The Müller-Lyer illusion in touch and vision: Implications for multisensory processes

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In six experiments, we used the Müller-Lyer illusion to investigate factors in the integration of touch, movement, and spatial cues in haptic shape perception, and in the similarity with the visual illusion. Latencies provided evidence against the hypothesis that scanning times explain the haptic illusion. Distinctive fin effects supported the hypothesis that cue distinctiveness contributes to the illusion, but showed also that it depends on modality-specific conditions, and is not the main factor. Allocentric cues from scanning an external frame (EF) did not reduce the haptic illusion. Scanning elicited downward movements and more negative errors for horizontal convergent figures and more positive errors for vertical divergent figures, suggesting a modality-specific movement effect. But the Müller-Lyer illusion was highly significant for both vertical and horizontal figures. By contrast, instructions to use body-centered reference and to ignore the fins reduced the haptic illusion for vertical figures in touch from 12.60% to 1.7%. In vision, without explicit egocentric reference, instructions to ignore fins did not reduce the illusion to near floor level, though external cues were present. But the visual illusion was reduced to the same level as in touch with instructions that included the use of body-centered cues. The new evidence shows that the same instructions reduced the Müller-Lyer illusion almost to zero in both vision and touch. It suggests that the similarity of the illusions is not fortuitous. The results on touch supported the hypothesis that body-centered spatial reference is involved in integrating inputs from touch and movement for accurate haptic shape perception. The finding that explicit egocentric reference had the same effect on vision suggests that it may be a common factor in the integration of disparate inputs from multisensory sources.

“Optical” illusions that also occur in touch (Fry, 1975; Robertson, 1902; Rudel & Teuber, 1963), even in the congenitally totally blind (Bean, 1938; Hatwell, 1960; Tsai, 1967), present a theoretical and practical challenge. The question is how inputs from very different sensory sources produce similar perceptual phenomena. Touch is of special interest in that regard. Touch, or haptic shape perception, involves inputs from multisensory touch, movement, and body-centered sources. The conditions that produce and reduce tactual illusions thus address an important aspect of the wider “binding” problem in intersensory processing that is not well understood. According to Helmholtz (1867), illusions arise from disparities in the very cues that normally produce accurate perception. In our view, accurate haptic shape and length perception depends on congruent spatial reference cues (Millar, 1994; Millar & Al-Attar, 2000). The implication that added reference information reduces the illusion and may also be involved in the similarity with vision was tested here with Müller-Lyer shapes.

The Müller-Lyer illusion is a striking example of a powerful involuntary illusion that occurs in touch as well as in vision. Müller-Lyer shapes consist of straight lines or

“shafts” that end either in diverging or in converging “fins.” The length of the shafts is overestimated in figures with diverging fins and is underestimated in figures with converging fins. The global shape and the constituent features of the figures produce discrepant cues to size. The reference hypothesis predicts that added reference cues should integrate or override the discrepancies and so reduce the illusion.

It was necessary first to check out two alternative hypotheses from studies of the visual Müller-Lyer illusion that could apply to touch, but have not yet been tested in touch. One is the movement time hypothesis. It explains the illusion by the time it takes to scan figures with divergent or convergent fins. The second is the distinctive feature hypothesis, which explains the illusion by the discriminability of fins from the shaft. Previous findings for the hypotheses, and the method of testing them, are briefly considered in turn in the following sections.

Movement Time

The movement time hypothesis is suggested in some studies of the visual Müller-Lyer illusion, though timing has not always been very precise. Visual Müller-Lyer figures with divergent fins required a longer exposure time, and figures with convergent fins took less time than expected (Erlebacher & Sekuler, 1969), suggesting that scanning time could also explain the haptic illusion. Shorter eye movement saccades for convergent than divergent figures

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(Festinger, White, & Allyn, 1968; Judd, 1905) and correlations between eye movements and unseen arm (pointing) movements have also been reported (Moses & DeSisto, 1970). Wong (1975) disputed the hypothesis that movement control mechanisms mediate the similarity of the illusion in touch and vision, on the grounds that the degree of excursive eye or hand movements had no effect on the visual or haptic Müller-Lyer illusion. But latencies were not tested directly.

Other haptic illusion have also suggested time-space (τ) effects. The length of felt pathways influences distance judgments in detour tasks, suggesting time- and/or movement-based heuristics (Lederman, Klatzky, & Barber, 1985). Speed as well as movement distance affects magnitude estimates of felt metal rods (Hollins & Goble, 1988). The haptic horizontal-vertical illusion (overestimation of verticals in L-shapes) has been attributed to speed differences between (radial vs. tangential) movements (Wong, 1977), though tests of the implied movement inertia assumption did not support the hypothesis (Marchetti & Lederman, 1983). The L-illusion actually differs in relation to the spatial frame in which the relevant movements are executed (Cheng, 1968). It has been found in 3-D space, for pivoting movements of the outstretched arm at shoulder height, relative to raised-arm movements toward the body, and with 3-D angular changes, but not for L-shapes scanned in the 2-D tabletop plane (Hatwell, 1960; Millar & Al-Attar, 2000). Such scanning involves mixed rather than opposed radial and tangential movements. We used a very precise method of measuring latencies for scanning movements (see Method) and found that latencies did not explain the haptic T-shape illusion, which also depends on comparing vertical and horizontal movements (Millar & Al-Attar, 2000).

Müller-Lyer judgments involve movements in the same direction, rather than different directions. But the discrepancies that produce perceptual biases are not identical for different illusions. The often-suggested hypothesis that scanning speeds account for the haptic Müller-Lyer illusion required direct testing. It predicts faster scanning of figures with convergent fins (hereafter referred to as convergent figures) and slower scanning of figures with diverging fins (hereafter, divergent figures). Latencies for scanning Müller-Lyer figures were, therefore, recorded and compared.

