distinguish among the possible interactions between the two processes in each experiment (H. Kadlec & J. T. Townsend, 1992a, 1992b). In Experiment 1, the percepts were independent, and there were no interactions between processes for verbal and visuomotor responses. In Experiment 2, the percepts associated with verbal and manual reports were independent, but the processes interacted at the levels of the stimulus information and the decision rules used to transform each percept into a response.

A number of studies have suggested that the mechanisms and processes underlying visual perception are independent from those underlying visuomotor control (see Goodale & Haffenden, 1998). Much of this research has focused on the finding that certain geometric illusions of size, such as the Ebbinghaus illusion, affect verbal or manual reports of perceived size differently from grasping. There are, however, also data to suggest that these illusions affect both perception and visuomotor control similarly (e.g., Franz, Gegenfurtner, Bülthoff, & Fahle, 2000). To address this discrepancy, we adapted and applied a psychophysical test of perceptual independence (Ashby & Townsend, 1986; Kadlec, 1995, 1999a, 1999b; Kadlec & Townsend, 1992a, 1992b) to this phenomenon in the present experiments. Verbal reports of perceived size were compared to the scaling of grip (Experiment 1) and manual reports of perceived size (Experiment 2). These psychophysical methods allowed us to identify where these processes interact and where they remain independent.

Independence of Perception and Action

Several approaches have been used to identify a distinction between perception and action. Using neurophysiological studies of monkeys with brain lesions, Ungerleider and Mishkin (1982) proposed two separate physiological pathways for processing visual information. They suggested that the ventral stream was responsible for recognizing objects whereas the dorsal stream was responsible for localizing objects. This hypothesis was extended with additional data from primates and from neurologically damaged patients (Goodale, 1993; Goodale et al., 1994; Goodale & Milner, 1992; Goodale, Milner, Jakobson, & Carey, 1991; Milner & Goodale, 1993, 1995). Patients who experienced damage to the superior regions of the posterior parietal cortex could identify stimuli correctly but were unable to grasp them. Conversely, a patient with damage to the occipitotemporal cortex was unable to identify or localize objects correctly yet could grasp them. Given these data, a task-based distinction was proposed in which the ventral stream processed optical information for use in perceptual reports whereas the dorsal stream processed optical information for use in controlling action.

A similar distinction has been made with data from neurologically intact participants. Many of these experiments used the Ebbinghaus illusion, a pictorial illusion of size consisting of a circle surrounded by a ring of circles. When the circles in the surrounding ring have a small diameter, the circle in the center appears larger than when the circles in the surrounding ring have a large diameter (Coren, 1971). In general, the strength of a pictorial size illusion is assessed by using verbal or manual estimates of the size of the center circle. In order to distinguish the effects of this illusion on perception and action, though, researchers compared such perceptual reports with the actual movements that participants made when reaching to grasp a disk that served as the center circle. In these experiments, the illusion was strongest in perceptual reports and was either weakened or absent in the scaling of the maximum grip aperture leading up to the grasp (Aglioti, DeSouza, & Goodale, 1995; Brenner & Smeets, 1996; Haffenden & Goodale, 1998, 2000). Similar results have been found in data from induced motion (Bridgeman, Kirch, & Sperling, 1981), visual search (Brown, Moore, & Rosenbaum, 2002), and visual masking, eye movements, and other pictorial illusions of size (reviewed in Goodale & Haffenden, 1998). Across multiple methodologies, optical information appears to be processed differently depending on the task.

Other researchers, however, have challenged these conclusions. Franz et al. (2000) pointed out that, although previous studies showed stronger effects of the illusion on perceptual reports, there were still noticeable effects on grasping. For instance, Aglioti et al. (1995) found a significant effect of the Ebbinghaus illusion on maximum grip aperture, just as Daprati and Gentilucci (1997) found with the Müller-Lyer illusion. Haffenden and Goodale (1998) found a nonsignificant effect of the Ebbinghaus illusion on maximum grip aperture. Brenner and Smeets (1996) found that a pictorial size illusion did not influence maximum grip aperture

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when reaching to the center disk but that it did influence the forces used to lift the disk. The strongest challenges, however, came from studies that identified significant and equivalent effects of the Ebbinghaus illusion on verbal reports and grip (Franz et al., 2000; Pavani, Boscagli, Benvenuti, Rabuffetti, & Farne, 1999).

On the basis of these seemingly contradictory results, alternate hypotheses have been offered regarding the independence of perception and action. Franz et al. (2000) made the strongest counterclaim and concluded that there was no difference between the two processes. Both the perceptual report and grasping movements were thought to be functions of a single internal representation. Brenner and Smeets (1996) argued for a limited form of independence in which perception and action (or different aspects of an action) were independent but only when controlled on the basis of independent information. Haffenden and Goodale (1998, 2000) presented a third interpretation in which the two processes were independent yet appeared to interact when the target displays affected each process similarly. In the present experiments, we applied a psychophysical analysis of perceptual independence to this phenomenon to generate and test a number of psychophysical hypotheses regarding the independence of, or interactions between, these two processes.

Forms of Independence

At the heart of the debate over the independence of perception and action is the fact that there are multiple ways in which perception and action may either interact or be independent. In the context of their *general recognition theory,* Ashby and Townsend (1986) provided generic definitions for each of the possible interactions (termed *varieties of independence*) and offered methods for testing the presence of each. It is important to note that general recognition theory was originally designed to identify the sources of interaction between two perceptual reports. This approach was extended and used in the present experiments to identify the sources of interaction between verbal reports of perceived size and either maximum grip aperture during grasping (Experiment 1) or manual reports of perceived size (Experiment 2). To show how we made this extension, below we define the intervening subprocesses used to generate a perceptual report and then apply them to visuomotor control. Perception and action may either interact or be independent in any of these subprocesses.

General recognition theory is an extension of *signal detection theory* (Green & Swets, 1966). According to signal detection theory, the process of generating a perceptual report (e.g., a verbal report of perceived size in the Ebbinghaus illusion) is a two-part process of detecting optical information and transforming that information into a response. For ultimately distinguishing the three possible interactions between perception and action under general recognition theory, the first part of the process, detecting optical information, is divided into the *sensory detection* of information about a circle's size and the resulting *percept* (sometimes referred to as a *representation* or *neural code*) of its size. The sensitivity of this percept to variations in the information is quantified by the signal detection parameter d'. Finally, a *decision rule* is applied to transform the percept into a verbal report of perceived size. In the present experiments, the decision rule for verbal reports involves a comparison of the percept of size of one circle to the percept of size of another in order to generate the proper response. The decision criterion used to transform the percept into an observable response is quantified by the signal detection parameter C. These three subprocesses are depicted graphically as a flow diagram in Figure 1 (see Process A under NO INTERACTION).

Although general recognition theory is generally used for perceptual reports, these same three subprocesses can also be applied to visuomotor control (see Process B under NO INTERACTION in Figure 1). Consider, for example, the process of controlling maximum grip aperture in order to grasp a disk. To begin, the participant must have optical information about relevant features such as size, location, and orientation of the disk. The participant must detect this information, which would result in some internal percept of the disk's size. (There are different opinions about the nature of this percept. Franz et al., 2000, referred to it as an internal, presumably mental, representation equivalent to the one associated with a perceptual report. Goodale and colleagues [e.g., Goodale, 1993; Goodale & Haffenden, 1998; Goodale & Milner, 1992; Goodale et al., 1991; Haffenden & Goodale, 1998, 2000; Milner & Goodale, 1993, 1995], however, have avoided discussing representations for visuomotor control and have instead used terms such as *streams* or *coding* for the processes that intervene between information and movement. Nevertheless, these processes could still be couched under the term *percept* with the caveat that this term may refer to a neural code rather than a languagelike mental representation. An advantage of general recognition theory is that it does not force particular definitions of what constitutes a percept or, later, a decision rule.) Finally, in order to control maximum grip aperture, the participant would apply a decision rule translating the percept into the observed visuomotor response. Again, there are multiple forms that this decision rule could take; it could be a languagelike rule but it could also be a bias engendered by physical constraints, neural processes, or other control strategies. In short, both the perceptual report and the visuomotor response are defined in the present study as processes of detecting optical information and then transforming that information into measurable responses.