Distinctiveness in Shape Features

Visual studies have produced both low-level (perceptual) and high-level (cognitive) explanations of the illusion. They include effects of lateral inhibition, spatial frequency, saturation, fundus pigmentation, incorrect encoding of spatial primitives, and assimilation and adaptation effects, confusing endpoints of shafts, conflicting orientation cues, and demands on attention (Carrasco, Figueroa, & Willen, 1986; Coren, 1970; Dewar, 1967; Ebert & Pollack, 1972; Erlebacher & Sekuler, 1969; Fellows, 1967; Fraisse, 1971; Glennerster & Rogers, 1993; Predebon, 1996; Pressey,

1974; Pressey & Pressey, 1992; Wenderoth, 1992; Wenderoth & Wade, 1981). The illusion reduces with repetition (Day, 1962; Judd, 1902; Predebon, 1992, 1998; Rudel & Teuber, 1963), suggesting shifts in attention from fins to shaft or progressive feature differentiation with perceptual learning (Coren, Girgus, & Schiano, 1986; Dewar, 1967; Goryo, Robinson, & Wilson, 1984). But the same reductions occur without repetition during the first minute of inspection (Predebon, 1998). Similarly, instructions to ignore the fins are not effective on their own (Anii & Kudo, 1997). Specific additional perceptual cues seem to be needed (Coren & Porac, 1983; Goryo et al., 1984).

The explanations are not necessarily mutually exclusive (e.g., Predebon, 1996; Wenderoth, 1992). More important, they all depend on experimental manipulations that affect the discriminability of shaft from fins (Mack, Heuer, Villardi, & Chambers, 1985). Variables include the length, angle, number, and density of dots in fins, the size of shafts, temporal intervals between successively presented fins and shafts, and adding surrounding lines or differentiating colors. The accounts imply that the distinctiveness of fins is the most significant factor in the illusion.

The hypothesis that the illusion depends on the distinctiveness of features within the shapes could explain the illusion in touch. It predicts that distinctive fins reduce the illusion. The visual illusion was reduced, rather than eliminated, by any single differentiating cue. To test whether the distinctive cue hypothesis can explain the haptic illusion, we therefore enhanced the discriminability of the fins by combining texture and length differences for the fins in all tests. A subsidiary hypothesis, implied by the visual findings (see above), was that instructions to ignore the fins are effective, but only in conjunction with distinctive fins. It was tested with and without additional spatial cues (see below) in the final studies in vision as well as in touch.

Spatial Reference: Shape-Based, External, and Body-Centered Cues

The reference view proposes that accurate shape perception depends on congruent spatial cues from diverse sources. It is suggested by findings on haptic perception (Millar, 1981, 1985, 1994, 1997, 1999; Millar & Al-Attar, 2000). But neuropsychological as well as behavioral evidence suggests that modality-specific inputs converge in a number of distributed cortical and subcortical areas that are known to be involved in spatial tasks (Arbib, 1991; Duhamel, Colby, & Goldberg, 1991; Graziano & Gross, 1994; Meredith & Stein, 1996; Stein, 1992). The findings are consistent with the proposed further hypothesis that the convergence of congruent and disparate spatial reference cues from multisensory sources is also a likely factor in intersensory similarities.

The sources of spatial reference can be categorized roughly as shape based, based on external (allocentric) frames, and based on body-centered (egocentric) frames. The Müller-Lyer illusion suggests that the disparities arise within the shape, because the shaft and fins are integral

features of the global shape, but provide discrepant cues to length and size. The question was, therefore, how the discrepant shape cues in the figures relate to reference information from external and from body-centered sources. Effects of external and body-centered reference cues can be distinguished experimentally (e.g., Millar, 1985), and processing probably depends on connected rather than identical parts of the neural network "circuitry." Possible effects of external-reference frames on the Müller-Lyer illusion are considered first.

Previous evidence on effects of external-reference cues on the illusion is both sparse and equivocal. External background cues are important in vision (e.g., Pashler, 1990). However, the fact that they are routinely present in vision, but that the illusion occurs nevertheless, suggests *prima facie* that the external background information is either an additional factor in the illusion or at best fails to reduce it. Hatwell (1960) suggested that the presence of external cues makes vision less veridical than touch. The illusion was found to be larger with sight than without sight of the pointing hand (Mack et al., 1985). However, smaller illusions with than without visual feedback have also been reported (Gentilucci, Chieffi, Daprati, Saetti, & Toni, 1996). Over (1968) found that people were able to report both "objective" and "apparent" shaft length in vision, but not in touch, and argued that the presence of external background cues in vision makes judgments more accurate. However, so far facilitation or interference from EFs has been inferred from the presence of external cues in vision, in contrast to touch. It is not yet clear whether the presence of external reference serves to override or to enhance discrepancies in feature cues within shapes. We therefore tested the hypothesis that external spatial cues reduce the haptic Müller-Lyer illusion by providing an actual, easily felt EF that was scanned concurrently with the figures.

Body-centered spatial reference is probably more important in touch. Haptic perception involves kinesthetic cues from scanning movements, as well as touch cues (Gibson, 1962; Katz, 1925). But blind scanning movements are more accurate when start and end locations are related to body-centered anchor cues (Millar, 1985, 1994, 1997). Neuropsychological evidence shows that body-centered cues can provide reference information for movements (Howard & Templeton, 1966; Paillard, 1991; Sakata & Iwamura, 1978; Stein, 1992). Shape symmetry is not as easily detected in touch as in vision without body-centered (proprioceptive, gravitational, and posture) cues (Ballesteros, Millar, & Reales, 1998). Instructions to relate scanning to egocentric cues reduced the T-illusion in touch (Millar & Al-Attar, 2000). But the two illusions are not identical. We therefore tested the hypothesis that the haptic Müller-Lyer illusion is reduced by using body-centered cues for spatial reference, with explicit instructions that also alerted participants to the fins as the points of confusion. The hypothesis was also tested in vision in the final experiments.

The first experiment tested the movement time hypothesis and the hypothesis that discriminability of fins from shaft is the main factor in haptic Müller-Lyer illusions.

EXPERIMENT 1

The movement time hypothesis predicts latency differences for scanning divergent and convergent shapes that explain the difference in bias. The distinctive feature hypothesis predicts that the illusion is reduced more in figures with small, distinctively textured fins than in figures with large fins that have the same texture as the shaft.

Method

Design and Participants. A convergent/divergent shapes $\times$ fin size/texture $\times$ runs (repeated measures) design was used with the method of adjustment. Participants scanned the standard and then the comparison figure and adjusted the comparison length by stopping the scanning finger on or beyond the trajectory of the comparison line at the distance at which they judged the comparison line to equal the length of the standard figure.

Ten right-handed undergraduate and graduate (nonpsychology) student (5 male, 5 female, aged 18–27 years) volunteers participated. (Gender was routinely included as a factor in the analyses of variance [ANOVAs] of all experiments in the study, but produced no significant main or interaction effects, and will not be discussed further.)

Materials. Raised-line horizontal Müller-Lyer shapes were embossed professionally on heat-resistant, transparent plastic (21×30 cm) sheets. Test shapes had 8-cm, plain line, horizontal shafts and divergent fins, angled at 135° , or convergent fins, angled at 45° , relative to the shaft.

To maximize fin differentiation, the fins in half the convergent and divergent shapes were 1.4 cm in length and consisted of raised dots (hereafter, small textured fins). The other half of figures had 2.8-cm length plain fins of the same texture as the raised lines of the shaft (hereafter, large plain fins). On each test sheet, both the standard (scanned first) and the comparison (scanned second) figures had either large plain fins or small textured fins. Each test sheet contained a standard figure at 5.8 cm above a comparison figure. Convergent and divergent shapes were standard and comparison figures on counterbalanced test sheets. The comparison was thus always between divergent and convergent shapes, as in the Brentano version of visual figures (e.g., Predebon, 1998), except that, for practical reasons, the comparison figures were here presented below each other, rather than side by side with shared fins (Figure 1).

Video recording apparatus. The movement hypothesis required latency as well as error data. These were obtained by filming the hands moving over raised-line stimuli, from below transparent surfaces, synchronously with cumulative real (1/100 sec) time, and voice output, whereas stimulus figures were scanned normally. The recording device was housed in two interconnecting units above a (knee-hole) stand. The larger ($57 \times 66 \times 30$ cm) unit contained a plate glass (66×30 cm) reading surface, situated at normal table height (25 cm above the unit base; 76 cm above the floor). An (45°) angled mirror, attached below the reading surface, and flanked by two strip lights, reflected the movement of the hands and fingers above raised line (darkened) designs, embossed on transparent test sheets. A transparent ruler (in millimeters) was fastened to the underside of the reading surface. The image was picked up by the video camera (Panasonic Wv-155/B with Computar lens 12.5 mm F 1.3) that was housed in the interconnecting second ($43 \times 39 \times 49$ cm) unit. A video recorder (Panasonic NV 180), video timer (GYR G77), monitor, and microphone were linked into the system. Video (solid state) monitors provided visual and auditory outputs. The scan coils of the camera were reversed and the camera was inverted to give a normally oriented picture on the monitor. Touching a raised stimulus point produced a slight depression on the ball of the finger, which showed up on the monitor as a circular patch lighter than the surrounding skin. The midpoint of that patch was the reference location

Figure 1. Horizontal standard and comparison Müller-Lyer figures with divergent and convergent fins. The shafts are always 8 cm. In Set A, the fins are large (2.8 cm) and plain (smooth raised line). In Set B, the fins are small (1.4 cm) and textured (raised dots). Horizontal Müller-Lyer figures were used in Experiments 1–3. The vertical Müller-Lyer figures in Experiments 3–6 were identical, but were rotated by 90°. (The figures are not to scale. The shaft ends were felt in the raised line figures, and clearly seen in visual conditions; see text).

for the digital time, shown above the stimuli on the monitor, in that frame. Latencies were read off in frame-by-frame (40-msec) replay for every location, as required (Millar, 1997).

Procedure. In all experiments the shapes were presented in the tabletop plane. Participants were blindfolded and the task was explained prior to tests. Participants were asked to scan the standard and comparison figures with the index finger of their preferred (right) hand. Their task was to judge whether the horizontal line in the comparison figure was the same length, or longer or shorter than in the standard figure. They were to adjust the length of the comparison figure by stopping the scanning finger on the comparison line or beyond it on the same trajectory to the point at which they judged the comparison line to equal the length of the standard.

At the start of each trial, the experimenter placed the participant's right index finger on the standard shape. Participants were asked to scan the whole of the standard figure, as often as they wished, before moving down to scan the whole of the comparison figure, also as often as they wished. The order of test sheets was counterbalanced across participants and 16 (4 stimuli $\times$ 4 runs) trials.

Scoring. Errors in adjusting the comparison shaft to the length of the standard shaft were read off from the ruler underneath the reading surface. In all analyses, overestimations of the standard figure were scored by positively signed algebraic (constant) errors. Underestimations of standards were scored by negatively signed algebraic (constant) errors. Latencies were scored from first to last touch, separately for scanning standard and comparison figures.

Results and Discussion

Constant errors. Mean constant (in centimeters) errors are shown in Table 1. The gender $\times$ divergent/convergent

standard figure $\times$ fin size/texture $\times$ runs ANOVA showed a highly significant effect of divergent/convergent standard figures [$F(1,8) = 65.96, p < .0001$]. As predicted by the illusion, convergent standards were underestimated whereas divergent standards were overestimated. The factor interacted significantly with fin size/texture [$F(1,8) = 5.33, p < .05$]. Small textured fins produced smaller constant errors than did large plain fins, as predicted, but the difference was significant only for convergent figures ($t = -3.27, p < .01$), not for divergent figures.