In this context, there are three ways that the two processes, one for a perceptual report and one for visuomotor control, may interact (see Figure 1). One possibility, of course, is that the processes do not interact at all. That is, perception and action may be parallel processes that rely on separate information, independent percepts, and unique decision rules. This possibility is depicted in the top panel of Figure 1. The remaining three panels in Figure 1 identify the three possible interactions. The first is a *sensory interaction* (second panel) in which the two processes rely on the same information. The second is a *perceptual interaction* (third panel) in which each process relies on the same percept. The last is a *decisional interaction* (bottom panel) in which the transformation of a percept into a report or an action is influenced by the percept associated with the other process. (When Ashby & Townsend, 1986, originally identified these three types of interactions for perception, they used a terminology associated with independence rather than interaction. In the language of general recognition theory, then, these three effects are referred to as *perceptual separability, perceptual independence,* and *decisional separability.*)

These three types of interaction can be applied to the debate reviewed above over the independence of perception and visuomotor control. The strongest position in support of their independence is that there are no interactions at any stage. The strongest

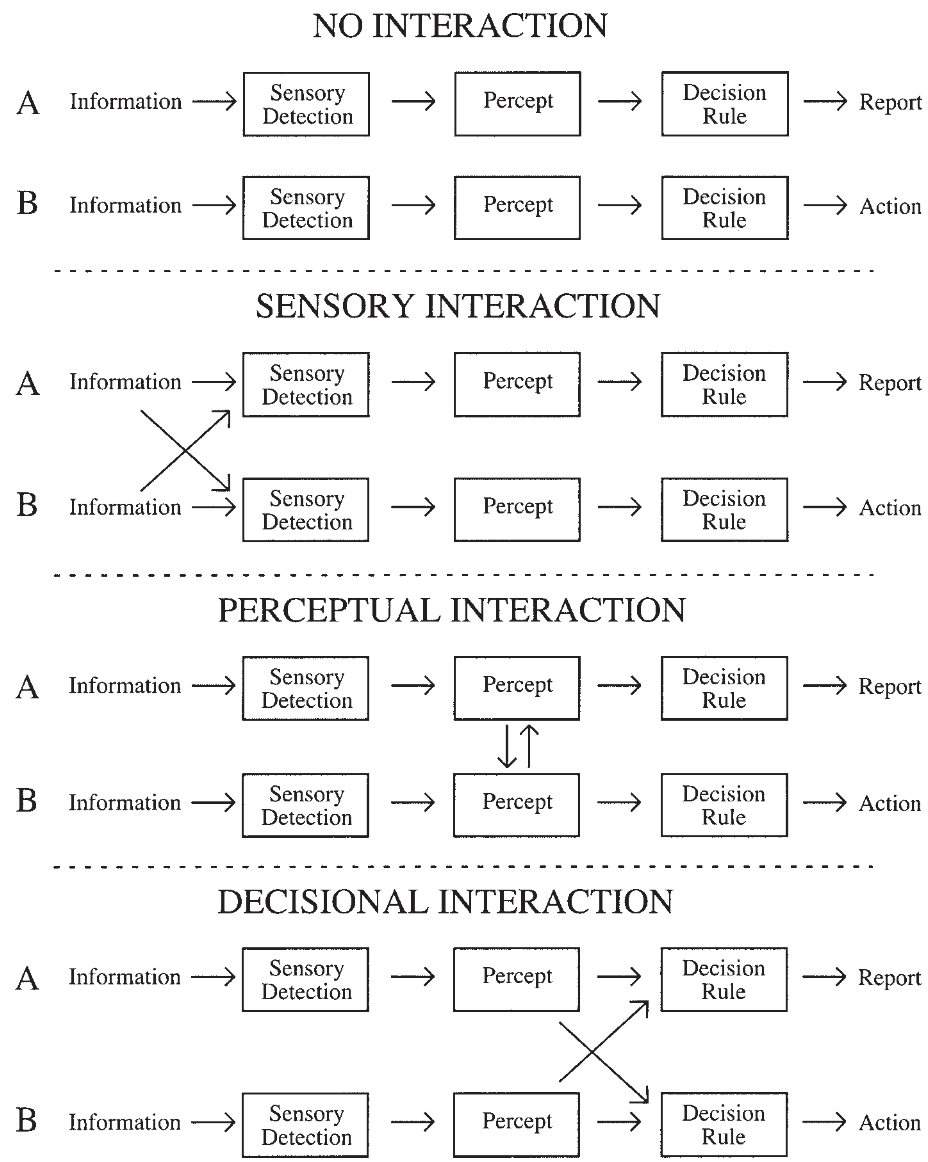

Figure 1. The hypotheses tested in the present experiments are expressed as interactions between the processes for generating two responses. Each response is a function of information that gives rise to an internal percept of the size of the center circle, which is transformed into the response by means of a decision rule. In Experiment 1, the two responses are verbal perceptual reports and visuomotor (action) responses. In Experiment 2, the action response is replaced with a manual perceptual response. The top panel depicts two processes that are independent at every stage. The second panel depicts a sensory interaction in which the two processes rely on the same information. The third panel depicts a perceptual interaction in which the two processes utilize the same percept. The bottom panel depicts a decisional interaction in which the two processes utilize the same decision rule. More than one type of interaction may exist in a data set.

counterclaim (e.g., that of Franz et al., 2000) is that the two processes overlap and interact at each stage. An intermediate possibility is that one or two forms of interaction exist. This possibility could lead to some instances in which perceptual reports and maximum grip aperture are independent and some instances in which they appear to interact. An advantage of identifying these possibilities with the constructs of general recognition theory is that psychophysical methods have been developed to test each of these hypotheses. These methods are described in the *Method* section below.

Overview

Using the Ebbinghaus illusion, we compared verbal reports of perceived size with maximum grip aperture (Experiment 1) and manual reports of perceived size (Experiment 2). The size of the center circle and the size of the surrounding circles were varied. Although both the inside and outside circles were varied, participants always responded to only the inside circle—that is, they grasped or reported the size of only the inside circle. In each experiment, the three hypotheses regarding the possible interactions between the two processes were tested. These hypotheses were tested by adapting and applying a method originally proposed by Ashby and Townsend (1986) and extended by Kadlec and Townsend (Kadlec, 1995, 1999a, 1999b; Kadlec & Townsend, 1992a, 1992b). These analyses used tests of response probabilities and tests of the signal detection parameters, d' and C. The results determined whether each response was a function of separate information (no sensory interaction), whether there were two noninteracting percepts of size (no perceptual interaction), and whether the responses were generated independently (no decisional interaction).

Experiment 1

Method

Participants. Eight (1 male, 7 female) students at Arizona State University participated in this study. All participants reported being right-handed.

Design. We compared verbal reports of perceived size with maximum grip aperture during grasping using the Ebbinghaus illusion. On each trial, the participant was presented with a pair of Ebbinghaus illusion diagrams. The center circle in each diagram was a disk that the participant could grasp. One of the two diagrams was always a standard and the second was the stimulus, although the participant was not aware of this fact. The stimulus set was created with a factorial combination of the two features relevant to the hypotheses, the diameters of the inside disk (I) and the outside circles (O). There were two levels of each feature (greater than [+] or less than [−] the standard), resulting in four stimuli, labeled I_-O_-, I_-O_+, I_+O_-, I_+O_+. Both perceptual and visuomotor responses were recorded for each trial. For both the standard and the stimulus, the perceptual (verbal) response was obtained by having the participant match the size of the inside disk to a circle on a card containing a matrix of 20 circles. For both the standard and the stimulus, the visuomotor response was obtained by having the participant grasp the inside disk, during which we recorded the maximum aperture between the thumb and forefinger. Each verbal and visuomotor response to the stimulus was coded as being either greater than (+) or less than (−) the corresponding response to the standard. The four possible joint responses for each stimulus (where m refers to the visuomotor response and v refers to the verbal response) were $\mathrm{m}_-\mathrm{v}_-$, $\mathrm{m}_-\mathrm{v}_+$, $\mathrm{m}_+\mathrm{v}_-$, $\mathrm{m}_+\mathrm{v}_+$.

With this design, the effects of each feature and the percept corresponding to the other response could be assessed separately. However, the present design differed from the design commonly used to assess perceptual independence. Normally, participants would be asked to make two perceptual reports simultaneously, each according to one of the two features (see, e.g., Amazeen, 1999; Oberle & Amazeen, 2003). This is commonly done by informing participants that there are four stimuli composed of two levels of each of two features and having them identify which of the four was presented on each trial. In the present experiment, though, participants were asked to make two different reports (one perceptual, one visuomotor) to the same feature, the size of the inside disk, on each trial. Despite this difference, there were still four possible joint responses, greater than or less than the standard on each report. The tests applied to these joint responses were the same as those used in the traditional design, except that the question in the present study was whether the two responses to the same feature interacted, rather than whether the two responses to two different features interacted.

Apparatus. A set of eight stimulus cards (38 cm × 50 cm) was created. Each card depicted a pair of Ebbinghaus illusion diagrams, one on the left and one on the right. The inside circle in each diagram was a disk (thickness = 5 mm) that the participant could grasp. One of the pair of diagrams was always the standard (I_s = 30 mm, O_s = 30 mm, line width = 1 mm), and the second was one of the four stimuli. To avoid any spatial bias, we depicted each of the four stimuli on two cards, once on the left and once on the right. The diameters corresponding to the two levels of each of the inside disks and outside circles were I_- = 28 mm, I_+ = 32 mm, O_- = 10 mm, and O_+ = 90 mm. The line width on each stimulus was 1 mm. The distance between the edges of the inside disk and the outside circles was 10 mm for each stimulus and for the standard. The number of outside circles on each diagram was as follows: For the standard there were 7 outside circles, for O_- there were 16 outside circles, and for O_+ there were 4 outside circles. The midpoints of each inside disk in the pair of diagrams on a card were aligned horizontally at a distance of 24.5 cm from each other.

A set of six response cards (25 cm × 38 cm) was created for the verbal reports. There were three cards to be presented over the left Ebbinghaus illusion diagram and an identical set of three cards to be presented over the right diagram. On each card was a matrix of 20 circles (line width = 1 mm) aligned in 4 columns (labeled *1–4*) and 5 rows (labeled *A–E*). From left to right and top to bottom, each circle was 0.5 mm larger than the previous. The diameter of the smallest circle differed across the three cards. The smallest circles on the three cards were 24.5 mm, 25 mm, and 25.5 mm. Participants knew that the sizes of the circles differed across cards, but they did not know how many cards were used, nor did they know which card would be presented to them on any given trial.

Maximum grip aperture for each grasp was recorded with an Optotrak 3020 motion measurement system (Northern Digital Inc., Waterloo, Ontario, Canada) situated 270 cm in front of the participant and 81 cm off of the floor. The Optotrak recorded the three-dimensional positions (100 Hz) of two infrared light-emitting diodes that were attached to the distal segments of the participant's right forefinger and thumb. The three-dimensional distance (grip aperture) between these two points at each sample was calculated for each grasp. The maximal distance that occurred between the initiation of the grasp and the contact with the inside disk was used as the maximum grip aperture.

Procedure. The participant sat in a chair in front of a table situated at the height of the participant's knees. From this vantage point, the participant was looking down at the stimuli that were placed on the table. All of the stimuli were kept behind the participant for the entire session. The session consisted of 144 randomly ordered trials (18 trials for each of the 8 cards or 36 trials for each of the 4 conditions). The three response cards for each diagram were evenly and randomly distributed across the 18 trials per card. In each trial, the participant both provided a visual estimate of the size of each inside disk (that is, the disk serving as the center circle on each Ebbinghaus illusion diagram) on the card and grasped each inside disk. A response card was placed on the far side of each diagram, and the participant made a visual estimate of size by verbally identifying the circle on the corresponding response card that was closest in size to each inside disk. The participant prepared to grasp each inside disk by placing their thumb and forefinger together on a point on the near side of the card, halfway between each diagram. Kinematic data collection began, and the experimenter instructed the participant to reach to the inside disk in the left Ebbinghaus illusion diagram. Data collection stopped when the participant grabbed the disk. The sequence was repeated for the right diagram. Each participant was randomly assigned to make either the visual or manual report first in each trial. The matched size and maximum grip aperture (both in millimeters) of each inside disk were recorded, and the stimulus was coded as being greater than or less than the standard on that trial. In the case of equal measures, a frequency of 0.5 was recorded for both greater than and less than the standard on that trial. Participants were allowed to rest during the session. All of the procedures in this experiment conformed to the ethical guidelines of the American Psychological Association (2002).

Analysis. The psychophysical test for interactions between perception and visuomotor control consisted of two sets of analyses, macroanalyses and microanalyses. The *macroanalyses* tested for changes in each process as a function of the stimulus features (the inside disk and outside circles). The *microanalyses* tested for changes in each process as a function of the other percept. Both sets of analyses used one test of response probabilities and two tests of the estimates of the signal detection parameters d' and C. All estimates of signal detection parameters included a log-linear rule transformation to correct for extreme proportions in the estimates of d' and C (Hautus, 1995). Familywise Bonferroni adjustments (Maxwell & Delaney, 2000) were used to maintain an error rate of .05 within each test; the p value reported with each test reflects the adjusted statistical criterion based on the number of comparisons for that test. Complete details can be found in Ashby and Townsend (1986), Kadlec (1995, 1999a, 1999b), and Kadlec and Townsend (1992a, 1992b). The inferences that are drawn from these tests are listed in Tables 1 and 2 of Kadlec (1995; see also Kadlec, 1999a).

The macroanalyses were used to test for sensory or decisional interactions (see Figure 1). These tests were termed *marginal* because they were calculated on the marginal response probabilities to identify changes across stimuli. The first test was the test of *marginal response invariance*. Marginal response invariance evaluated whether there was an effect of each feature on the probability of each response. The probability of each report was compared across the two levels of each feature. For example, the probability of maximum grip aperture being smaller than the standard when the outside circles were small, $P(m_-|I_-O_-)$, was compared with the probability of the same response when the outside circles were large, $P(m_-|I_-O_+)$. If both features influenced the response, then they were integrated somewhere in the process.

The remaining macroanalyses compared marginal estimates of d' (sensitivity to stimulus information) and C (decision bias) for each report across the two levels of each feature. For example, the sensitivity of maximum grip aperture to the size of the inside disk (measured by d') when the outside circles were small was compared with the same sensitivity when the outside circles were large. A difference indicated that both features influenced the sensory component of the visuomotor response. Similarly, the bias toward using a larger grip aperture (measured by C) when the outside circles were small was compared with the same bias when the outside circles were large. A difference indicated that both features influenced the decision rule leading to the visuomotor response.

Unlike the macroanalyses, we conducted the microanalyses using only the data from a single stimulus or the data from a single level of one feature to make the microanalyses immune to variations in the information across stimuli. Any effects identified by these tests, then, existed in the perceptual or decisional subprocesses (see Figure 1). The first test was the test of *sampling independence*. Sampling independence tested whether the percepts for the verbal and visuomotor responses were independent. The criterion of statistical independence was used. Within a single stimulus, the two responses were independent when the probability of making two responses together equaled the product of the probabilities of each response alone. A difference suggested that the percepts of size were correlated or linked together in some way.