The hypothesis that the discriminability between shaft and fins is a factor in the haptic illusion was supported only for convergent figures. Differentiating cues may be effective in touch only when the fin and shaft elements are in close proximity, as in convergent figures. Some people also veered slightly in moving down from standard to comparison shapes, possibly muting the fin size/texture effect additionally. But that could not, of course, explain the very significant difference between the negative illusion for convergent figures and the positive illusion for divergent figures.

Latencies. Mean latencies (in seconds) for standard shapes are graphed in Figure 2. Contrary to the movement time hypothesis, the ANOVA showed no significant difference between convergent and divergent standard figures. There was a significant effect of runs [$F(3,24) = 20.227, p < .0001$] and a tendency for an interaction between runs and the fin size/texture factor, but it did not reach

Table 1
Mean Constant Errors (in Centimeters) and Standard Deviations in Touch for Horizontal Convergent and Divergent Müller-Lyer Figures With Small Textured (SMT) and Large Plain (LP) Fins, With No External Frame (NF) and With an External Frame (EF)

	Horizontal Müller-Lyer Figures									
	Convergent					Divergent				
	SMT		LP		M	SMT		LP		M
	M	SD	M	SD		M	SD	M	SD	
NF	-0.49	0.51	-0.96	0.39	-0.73	0.48	0.67	0.54	0.60	0.51
EF	-0.88	0.55	-1.19	0.40	-1.04	0.53	0.36	0.52	0.34	0.53

significance [$F(1,8) = 4.658, p < .063$]. Latencies were reduced with repeated runs, and somewhat more for figures with large plain than with small textured fins.

The ANOVA on scanning latencies for the comparison shapes (Figure 3) also failed to show significant differences between convergent and divergent figures. Significant effects were found for fin size/texture [$F(1,8) = 9.56, p < .015$] and runs [$F(3,24) = 9.83, p < .0001$], as well as an interaction between these [$F(3,24) = 5.16, p < .007$]. Figures with large plain fins took longer to scan on the initial trial. But for the remaining runs there was no difference between these figures and figures with small textured fins.

The latency results for both standard and comparison figures provide evidence against the movement time hypothesis as an explanation for the substantial illusion shown by the error data. The distinctive fin hypothesis was supported for convergent fin figures, but the difference in dis-

tinctiveness did not reach significance for divergent fin figures. The findings suggest that distinctive fin cues are a factor also in the haptic illusion. But the fin cues were clearly not sufficient on their own to eliminate the illusion or to produce a reduction also in the overestimation of divergent figures.

EXPERIMENT 2

Experiment 2 tested the hypothesis that EF cues reduce the haptic Müller-Lyer illusion. Current external background cues are normally absent in touch without vision. The hypothesis was, therefore, tested by providing the external information quite literally by a square frame that could be felt to surround the figure (Millar, 1985). The frame was first explored with both hands, and the Müller-Lyer figures were then scanned in relation to the frame. The

Figure 2. Mean latencies (in seconds) in four runs to scan horizontal standards with divergent large plain fins, convergent large plain fins, divergent small textured fins, and convergent small textured fins.

Figure 3. Mean latencies (in seconds) in four runs for horizontal comparison figures with convergent large plain fins, divergent large plain fins, convergent small textured fins, and divergent small textured fins.

point was to provide maximum current external coordinate spatial information relative to the figures; that is to say, precisely the current external information that is most reduced in blind conditions.

Method

Design, Participants, Materials, and Procedure. An NF/EF $\times$ convergent/divergent shapes $\times$ fin size/texture $\times$ runs (between-subjects first factor) design was used with the same task as before. Twelve right-handed, naive high school student volunteers (8 female, 4 male) were tested in the new EF condition. The comparison was with the NF baseline condition.

The figures were precisely the same as in Experiment 1 except that test sheets were fastened to (20 $\times$ 20 cm) hard plastic squares (3.5-mm deep), which provided an easily felt square frame. Participants were asked to use both hands in parallel to explore the square frame initially. The preferred right hand was then used to scan the standard figure and moved down to scan the comparison figure, as before. The left hand was free to scan the frame concurrently as the right hand scanned the figure, so that the movements could be aligned. Errors in adjusting the shaft length of comparison (lower) figures were read off from ruler markings. The task and all other procedures were the same as in Experiment 1.

Results and Discussion

The ANOVA on mean constant (in centimeters) errors (Table 1) showed no significant main difference between NF and EF conditions ($p > .3$). The convergent/divergent standard figure difference was highly significant [$F(1,20) = 159.05, p < .0001$], showing the illusion. The fin size/texture factor was also significant [$F(1,20) = 5.89, p < .025$] and interacted significantly with convergent/divergent

standard figures [$F(1,20) = 7.08, p < .015$]. Convergent figures with large plain fins were underestimated significantly more than shapes with small textured fins [$t(21) = -3.82, p < .001$, two-tailed]. The difference was not significant for divergent shapes. Mean errors and the interaction of convergent and divergent figures with the fin size/texture factor is shown later (Figure 4) in a graph that combines all finding on touch.

The hypothesis that EF information reduces the illusion was not supported. If anything, the EF condition increased errors relative to the NF baseline condition for convergent figures (from -9.13% to -13%), although the difference was significant only in relation to the fin size/texture effect. It seemed possible that a difference in the direction of scanning movements was involved. Horizontal figures require mainly lateral scanning movements, but participants mainly scanned the frame concurrently in a downward direction.

Effects of the EF on the illusion were consequently tested further with vertical figures. Vertical figures depend mainly on downward scanning, so that the direction of scanning is congruent for the figures and the EF. Congruent vertical movements should also eliminate any "muting" of fin effects, if "veering" between shapes had been an added factor in the difference between fin effects for divergent relative to convergent figures.

EXPERIMENT 3

The experiment tested EF effects with vertical figures, so that the direction of scanning movements for the figures

and the frame were congruent. The hypothesis was again that relating scanning the figure to an EF reduces the Müller-Lyer illusion.