The remaining microanalyses compared estimates of d' and C for each report across levels of the other report. Because these estimates were based on (conditioned upon) data from one level of the other report, they were termed *conditional*. For example, for the stimuli with large outside circles alone, estimates of d' and C for maximum grip aperture from those trials in which the participant reported that the inside disk was smaller than the standard were compared with those same estimates when the participant reported that the inside disk was larger. A difference suggested that one percept of size was influencing how the other percept of size was transformed into a response. These comparisons were similar to those of Haffenden and Goodale (1998), in which the effects of the outside circles on manual and visuomotor responses were assessed separately under conditions in which the inside circles were either physically different but perceived to be identical or physically identical but perceived to be different. In both the present microanalyses and the methods of Haffenden and Goodale, the goal was to identify the role of the percept separately from the role of the stimulus information.

Results and Interpretation

Mean perceived size and maximum grip aperture. Mean perceived size and maximum grip aperture (both in millimeters) were calculated. A within-groups analysis of variance (ANOVA) of each measure as a function of the size of the inside disk and outside circles was performed. The ANOVA on verbal reports of the perceived size of the inside disks identified significant main effects of both independent variables. As the inside disks increased from 28 mm to 32 mm, verbal reports of size increased from 27.85 mm to 31.40 mm, $F(1, 7) = 156.81$, $p < .001$. As the outside circles increased from 10 mm to 90 mm, verbal reports of the size of the inside disks decreased from 29.88 mm to 29.37 mm, $F(1, 7) = 34.08$, $p < .001$. This latter effect demonstrated the Ebbinghaus illusion. It is worth noting that the magnitude of this effect (1.67% decrease), although significant, was less than that in other studies (3.60% decrease with a similar matching procedure; Coren & Enns, 1993). This may have been because the disks in the present experiment were deliberately very similar in size in order to generate sufficient "errors" (i.e., *misses* and *false alarms* in the language of signal detection theory) for the psychophysical analyses. This may have led the participants to adopt a strategy of using a small range in their reports. There was no significant interaction between the two variables ($F < 1$).

The ANOVA on maximum grip aperture showed a different pattern of results. Only the main effect of the inside disks was significant, $F(1, 7) = 374.76$, $p < .001$. As the inside disks increased from 28 mm to 32 mm, the maximum grip aperture during the reach to grasp the inside disks increased from 46.43 mm to 50.78 mm. Participants increased the size of their grasp to accommodate the larger disks. However, even though participants verbally reported that the inside disks appeared smaller when surrounded by the larger circles, there was no significant accompanying change in maximum grip aperture, $F(1, 7) = 3.73$, $p > .05$. Maximum grip aperture while reaching to grasp the inside disks was 48.84 for the 10-mm outside circles and 48.37 for the 90-mm outside circles. This latter nonsignificant effect is similar to the nonsignificant decrease in maximum grip aperture accompanying an increase in the size of the surrounding circles that was reported by Haffenden and Goodale (1998). There was no significant interaction between the two variables ($F < 1$).

Macroanalysis results. The results of the test of marginal response invariance are reported in Table 1. Each pair of probabilities represents the effects of one feature on the probability of the participant making a particular response. As expected, the size of the inside disk had a significant effect on both the verbal and visuomotor responses. As the inside disks increased in size, the probability of the participant making a *larger* response increased whereas the probability of making a *smaller* response decreased. In contrast to the results of the ANOVA from above, though, there were no significant effects of the outside circles on the probability of either response. Despite being nonsignificant, however, both the verbal and visuomotor responses shifted in a direction consistent with the Ebbinghaus illusion (i.e., more likely *larger* for the small outside circles and *smaller* for the large outside circles). Considering the results of the ANOVA and the test of marginal response invariance together, we suggest that it appears as though there was a weak Ebbinghaus illusion on verbal reports and little or no illusion on visuomotor responses.

The results of the test of marginal d' are reported in Table 2. This signal detection parameter was estimated across levels of each feature to determine how each feature affected the sensitivity of each report. Neither of the paired estimates of $d'(O)$ were significantly different. The sensitivity of each report was unaffected by the size of the outside circles. To provide additional evidence for a lack of sensory interaction, we evaluated each estimate of $d'(I)$ against zero.[1] For verbal reports, the values of $d'(I)$ were not significantly different from zero: $d'_v(I_-)$: $t(7) = 2.48$, $p > .025$; $d'_v(I_+)$: $t(7) = 1.40$, $p > .025$. For maximum grip aperture, the values of $d'(I)$ were also not significantly different from zero: $d'_m(I_-)$: $t(7) = 0.88$, $p > .025$; $d'_m(I_+)$: $t(7) = 0.12$, $p > .025$. Again, the sensitivity of each report was unaffected by the size of the outside circles.

The results of the test of marginal C are reported in Table 2. This signal detection parameter was estimated across levels of each feature to determine how each feature affected the decision bias associated with each report. Both of the paired estimates of the decision criterion C across I were significantly different. For both verbal and visuomotor responses, participants were biased to report that the disk was smaller when it was actually smaller and biased to report that it was larger when it was actually larger. Neither of the paired estimates of C across O was significantly different. The size of the outside circles did not introduce a bias into either report.

Macroanalysis interpretation. For the verbal responses, contrary to the results of the ANOVA on mean reported size, the test of marginal response invariance found no effects of the outside circles on the probability of reporting *smaller* or *larger*. It seems, then, that the Ebbinghaus illusion on verbal reports was weak at best. There was no significant effect of the Ebbinghaus illusion on maximum grip aperture. Further, the tests of marginal d' and C did not identify any shifts in sensitivity or decision bias that would have been the source for this illusion.

Table 1
Test of Marginal Response Invariance for Maximum Grip Aperture (m) and Verbal Perceptual Reports (v) as a Function of the Size of the Center Disk (I) and the Outer Circles (O) in the Ebbinghaus Illusion Diagrams in Experiment 1

Maximum grip aperture		Verbal perceptual reports	
Test	Result	Test	Result
$P(m_-\|I_-O_+)$	.67	$P(v_-\|I_-O_+)$	.88
$P(m_-\|I_+O_+)$	.35	$P(v_-\|I_+O_+)$	.15
$t(7)$	9.32**	$t(7)$	18.25**
$P(m_+\|I_-O_-)$	.38	$P(v_+\|I_-O_-)$	.19
$P(m_+\|I_+O_-)$	.69	$P(v_+\|I_+O_-)$	.89
$t(7)$	−6.49**	$t(7)$	−18.45**
$P(m_-\|I_-O_-)$	.63	$P(v_-\|I_-O_-)$	.81
$P(m_-\|I_-O_+)$	.67	$P(v_-\|I_-O_+)$	.88
$t(7)$	−0.86	$t(7)$	−2.03
$P(m_+\|I_+O_-)$	.69	$P(v_+\|I_+O_-)$	.89
$P(m_+\|I_+O_+)$	.65	$P(v_+\|I_+O_+)$	.85
$t(7)$	0.94	$t(7)$	1.68

Note. Subscripts refer to greater than (+) or less than (−) the standard.
** $p < .025$.

Table 2
Macroanalysis Estimates of Sensitivity (Marginal d′) and Bias (Marginal C) for Maximum Grip Aperture (m) and Verbal Perceptual Reports (v) in Experiment 1

Marginal d'		Marginal C	
Test	Result	Test	Result
Maximum grip aperture			
$d'_m(I_-)$	0.12	$C_m(I_-)$	0.34
$d'_m(I_+)$	0.11	$C_m(I_+)$	−0.40
$t(7)$	0.04	$t(7)$	4.62*
$d'_m(O_-)$	0.81	$C_m(O_-)$	−0.09
$d'_m(O_+)$	0.82	$C_m(O_+)$	0.03
$t(7)$	−0.04	$t(7)$	−1.07
Verbal perceptual reports			
$d'_v(I_-)$	0.34	$C_v(I_-)$	1.03
$d'_v(I_+)$	0.17	$C_v(I_+)$	−1.16
$t(7)$	2.19	$t(7)$	12.86*
$d'_v(O_-)$	2.11	$C_v(O_-)$	−0.19
$d'_v(O_+)$	2.27	$C_v(O_+)$	0.07
$t(7)$	−2.19	$t(7)$	−2.08

Note. Subscripts on d' and C identify the report, and the terms in parentheses identify the level (+ = greater than the standard; − = less than the standard) of the stimulus dimension (I = size of the inside disk; O = size of the outside circles) at which the parameter was estimated.
* $p < .05$.