Method

Design, Participants, Materials, and Procedure. A figure orientation (horizontal/vertical) $\times$ convergent/divergent standards $\times$ fin size/texture $\times$ runs (between-subjects first factor) design was used with the same task as before. Twelve further naive (6 male, 6 female) volunteers of the same type of school and age group as participants in Experiment 3 were tested with identical, but vertically (90° rotated) oriented Müller-Lyer shapes. Standard (scanned first) shapes were located on the left and comparison shapes on the right of test plates. The distance between standard and comparison shapes was 5.8 cm.

On the initial trial with vertical figures, the experimenter placed the participant's right index finger on the standard shape, and on completion of the exploratory movement, guided the finger from the standard to the comparison shape. On subsequent trials participants moved across from standard to comparison shapes independently. Participants scanned the whole frame initially. They then scanned the figures with the right hand, using the left hand to scan the frame concurrently. All other procedures for the EF condition with vertical shapes were precisely the same as for the horizontal EF condition.

Results and Discussion

The figure orientation (horizontal/vertical) $\times$ convergent/divergent shape $\times$ fin size/texture $\times$ runs ANOVA on constant errors (Table 1) showed no significant fin size/texture effect. Figure orientation was significant [$F(1,22) = 13.76$, $p < .001$], due to an overall more negative mean for horizontal figures (−0.26 cm) and an overall more positive mean for vertical (0.20-cm) figures. The divergent/convergent figure effect was again highly significant [$F(1,22) = 200.83$, $p < .0001$] and did not interact with figure orientation. Both vertical and horizontal figures thus showed the significant underestimation of convergent figures, and the significant overestimation of divergent figures, that typifies the Müller-Lyer illusion.

Congruent vertical scanning of the EF relative to the figure clearly did not reduce the illusion. If anything, the EF cues increased the percentage of errors from horizontal to vertical figures (9.82%–12.63%), although the figure orientation effect was mainly due to a shift to larger positive errors for divergent vertical than for divergent horizontal figures (6.63%–15.13%). There was also a small shift from larger negative errors for convergent horizontal than for convergent vertical figures (from −12.93% to −10.06%, respectively). The comparison is graphed later (Figure 4) together with the other effects of experimental conditions on the illusion in touch.

It should be noted that the negative illusion for convergent figures, as well as the positive illusion for divergent figures, was as significant for the vertical as for the horizontal figures in the ANOVA. That could not be explained by a horizontal–vertical bias, as suggested by one reviewer. The haptic horizontal–vertical illusion could not apply here, in any case, since participants did not compare the vertical figures with horizontal figures at any time. The vertical/horizontal figure comparison was strictly statistical. Ver-

tical figures were used precisely to ensure that the main direction of scanning the figure and frame was identical.

The findings provided no support for the assumption that external reference frames reduce the illusion for vertical figures, either. On the contrary, relating the downward movements in scanning vertical figures to concurrent, mainly downward, scanning of the EF, seemed to make vertical scanning movements more salient, increasing the elongating effect of divergent fins. Effects of scanning movements explain the differences shown between vertical and horizontal divergent and convergent figures. The results suggest a modality-specific effect from scanning movements.

The next experiment tested the hypothesis that using body-centered spatial reference cues for the length of shafts reduces the illusion for vertical figures when participants are alerted to the site of the confusing information.

EXPERIMENT 4

As noted in the introduction, the reference hypothesis suggests that body-centered cues can provide spatial reference anchors for accurate haptic shape and length perception. In principle, egocentric cues were present in all conditions. Their presence alone clearly did not produce accurate length judgments here, possibly because discrepant length cues require a more precise or explicit use of spatial reference anchors. People are not usually aware of egocentric cues as factors in perception. It is also known that using the hands relative to each other and to body-centered postures to provide spatial anchor cues requires instruction and/or experience even for congenitally totally blind children (Millar, 1997, chap. 3), although such heuristics can become “automatic” quite early. Participants in the present study were therefore explicitly instructed to use the two hands relative to each other and to body-centered (midline) cues as reference anchors in judging shaft length.

The distinctive fin cues alone were evidently not sufficiently effective. In order to reinforce information for the shaft length, we combined instructions to use egocentric spatial cues with instructions to ignore the fins as points of confusion. The illusion is involuntary. As noted earlier, simply instructing people to ignore the fins was not effective in vision (Anii & Kudo, 1997). However, though restricting eye movements had no effect (Bolles, 1969), instructions to attend to a specially colored portion of the figure reduced the illusion, although it did not eliminate it (Coren & Porac, 1983; Goryo et al., 1984).

In touch, that particular instruction would be tantamount to asking people to scan only the shaft and not the fins. Instead, we asked people to scan the whole figure, including the fins, but to ignore the fins in judging the length of shaft relative to body-centered reference cues. We expected the instruction to add to the means of differentiating the end-points of the shaft in relating it to body-centered anchor cues.

The experiment tested the hypothesis that the haptic illusion is reduced by instructions to relate scanning move-

ments to self-referent cues in conjunction with instructions to ignore the fins.

Method

Design, Participants, Materials, and Procedure. An EF, self-referent instruction condition $\times$ convergent/divergent shapes $\times$ fin size/texture (repeated measures for the last two factors) design was used with vertical figures in the same task as before. The self-referent instruction condition included instructions to ignore the fins.

Participants in the self-referent instruction condition were 18 new high school volunteers, in the same age range (14–15 years) as participants in the previous EF condition. (The number of participants was increased, because the first 12 participants in the self-referent instruction conditions produced a highly significant reduction in the illusion. Since the result was important, it was decided to extend the number to ensure that the finding could not be attributed to individual difference factors.)

Vertical Müller-Lyer shapes were produced as before, but without the surrounding frame. The new instructions emphasized the relation of scanning the straight vertical line in the figures to the participant's body. As before, participants were asked to scan the whole of the standard and the whole of the comparison figure, as often as they wished to do so, before responding. They were informed that the arrowheads of the figures might make the straight line feel longer or shorter than it was. In adjusting the comparison length to equal the standard, they were to ignore, as far as possible, the tactile cues in the immediate neighborhood of the straight lines in both figures. Instructions emphasized that participants were to judge the comparison length by how long it felt and not by what they conjectured the answer ought to be. Tasks, scoring, and procedures were the same as before in all other respects.

Results and Discussion

Mean constant (in centimeters) errors (Figure 4) showed highly significant effects of instructions to ignore the fins and to use self-reference (SF) compared with EF instructions in the ANOVA for divergent standard figures [$F(1,28) = 65.85, p < .0001$]. The effect was also highly significant in the ANOVA for convergent figures [$F(1,28) = 38.79, p < .0001$]. There were no other effects.

The considerable reduction in illusion for divergent standard figures from 15.13% in EF instruction condition, to 2.06% with instructions to use SF and to ignore the fins, and for convergent standard figures from -10.06% in the EF condition to -1.44% with instructions to use SF and to ignore the fins instructions, is graphed in Figure 4. The finding, incidentally, further confirms that radial movements could not explain the illusions for vertical figures, since the errors were virtually eliminated, although the vertical scanning movements were precisely the same.

The near elimination of the haptic Müller-Lyer illusion is a new finding. It supports the hypothesis that the illusion is substantially reduced by using self-referent spatial cues for kinesthetic length inputs, consistent with the assumption that the illusion is due to discrepancies in length cues from constituent features inherent in shape.

We had used the additional instruction to ignore the fins in order to make the use of body-centered reference explicit to naive participants (see earlier) and to maximize the chances of reducing the tactile illusion by alerting participants to the misleading cues. The next question was, therefore, about the influence of the instruction to ignore

the fins. We decided to test the illusion in vision. The literature on the visual illusion shows that instructions to ignore fins reduced the illusion in conjunction with distinctive fin cues (see introduction). We argued that, if the instruction to ignore the fins is the main factor, it should reduce the visual illusion to near floor level, as in touch, when used with the same sets of vertical figures, which included figures with distinctive fins.

EXPERIMENT 5

The aim of Experiment 5 was to test the Müller-Lyer illusion as it is normally tested in vision and to add the conditions that previous studies have shown to reduce the visual illusion. As noted in the introduction, instructions to ignore the fins, though not effective on their own (Anii & Kudo, 1997), reduce the visual illusion when there are also distinctive perceptual cues that distinguish the fins from the shaft (Coren & Porac, 1983; Goryo et al., 1984). We used the same instructions to ignore the fins as in the previous touch (T+SF) condition, together with the sets of vertical figures that included distinctive fin figures. These conditions, therefore, conformed precisely to the conditions under which previous studies had shown a reduction in the visual illusion. As in the previous visual studies, normal visual conditions meant that participants had full view of the standard and comparison shapes, and were, of course, also able to see the external background throughout. As usual, visual conditions therefore also included external-reference cues. The hypothesis was, therefore, that in these conditions, instructions to ignore the fins would reduce the visual illusion for these figures to a similar level as the illusion in touch.

The point was to compare the visual and haptic illusion with the same figures, including the distinctive fins, and with the same instructions to ignore the fins, but in different reference conditions. The haptic condition lacked the external reference cues of the visual conditions, but used body-centered reference instructions instead. On the assumption that external reference cues, though ineffective or counterproductive in touch, are useful reference cues for the illusion in vision (see the introduction), whereas body-centered reference cues are more useful in touch, similar (low) levels of illusion would be expected for the two conditions.

It should be noted that the interest in comparing an illusion in two modalities is precisely because the illusion is the same, although the input conditions are totally different. In all haptic presentations, participants had always been able to scan standards and comparison shapes as often as they wished. But tactual scanning takes considerably longer than visual scanning. We therefore deliberately refrained from asking participants also to move back to and from the standards because prolonging scanning times yet further produces serious problems of boredom and fatigue. The objection of one referee, that moving back and forth repeatedly to standards would increase the similarity with vision, cannot be sustained. Prolonging tactual scanning

Figure 4. Mean constant (in centimeters) errors in touch for convergent and divergent Müller-Lyer figures in horizontal orientation without frame (NF) cues and with external frame (EF) cues, in vertical orientation with EF cues and with instructions to ignore the fins and to use self-reference (SF).

time even further beyond the visual inspection time would magnify rather than reduce the inevitable input differences between the two sense modalities. The alternative of making visual inputs similar to touch by sequential presentations would involve using point-by-point tunnel vision. That would totally alter the conditions that normally produce the visual illusion and would also make it pointless to compare results with previous findings on the visual illusion. There are no valid criteria for equating input conditions in different modalities, even though they may elicit different strategies. More important, to understand the basis of the similarity of illusions in different modalities, it is necessary to compare conditions that reduce the illusion in each, as well as in both modalities. The present experiment was designed to test the visual illusion in conditions that have previously been found to reduce it. These included EF cues but excluded body-centered reference. The important point was to compare these reference conditions with those we had found to reduce the tactual illusion. (In the event, as will be shown later, exactly the same visual input conditions showed different effects with different reference conditions and the same effects as in touch with the same reference conditions.)

Method

Design, Participants, Materials, and Procedure. A modality conditions $\times$ fin direction (convergent/divergents) $\times$ fin size/texture (first factor, between-subjects) design was used with the same task

and materials as before. Participants were 18 sighted (12 female, 6 male) volunteers from the same high school as participants tested in the tactual condition with instructions to ignore the fins.

The materials in the visual condition were the same as in Experiment 4. The transparent test sheets were placed on bright green mats so that the raised-line figures could be seen clearly. As in all previous visual studies, no mention was made of the background cues that are automatically available in normal visual conditions, including edges of tests sheets, table edges, and the like. Participants were instructed to look carefully at the figures and to see if the straight lines in the two figures looked as if they were the same length, or whether the comparison shape looked longer or shorter. They were to say "same" if the two lines looked the same. If the lengths looked different, participants were to run their finger along the comparison stimulus line to a point on the trajectory at which they judged the comparison to equal the standard.