Microanalysis results and interpretation. The results of the test of sampling independence are shown in Table 3. A difference between the two probabilities in a pair would indicate that the two responses were correlated. None of the pairs of probabilities were significantly different. Verbal responses and maximum grip aperture were independent for each stimulus. The results of the tests of conditional d' and C are shown in Table 4. These tests were used to identify whether sensitivity or decision bias for each report was influenced by the percept associated with the other. None of the paired estimates of d' were significantly different for either verbal reports or maximum grip aperture. Similarly, none of the paired estimates of C were significantly different for either report. Taken together, the results of the microanalyses suggest that the two

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[1] Because the two-dimensional distributions are collapsed onto one-dimensional marginal distributions, the difference in d' across levels of I is equal to the difference in d' across levels of O. The psychophysical analysis of perceptual independence generally requires that d' be estimated only across levels of the inappropriate feature. As was described in the *Analysis* section above, a difference in this situation indicates a possible sensory interaction. However, a true lack of a sensory interaction requires that each d' for the unattended feature (in this case, O; reported as $d'[I]$) also be equal to zero. Therefore, if d' for each level of I does not equal zero, then it suggests that the size of the outside circles shifts the entire distribution of perceptual effects, not just their sensitivity.

Table 3
Test of Sampling Independence of Maximum Grip Aperture (m) and Verbal Perceptual Reports (v) for Each Stimulus in Experiment 1

Stimulus and test	Result
I_-O_-	
$P(m_-v_+)$	.12
$P(m_-)\cdot P(v_+)$	.12
$t(7)$	0.00
I_-O_+	
$P(m_-v_-)$	.60
$P(m_-)\cdot P(v_-)$	.59
$t(7)$	0.28
I_+O_-	
$P(m_+v_+)$	.62
$P(m_+)\cdot P(v_+)$	.62
$t(7)$	−0.42
I_+O_+	
$P(m_+v_-)$	.09
$P(m_+)\cdot P(v_-)$	.10
$t(7)$	−0.68

Note. Subscripts refer to greater than (+) or less than (−) the standard. A statistical criterion of $p < .0125$ was used for all tests. I = size of the inside disk; O = size of the outside circles.

percepts were independent (no perceptual interaction) and that there was no decisional interaction.

Discussion

Analyses of the means and probabilities of perceived size and maximum grip aperture suggested a weak illusion in verbal reports and no illusion in maximum grip aperture. That is, verbal reports were influenced by both the inside disk and outside circles, whereas maximum grip aperture was influenced only by the size of the inside disk. Such mean data and debates over what constituted a sufficiently strong effect, though, were the basis for contesting the conclusion that perception and action were independent in the first place. An important alternate hypothesis offered in that debate, which was tested in the present data, was that both perception and action relied on the same percept of size. The results of the present experiment showed that each report varied independently across repeated presentations of each stimulus. Such an effect suggests that the percepts corresponding to each response in this experiment were independent. Apparently, then, perceptual reports did not interact with the visuomotor response at the sensory, perceptual, or decisional levels (no interaction; see Figure 1). The source of the weak illusion in the verbal reports was not identified.

Experiment 2

A similar methodology was used in this experiment to evaluate the independence of verbal and manual reports of perceived size. Previous research has shown that manual reports of the perceived size of the inside circle (during a manual magnitude estimation task) were subject to the Ebbinghaus illusion (Haffenden & Goodale, 1998). The psychophysical test of perceptual independence was applied in the present experiment to determine whether the processes for verbal and manual reports were the same or whether they were two separate processes that interacted with each other at a sensory, perceptual, or decisional level.

Method

Participants. Eight (3 male, 5 female) students at Arizona State University participated in this study. Seven participants reported being right-handed, and 1 participant reported being left-handed.

Design. The design was similar to Experiment 1 except that verbal reports of perceived size were compared with manual reports of perceived size. On each trial, the participant was presented with a pair of Ebbinghaus illusion diagrams, one of which was a standard. The four-stimulus set was created with a factorial combination of the diameters of the inside circle and the outside circles. Participants did not grasp the inside circle, and so the circle in the center was not a raised disk. Both perceptual reports (verbal and manual) were recorded on each trial. The verbal report was obtained by having the participant identify which inside circle in the pair of Ebbinghaus illusion diagrams appeared larger. The manual report was obtained by having the participant match the size of the inside circles in each diagram using their thumb and forefinger. The matched size of the stimulus was coded as being either greater than or less than the standard. As in Experiment 1, then, there were four possible joint responses to each stimulus, m_-v_-, m_-v_+, m_+v_-, m_+v_+. The frequencies of each joint response were analyzed to test the interactions between the two reports.

Apparatus. A set of eight cards (38 cm × 50 cm) was created. Each card depicted a pair of Ebbinghaus illusion diagrams, one on the left and one on the right. One of the pair of diagrams was always the standard (I_s = 30 mm, O_s = 30 mm, line width = 1 mm), and the other was one of the four stimuli. To avoid a spatial bias, we depicted each of the four stimuli on two cards, once on the left and once on the right. The circle diameters corresponding to the two levels each of I and O were as follows: I_- = 27 mm, I_+ = 33 mm, O_- = 10 mm, O_+ = 90 mm. The line width on each stimulus was 1 mm. The distance between the edges of the inside circle and

Table 4
Microanalysis Estimates of Sensitivity (Conditional d′) and Bias (Conditional C) for Maximum Grip Aperture (m) and Verbal Perceptual Reports (v) in Experiment 1

Conditional d'		Conditional C	
Test	Result	Test	Result
Maximum grip aperture			
$d'_m(v_-\mid O_-)$	0.82	$C_m(v_-\mid O_-)$	−0.09
$d'_m(v_+\mid O_-)$	0.83	$C_m(v_+\mid O_-)$	−0.07
$t(7)$	−0.03	$t(7)$	−0.21
$d'_m(v_-\mid O_+)$	0.66	$C_m(v_-\mid O_+)$	0.11
$d'_m(v_+\mid O_+)$	0.78	$C_m(v_+\mid O_+)$	0.16
$t(7)$	−0.47	$t(7)$	−0.34
Verbal perceptual reports			
$d'_v(m_-\mid O_-)$	2.04	$C_v(m_-\mid O_-)$	−0.19
$d'_v(m_+\mid O_-)$	2.04	$C_v(m_+\mid O_-)$	−0.18
$t(7)$	0.00	$t(7)$	−0.17
$d'_v(m_-\mid O_+)$	2.11	$C_v(m_-\mid O_+)$	0.13
$d'_v(m_+\mid O_+)$	2.22	$C_v(m_+\mid O_+)$	0.03
$t(7)$	−0.53	$t(7)$	0.71

Note. Subscripts on d' and C identify the report for which the parameter was estimated. Terms in parentheses identify the levels (+ = greater than the standard; − = less than the standard) of the report and the stimulus dimension (O = size of the outer circles) at which the parameter was estimated. A statistical criterion of $p < .025$ was used for all tests.

the outside circles was 10 mm for each stimulus and for the standard. The number of outside circles on each diagram was as follows: For the standard there were 7 outside circles, for O_- there were 16 outside circles, and for O_+ there were 4 outside circles. The midpoints of the center circles in each pair of diagrams were aligned horizontally at a distance of 24.5 cm from each other.

The manual reports were made by having the participant open the thumb and index finger on his or her right hand as if to grab the outside edge of the center circle. The apparatus that was used to measure the distance between the thumb and index finger was constructed from clear plastic and is depicted in Figure 2. The participant's thumb was inserted into a hole in a block attached securely to the base. A second block was inserted into a groove that ran along the base. This block could move freely along the groove. The participant's index finger was inserted into a hole in this second block. With the thumb and index finger inserted in the proper holes, the participant could vary the span between the two by sliding the second block along the groove. The distance between the thumb and index finger was measured (in millimeters) on a ruler that was attached to the base on the side of the experimenter. This apparatus was mounted inside of a cardboard box (22 cm × 30 cm × 42 cm) so that the participant could not view his or her hand while making the manual report. A hole was cut into the side of the box facing the participant. The participant's right arm was extended into the box through this hole. A piece of cloth draped across the hole and over the forearm occluded the participant's view through this hole. The box was open to the experimenter who sat facing the participant so that the experimenter could record the manual reports.

Procedure. The participant sat at a table facing the experimenter. On the table in front of the participant was the box containing the manual report apparatus. All of the stimuli were stacked below the table and behind a curtain so that they remained out of the view of the participant for the entire session. The session consisted of 240 randomly ordered trials (30 trials for each of the 8 cards or 60 trials for each of the 4 conditions). In each trial, the participant made both a verbal and a manual comparison of the two inside circles in the pair of Ebbinghaus diagrams. Each participant was randomly assigned to make either the visual or manual report first in each trial. The card with the two diagrams was presented to the participant by holding it on top of the box containing the manual report apparatus. At this position, the card was situated above the participant's reporting hand at the participant's eye height. For the verbal response, the participant reported which of the two inside circles appeared larger. For the manual response, the participant used the manual report apparatus to indicate the size of each inside circle. The reported size (in millimeters) of each circle was recorded and the stimulus was coded as being reported to be greater than or less than the standard. For the two manual reports per trial (once for each diagram on a card), the participant was instructed to make one report by opening the fingers from their most closed position and to make the other by closing the fingers from their most open position; the participant could choose which to do first. The participant's choice here was not recorded. Participants were allowed to rest during the session. All of the procedures in this experiment conformed to the ethical guidelines of the American Psychological Association (2002).

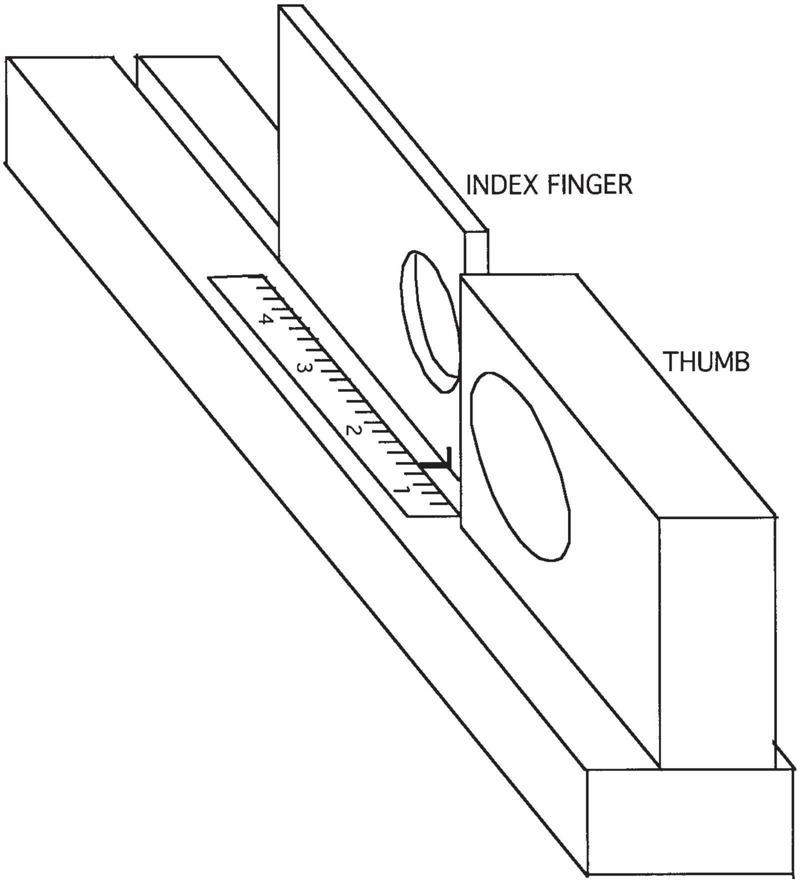

Figure 2. Apparatus used for obtaining the manual reports in Experiment 2. This apparatus measured the span between the thumb and index finger.

Results and Interpretation

Macroanalysis results. The results of the test of marginal response invariance are reported in Table 5. The size of the inside circle had a significant effect on both the verbal and manual perceptual reports. Participants were more likely to make *smaller* responses for the small inside circles and *larger* responses to the large inside circles. The effects of the outside circles, however, were mixed. For the manual reports, the pairs were significantly different in the direction predicted by the Ebbinghaus illusion. Participants were more likely to report that the inside circle was smaller when the outside circles were large and, conversely, to report that the inside circle was larger when the outside circles were small. For the verbal reports, though, there were no significant effects of the outside circles on the probability of reporting either *smaller* or *larger*. However, despite being nonsignificant, the verbal responses differed in a direction consistent with the Ebbinghaus illusion (i.e., more likely *greater* for the small outside circles and *smaller* for the large outside circles). This apparent lack of an effect may have resulted from a ceiling effect associated with correctly identifying the size of the inside circles that obscured a relatively small Ebbinghaus illusion.

Estimates of the marginal signal detection parameter d' across levels of each feature are reported in Table 6. Neither of the paired estimates of $d'(\mathrm{O})$ were significantly different. Each estimate of $d'(\mathrm{I})$ was evaluated against zero. For verbal reports, the values of $d'(\mathrm{I})$ were not significantly different from zero: $d'_{\mathrm{m}}(\mathrm{I}_-)$: $t(7) = 2.03$, $p > .025$; $d'_{\mathrm{m}}(\mathrm{I}_+)$: $t(7) = 2.04$, $p > .025$. The percepts associated with the verbal reports were unaffected by the size of the outside circles. For the manual reports, $d'(\mathrm{I})$ was significantly different from zero at both levels of I: $d'_{\mathrm{m}}(\mathrm{I}_-)$: $t(7) = 5.38$, $p < .025$; $d'_{\mathrm{m}}(\mathrm{I}_+)$: $t(7) = 3.28$, $p < .025$. The significant effects on $d'(\mathrm{I})$ indicate that increasing the size of the outside circles shifted the percept associated with the manual report.

Estimates of the marginal signal detection parameter C across levels of each feature are reported in Table 6. Both of the paired estimates of C across I were significantly different, indicating that participants were biased to report that the inside circle was smaller when it was actually smaller and biased to report that it was larger when it was actually larger. Both of the paired estimates of C across O were also significantly different. Participants adopted a selection criterion that was biased toward responding *smaller* when the outside circles were large and responding *larger* when the outside circles were large. For the verbal reports, this bias was the only place in which a significant effect of the Ebbinghaus illusion was demonstrated. For the manual reports, the Ebbinghaus illusion produced significant effects on both the percept and the decision bias.