In visual conditions, as in the tactual condition, participants were told that the arrowheads could give the impression that one of the straight lines in the figures looked longer or shorter than the other. Participants were asked to ignore the arrowheads when they looked at the straight vertical lines to judge the equality or inequality of the straight lines in the two figures. They were to adjust the comparison length by placing the finger on or beyond the comparison stimulus line to the point at which they judged it to equal the standard. The instructions emphasized that participants should judge by how the two lines looked to them and not by what they thought the length ought to be.

Results and Discussion

Mean constant (in centimeters) errors for visual condition are shown in Table 2. The ANOVA on divergent figures showed a highly significant modality conditions effect

Figure 5. Mean constant (in centimeters) errors for vertical convergent and divergent Müller-Lyer figures, with small textured and large plain fins, in vision with instructions to ignore fins (Vs), in vision with instructions to ignore fins and to use self-reference (Vs+SF), and in touch with instructions to ignore the fins and to use self-reference (T+SF).

[$F(1,34) = 16.22, p < .0001$]. The overestimation was larger in the visual condition ($M = 0.38$ cm) than in the touch conditions (0.17 cm). The effect of fin size/texture was significant [$F(1,34) = 11.61, p < .002$]. The illusion was larger for figures with large plain than with small textured fins. There was no interaction, but the difference was significant on a subsequent t test in the vision condition [$t(17) = 3.13, p < .006$, two-tailed], but not in the touch condition [$t(17) = 1.43, p < .172$].

The ANOVA on convergent figures (Table 2) also showed a highly significant modality effect [$F(1,34) = 24.40, p < .0001$]. The underestimation was larger for the visual condition. The fin size/texture effect was also significant [$F(1,34) = 16.43, p < .000$] and interacted with modality [$F(1,34) = 4.60, p < .039$]. Figures with large plain fins were underestimated significantly more than figures with small textured fins in the visual condition [$t(17) = 4.6, p < .0001$], but the difference was not significant in the touch conditions [$t(17) = 1.29, p = .213$].

The visual conditions here combined instructions to ignore the fins with distinctive fin cues because previous visual studies have shown that these conditions reduce the normal level of illusion. External reference cues are always present in visual backgrounds, whereas touch conditions lack external backgrounds but provide egocentric cues in-

stead. We therefore expected the visual condition and the touch (SF, Figure 4) conditions to produce comparable levels of illusions. That was clearly not the case.

The next experiment, therefore, tested the combined effect of instructions to ignore the fins and to use self-referent cues in vision, relative to touch. It was conducted partly as a control condition, suggested by a referee, but more specifically because it provided a test of whether the same (self-referent) instructions/conditions have similar effects in vision as in touch.

EXPERIMENT 6

The hypothesis was that the same instructions that reduced the illusion in touch (i.e., T+SF) would reduce the illusion in vision to the same level as in touch. The new visual condition (i.e., Vs+SF) was therefore tested with instruction to use body-centered (self-referent) cues, combined with instructions to ignore the fins, as in the T+SF condition.

Method

Design, Participants, Materials, and Procedure. The experiment was designed to compare the Vs+SF condition with the original visual condition from Experiment 5 and with the T+SF condition, which used identical instructions. Participants in the Vs+SF

Table 2
Mean Constant Errors (in Centimeters) and Standard Deviations for Vertical Convergent and Divergent Müller-Lyer Figures, With Small Textured (SMT) and Large Plain (LP) Fins, in Vision (External Cues Present) With Instructions to Ignore Fins (Vs), and With Instructions to Ignore Fins and to Use Self-Referent Cues (Vs+SF)

	Vertical Müller-Lyer Standard Figures									
	Convergent					Divergent				
	SMT		LP		<i>M</i>	SMT		LP		<i>M</i>
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>		<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	
Vs	-0.28	0.21	-0.56	0.32	-0.42	0.26	0.20	0.50	0.30	0.38
Vs+SF	-0.14	0.15	-0.17	0.14	-0.16	0.12	0.13	0.17	0.22	0.15

condition were 12 (8 female, 4 male) further volunteers, tested with instructions to ignore fins and to use self-referent cues, as in touch.

Materials, procedures, tasks, and instructions were identical with the vision condition in the previous experiment, but included the explicit self-referent instructions used for touch (T+SF) in Experiment 4. The wording in vision indicated that participants should scan the lines relative to their body in judging the lengths.

Results

The ANOVA comparing errors (in centimeters) in the two visual conditions (Table 2) showed significantly larger overestimation of divergent figures for the previous visual condition than for the Vs+SF condition [$F(1,28) = 11.78$, $p < .002$]. The fin size/texture effect was significant for both visual conditions [$F(1,28) = 8.50$, $p < .007$]. Similarly, the ANOVA comparing the two visual conditions for convergent figures showed that the previous visual condition produced a significantly greater underestimation error than the Vs+SF condition [$F(1,28) = 11.86$, $p < .002$]. The fin size/texture effect was significant [$F(1,28) = 16.44$, $p < .0001$]. There was an interaction with the visual conditions [$F(1,28) = 10.37$, $p < .003$]. On a t test the size/texture effect was significant only for the first visual condition [$t(17) = 3.13$, $p < .006$, two-tailed], suggesting that distinctive cues were more important for that condition.

The two visual conditions, which were identical in input conditions and differed only in self-referent instructions, differed significantly in the level of the illusion. It is important to note that the difference resembled that between vision without SF instructions and touch with self-referent instructions that had been found in Experiment 5.

By contrast, the illusion in vision (Vs+SF) and in touch (T+SF) with same self-referent instructions did not differ significantly from each other either in the ANOVA on divergent figures ($p = .358$), or in the ANOVA on convergent figures ($p = .794$), and produced no significant fin size/texture effects ($p = .315$ and $p = .073$, respectively).