Table 5

Test of Marginal Response Invariance for Manual Perceptual Reports (m) and Verbal Perceptual Reports (v) as a Function of the Size of the Center Circle (I) and the Outer Circles (O) in the Ebbinghaus Illusion Diagrams in Experiment 2

Manual perceptual reports		Verbal perceptual reports	
Test	Result	Test	Result
$P(\mathrm{m}_- \mid \mathrm{I}_-\mathrm{O}_+)$	.89	$P(\mathrm{v}_- \mid \mathrm{I}_-\mathrm{O}_+)$	1.00
$P(\mathrm{m}_- \mid \mathrm{I}_+\mathrm{O}_+)$	.30	$P(\mathrm{v}_- \mid \mathrm{I}_+\mathrm{O}_+)$	.21
$t(7)$	5.86**	$t(7)$	6.49**
$P(\mathrm{m}_+ \mid \mathrm{I}_-\mathrm{O}_-)$	.21	$P(\mathrm{v}_+ \mid \mathrm{I}_-\mathrm{O}_-)$	.07
$P(\mathrm{m}_+ \mid \mathrm{I}_+\mathrm{O}_-)$	.87	$P(\mathrm{v}_+ \mid \mathrm{I}_+\mathrm{O}_-)$	.99
$t(7)$	−9.52**	$t(7)$	−24.94**
$P(\mathrm{m}_- \mid \mathrm{I}_-\mathrm{O}_-)$	.79	$P(\mathrm{v}_- \mid \mathrm{I}_-\mathrm{O}_-)$	.93
$P(\mathrm{m}_- \mid \mathrm{I}_-\mathrm{O}_+)$	.89	$P(\mathrm{v}_- \mid \mathrm{I}_-\mathrm{O}_+)$	1.00
$t(7)$	−4.77**	$t(7)$	−1.93
$P(\mathrm{m}_+ \mid \mathrm{I}_+\mathrm{O}_-)$	.87	$P(\mathrm{v}_+ \mid \mathrm{I}_+\mathrm{O}_-)$	.99
$P(\mathrm{m}_+ \mid \mathrm{I}_+\mathrm{O}_+)$	.70	$P(\mathrm{v}_+ \mid \mathrm{I}_+\mathrm{O}_+)$	.79
$t(7)$	2.92**	$t(7)$	1.62

Note. Subscripts refer to greater than (+) or less than (−) the standard.
** $p < .025$.

Table 6

Macroanalysis Estimates of Sensitivity (Marginal d′) and Bias (Marginal C) for Manual Perceptual Reports (m) and Verbal Perceptual Reports (v) in Experiment 2

Marginal d'		Marginal C	
Test	Result	Test	Result
Manual perceptual reports			
$d'_{\mathrm{m}}(\mathrm{I}_-)$	0.51	$C_{\mathrm{m}}(\mathrm{I}_-)$	1.10
$d'_{\mathrm{m}}(\mathrm{I}_+)$	0.63	$C_{\mathrm{m}}(\mathrm{I}_+)$	−0.93
$t(7)$	−0.71	$t(7)$	5.97*
$d'_{\mathrm{m}}(\mathrm{O}_-)$	2.09	$C_{\mathrm{m}}(\mathrm{O}_-)$	−0.20
$d'_{\mathrm{m}}(\mathrm{O}_+)$	1.97	$C_{\mathrm{m}}(\mathrm{O}_+)$	0.37
$t(7)$	0.70	$t(7)$	−4.60*
Verbal perceptual reports			
$d'_{\mathrm{v}}(\mathrm{I}_-)$	0.29	$C_{\mathrm{v}}(\mathrm{I}_-)$	2.05
$d'_{\mathrm{v}}(\mathrm{I}_+)$	0.58	$C_{\mathrm{v}}(\mathrm{I}_+)$	−1.65
$t(7)$	−1.10	$t(7)$	10.53*
$d'_{\mathrm{v}}(\mathrm{O}_-)$	4.00	$C_{\mathrm{v}}(\mathrm{O}_-)$	−0.24
$d'_{\mathrm{v}}(\mathrm{O}_+)$	3.41	$C_{\mathrm{v}}(\mathrm{O}_+)$	0.64
$t(7)$	1.09	$t(7)$	−2.40*

Note. Subscripts on d' and C identify the report, and the terms in parentheses identify the level (+ = greater than the standard; − = less than the standard) of the stimulus dimension (I = size of the inside circle; O = size of the outer circles) at which the parameter was estimated.
* $p < .05$.

Macroanalysis interpretation. These analyses revealed a significant effect of the Ebbinghaus illusion on the manual reports and a weak effect on the verbal reports. The fact that the illusion appears in manual estimations of size has been shown previously by Haffenden and Goodale (1998). The present data, though, identified a source for this illusion. Specifically, increasing the size of the outside circles resulted in both a decrease of the percept and a decision bias toward responding *smaller*. The outside circles influenced both the sensory and decisional processes used to generate a manual estimation of size (i.e., both a sensory and decisional interaction for manual reports; see Figure 1). The effect of the illusion on verbal reports was weak. In fact, it was clearly evident only in the decision bias (decisional interaction for verbal reports; see Figure 1); participants exhibited a bias toward responding *smaller* for the large outside circles and *larger* for the small outside circles.

Microanalysis results and interpretation. The results of the test of sampling independence are reported in Table 7. A difference between the two probabilities in a pair would indicate that the two responses were correlated. None of the pairs of probabilities were significantly different. Manual and verbal reports were statistically independent for each stimulus. Variations in one percept of size did not induce variations in the other.

The results of the tests of conditional d' and C are shown in Table 8. These tests were used to identify whether sensitivity or decision bias were influenced by the other percept. None of the paired estimates of d' were significantly different for either the manual or verbal reports. The sensitivity of each percept was unaffected by the level of the other report. For both reports, though, the paired estimates of C were significantly different. These differences were all in a direction to suggest that participants adopted a decision criterion biased toward the level of the other report. That is, it appears as though there was a decisional interaction in these data (see Figure 1).

Discussion

Previous research has suggested that perception and action are independent but that verbal and manual perceptual reports are not (e.g., Goodale & Haffenden, 1998). This conclusion has been made on the basis of the observation that verbal and manual perceptual reports are subject to pictorial illusions of size whereas visuomotor control is not. In the present experiment, there was also a clear Ebbinghaus illusion for manual perceptual reports. Comparing the results of Experiments 1 and 2, then, we suggest that it is clear that the process of making a manual estimation response was not the same as the process of visuomotor control during actual grasping. Such an effect was expected and follows the distinction between manual perceptual reports and visuomotor control that has been made by Goodale, Milner, and colleagues (e.g., Goodale & Milner, 1992; Goodale et al., 1991).

Table 7

Test of Sampling Independence of Manual Perceptual Reports (m) and Verbal Perceptual Reports (v) for Each Stimulus in Experiment 2

Stimulus and test	Result
I_-O_-	
$P(m_-v_+)$	.03
$P(m_-)\cdot P(v_+)$	.05
$t(7)$	−1.91
I_-O_+	
$P(m_-v_-)$	.89
$P(m_-)\cdot P(v_-)$	.89
$t(7)$	0.00
I_+O_-	
$P(m_+v_+)$	.87
$P(m_+)\cdot P(v_+)$	.86
$t(7)$	1.00
I_+O_+	
$P(m_+v_-)$	.09
$P(m_+)\cdot P(v_-)$	.10
$t(7)$	−1.00

Note. Subscripts refer to greater than (+) or less than (−) the standard. A statistical criterion of $p < .0125$ was used for all tests. I = size of the inside circle; O = size of the outside circle.

Table 8

Microanalysis Estimates of Sensitivity (Conditional d′) and Bias (Conditional C) for Manual Perceptual Reports (m) and Verbal Perceptual Reports (v) in Experiment 2

Conditional d'		Conditional C	
Test	Result	Test	Result
Manual perceptual reports			
$d'_m(v_-\mid O_-)$	1.12	$C_m(v_-\mid O_-)$	0.39
$d'_m(v_+\mid O_-)$	1.12	$C_m(v_+\mid O_-)$	−0.69
$t(7)$	0.01	$t(7)$	7.15**
$d'_m(v_-\mid O_+)$	1.26	$C_m(v_-\mid O_+)$	0.72
$d'_m(v_+\mid O_+)$	0.75	$C_m(v_+\mid O_+)$	−0.29
$t(7)$	1.65	$t(7)$	4.11**
Verbal perceptual reports			
$d'_v(m_-\mid O_-)$	3.24	$C_v(m_-\mid O_-)$	0.28
$d'_v(m_+\mid O_-)$	3.21	$C_v(m_+\mid O_-)$	−0.60
$t(7)$	0.12	$t(7)$	6.31**
$d'_v(m_-\mid O_+)$	2.90	$C_v(m_-\mid O_+)$	0.85
$d'_v(m_+\mid O_+)$	2.49	$C_v(m_+\mid O_+)$	0.05
$t(7)$	1.53	$t(7)$	3.94**

Note. Subscripts on d' and C identify the report for which the parameter was estimated. Terms in parentheses identify the levels (+ = greater than the standard; − = less than the standard) of the report and the stimulus dimension (O = size of the outside circles) at which the parameter was estimated.

** $p < .025$.

The fact that the manual reports appeared more like perceptual than visuomotor responses, though, does not mean that both perceptual responses (verbal and manual) were the same. In fact, these data suggest that there is a distinction to be made between the two responses. First, the effects of the Ebbinghaus illusion on verbal reports were seen only in the decision criteria and were not apparent in any of the other analyses, as they were for manual reports. Second, the test of sampling independence showed that the percepts associated with the verbal and manual reports were independent. Even though the manual reports were subject to the Ebbinghaus illusion, they were still a function of a different percept.

Despite their independence, the present analyses identified decisional interactions in the processes for generating verbal and manual reports. Participants used two separate percepts, yet their responses were biased toward the percept associated with the other dimension. It remains to be determined, though, why these two perceptual reports should appear to be associated with unique percepts of size. One possibility is that unique, task-specific perceptual systems are assembled for each report (see Gibson, 1966; Runeson, 1977). Even though the participants are judging the size of the center circles in the same Ebbinghaus illusion diagrams, the different report modalities may lead to different cognitive processes. A second possibility is that the manual report system interacts with the action system in some way. However, this possibility cannot be evaluated with the present data. An experiment in which manual reports are compared with actual grasping could address this hypothesis.

General Discussion

Research has suggested that the mechanisms and processes serving visual perception may be independent from those serving the visual control of action. This conclusion was based in part on the observation that certain geometric illusions of size, such as the Ebbinghaus illusion, affect both verbal and manual reports of the perceived size but do not affect maximum grip aperture (e.g., Goodale & Haffenden, 1998). However, contradictory results from other studies have questioned this conclusion (e.g., Franz et al., 2000). The present studies were motivated by the fact that simply observing that two responses are similarly or differently affected by a particular stimulus is not sufficient to conclude that these processes are either identical or independent. There are multiple ways in which two such processes might interact, and so certain interactions may cause the responses to covary in some situations but not in others. The goal of the present experiments, then, was to adapt and use a psychophysical analysis of perceptual independence to identify whether and how verbal reports of perceived size interacted with visuomotor control (Experiment 1) and manual estimates of size (Experiment 2).

Interactions Between Processes

An important question regarding the independence of perception and action is whether the two processes use the same percept or two independent percepts. The primary test for assessing a perceptual interaction separately from the other potential interactions (sensory and decisional) was the test of sampling independence. The key in the present study is that statistical independence was evaluated within a single stimulus. As a result, the presence or absence of statistical independence could not be attributed to the variations in the information (in the present case, the size of the outside circles) that occurred across stimuli. The only variability was the natural variation in percepts that accompanied repeated presentations of a single stimulus. If both responses used the same percept, then they should have covaried under these conditions. However, when this test was applied in both Experiments 1 and 2, the two responses were always independent, which suggests that the percepts themselves were independent. It appears that the percepts for perception and action and for verbal and manual perceptual reports are independent.

Because the variability associated with changing one of the stimulus features is removed in this test, it is possible to evaluate the independence of two percepts even if both percepts are subject to the same illusion. That is, if each response is based on a unique percept, even if both percepts are subject to the illusion, then the variability in each perceptual effect across repeated presentations of the same stimulus should be independent. This fact has important implications for the debate over the independence of perception and action—namely, it is not possible to claim, as Franz et al. (2000) do, that the presence of an illusion on both perception and action implies that both are a function of the same internal representation. Although covariations in responding across stimuli are certainly relevant to the independence of perception and action in general, they are more specifically relevant to possible sensory interactions as opposed to perceptual interactions.

Although the two responses used independent percepts in both experiments, the effects of the illusion differed across the two nonverbal responses. There was a significant effect of the illusion on the manual matching response used in Experiment 2, but there was no significant effect on the maximum grip aperture recorded in Experiment 1. These results are similar to those of Haffenden and Goodale (1998), in which the illusion influenced manual estimation but not maximum grip aperture. The presence of an illusion in the manual matching task, however, did not indicate that one percept was used to control both manual estimation and the verbal response. The two percepts were independent. Rather, there was a sensory effect in which the illusion shifted the percept and a decisional effect in which the illusion introduced a bias in responding. This decisional effect was also seen in the verbal responses. It appears, then, that the participant making a manual estimation of size used a percept specific to that task but may have also taken advantage of the information available from the percept associated with the verbal response.

Future experiments with additional analyses may be able to provide convergent evidence to further support or extend these hypotheses. One issue that was a factor in the present experiments was the distinction between decisional effects resulting from changing decision criteria (that is, bias) and seeming decisional effects resulting from shifting the percepts relative to the decision criterion. This distinction was addressed through the analyses of $d'(\mathrm{I})$. The values of $d'(\mathrm{I})$ identified whether the percepts for the same inside circles differed as a function of the size of the outside circles. If there was no difference, then $d'(\mathrm{I})$ would have equaled zero. There were some situations, though, in which these values did not equal zero. This suggests that the percepts were shifted relative to the decision criteria. Thomas (1999) defined this phenomenon in detail (see also, Maddox, 1992) and offered a test based on the same analyses used in the present experiments. This test would not have been appropriate for these stimuli, though, because comparisons were made across pairs of stimuli that varied on both dimensions (that is, diagonal pairs). The obvious differences in the size of the outside circles would have made these pairs perfectly discriminable even if the inside circles, to which the participant should have attended, were not discriminable. Future experiments, however, could further investigate the sensory or decisional interactions in these phenomena through a careful application of Thomas's (1999) analysis (perhaps using different stimulus parameters or even another illusion) or through another response measure (such as a matching task) that would allow for an estimation of the multidimensional percept distributions (see Maddox & Dodd, 2003).

Ebbinghaus Illusion

The magnitude of the Ebbinghaus illusion in the present experiments was small. Even considering the fact that the magnitude of size contrast illusions is generally small (see Coren & Enns, 1993), the magnitude observed in the present experiments was smaller than that observed in other experiments using the same methodology (Coren & Enns, 1993). Other methods, though, can produce substantial increases in illusion magnitude. Using a method of magnitude estimation, Coren and Enns (1993) found an illusion magnitude of 6.10%. Studies that have used the Ebbinghaus illusion to investigate the independence of perception and action have used a modified matching procedure in which both the stimulus and the matching target were surrounded by outside circles (e.g., Haffenden & Goodale, 1998). Under these conditions, they reported a mean illusion magnitude of 8.13% (2.44-mm increase for a 30-mm target).

The fact that size contrast illusions are so sensitive to the experimental methods used suggests that the smaller magnitude found in the present experiments may have followed from the choice of stimuli and methods in the present experiments. In particular, the experiments were designed in order to demonstrate the Ebbinghaus illusion while producing sufficient "errors" (misses and false alarms) for the psychophysical analysis. Nevertheless, despite the fact that the magnitude of the illusion was smaller than usual in the present experiments, the psychophysical analysis of perceptual independence was sensitive to interactions between the two processes even in situations in which the illusion was weakened.

Conclusions

As others have suggested (e.g., Goodale, 1993; Goodale & Haffenden, 1998; Goodale & Milner, 1992; Goodale et al., 1991; Haffenden & Goodale, 1998, 2000; Milner & Goodale, 1993, 1995), the process of generating verbal reports of size is not identical to the process of generating either visuomotor responses or manual reports. The methods used in the present experiments were specifically designed to go further and identify the sources of interaction between two responses. Nevertheless, the present analyses share logic with previous studies on these same phenomena—namely, the influence of stimulus information was separated from the influence of an internal percept. These analytic tools allowed us to identify that verbal reports used a percept that was independent from the percepts used by either visuomotor or manual responses. However, it was also shown that the processes interacted at times either by using the same information or by introducing a response bias based on the other percept. Additional methods and analyses (e.g., Maddox & Dodd, 2003; Thomas, 1999) may be necessary in the future to further distinguish the effects at the sensory and decisional levels of processing.

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