There were small residual errors in touch (T+SF) and vision (Vs+SF) for convergent figures (-0.12 and -0.16 cm, respectively) and for divergent figures (0.17 and 0.15 cm, respectively), which differed significantly from zero on one-sample t tests ($p < .01$). It is very unlikely that errors of less than 2 mm would be seriously misleading in practice in touch. Eliminating even the residual errors completely may depend on combined effects with additional modality-specific fin and movement effects that are considered in the General Discussion.

The near elimination of the illusion also in vision with instructions to use SF as well as to ignore the fins, which no longer differed from touch, contrasts with the significant illusion found in the first visual condition.

These findings show that same reference instruction reduces the illusion in both modalities to near zero. The comparisons are all graphed in Figure 5.

GENERAL DISCUSSION

The virtual elimination of the Müller-Lyer illusion in touch and in vision by explicit instructions to use body-centered cues for spatial reference and to ignore the fins is an important finding that has not been reported before. It provides new evidence that the same conditions reduce a powerful illusion in touch and in vision to near zero effects. The findings on alternative factors tested by the hypotheses here are considered in turn.

The movement time hypothesis has to be rejected. Scanning time can, of course, be a valid indication of distance, and is often used as such. But the latency data could clearly not explain the haptic Müller-Lyer illusion shown by the errors.

The hypothesis that the distinctiveness of fins is a factor in the illusion was supported by findings for the first visual condition. Interestingly enough, the finding is entirely consistent with previous results on the visual illusion in the same conditions (see the introduction). But the results here also show that distinctive fins are not the main factor in the illusion. They failed to reduce the illusion to near floor level even in vision. Moreover, the difference in touch, where distinctive fins affected only horizontal convergent figures in which the fins are in close proximity to the shaft, suggests that effects of distinctive fins depend on modality-specific conditions. The results suggest that cue distinctiveness is a contributory factor that has to be considered in some conditions. But it does not explain the illusion in either vision or touch.

The hypothesis that external-reference information reduces the haptic illusion has to be rejected also. Haptic conditions typically lack external background cues. But concurrent scanning of the actual external frame that was provided here did not reduce the highly significant illusion for vertical or horizontal figures. The frame here was designed to substitute for external coordinate information. The present findings suggest that it was not used as such

here. However, the frame had some effect in that it elicited mainly downward scanning movements. They explain the significant subsidiary differences for vertical and horizontal divergent and convergent figures and suggest that modality-specific effects from scanning movements may have to be taken into account in some conditions. But external reference is evidently not a major factor that either increases or decreases the haptic Müller-Lyer illusion.

External background cues were present in both the visual conditions, as in all previous studies of the visual illusion. The literature (see the introduction) suggests both that external visual backgrounds contribute to the illusion and that they serve to reduce it. In this study, the presence of external cues, combined with distinctive fins and instructions to ignore the fins, failed to reduce the visual illusion to near floor effects. Insofar as visual background cues enhance global shape perception, they may even increase the effect of the discrepancies inherent in Müller-Lyer shapes. That needs specific visual tests, which were beyond the present paper. It is nevertheless of interest that almost all participants in the second visual condition commented spontaneously that they found the instruction to use body-centered cues a hindrance rather than a help, although the illusion was, in fact, drastically reduced. These comments suggest that the instructions interfered with a normal habit of viewing the figure as a whole.

By contrast, the hypothesis that body-centered reference produces more accurate shape perception was supported, in conjunction with instructions that were designed to draw attention to the fins as misleading cues. It should be noted that body-centered information was also present in all other haptic and both the visual conditions. But only explicit instructions to use body-centered cues for reference and to ignore the fins reduced the illusion effectively in touch and in vision. Egocentric coding was thus the potent factor in the near elimination of the illusion in vision and touch. But its use evidently required explicit instruction. People are normally unaware of the body-centered (proprioceptive and gravitational) cues that influence accurate perception (e.g., Howard & Templeton, 1966). Instruction and/or experience is required even by congenitally blind children to use body-centered cues explicitly as spatial reference anchors for scanning movements (Millar, 1997).

It is not assumed here that egocentric spatial reference is the only integrating factor in processing multisensory inputs, much less that modality-specific information is irrelevant. The effects of distinctive cues and of two-handed scanning movements suggest the contrary. It cannot be assumed that processing is either purely cognitive or entirely peripheral. The role of body-centered cues in reducing perceptual discrepancies in both sensory modalities is intelligible, since they are constantly present, and coincide in time, in all perceptual modality (including visual) conditions. They are thus a relevant factor in intersensory processes. This interpretation is consistent with evidence on the convergence of inputs from touch and vision in areas of the cerebral cortex (e.g., postparietal) that are involved in

egocentric spatial processes (Arbib, 1991; Duhamel et al., 1991; Stein, 1992). But explicit use of egocentric reference seems to be needed to counteract effects of contradictory perceptual cues to size from the fins and shaft that are integral features in Müller-Lyer shapes.

The findings have practical implications for shape perception in blind conditions. These relate particularly to instructions for the early stages in learning to use tactile maps and other raised-line displays. Müller-Lyer configurations actually occur as road junctions in maps and produce perceptual errors (Gilliam & Schmidt, 1999). Explicit instructions on how to proceed and to gain relevant reference information seem to be important. Adding distinctive fin cues and anchor cues for scanning movements may also serve to eliminate residual effects of the illusion for practical purposes. Tests, including specific location cues for tactile maps, are in progress.

The important new evidence shows that the same explicit instructions reduced a powerful illusion to near zero effects in both touch and vision. This result suggests that the similarity of the illusion in the two modalities is unlikely to be fortuitous. The findings on touch support the hypothesis that the use of (at least initially explicit) body-centered reference is an important factor in integrating inputs from touch and movement for accurate haptic shape and length perception. They also suggest that it is a significant factor in the similarity of the illusion in vision and touch and in intersensory processing of inputs from different sources.

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