The effect of the Müller-Lyer illusion on map reading

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One important reason for studying visual illusions is that they can influence real-world perception as people interact with human-made displays. Three experiments examined how the Müller-Lyer illusion affects distance judgments and decision-making in the complex graphical context of a map by having subjects estimate the lengths of road segment lines framed by inward-going or outward-going wings in actual maps, in control displays that had the map context removed, and in simulated maps. The experiments showed that (1) outward-going wings led to higher distance estimates than did inward-going wings to the same extent both with and without the map context, (2) decisions based on distances determined from maps were affected by Müller-Lyer elements in the maps, and (3) map readers' measurement behavior influenced the effect of the Müller-Lyer elements in maps. The discussion focuses on how certain display manipulations and task manipulations affect the Müller-Lyer illusion. In addition, the discussion addresses the instances in which using a map might be affected by misestimation due to Müller-Lyer elements.

Psychologists study visual illusions for three primary reasons. First, visual illusions provide a clear illustration that the human perceptual-cognitive system does more than simply record the input from the world around us with perfect accuracy. Rather, these illusions show that factors, such as the context in which a stimulus occurs, influence people's perceptions. This illustrative function of illusions may account for their popularity in introductory psychology texts (for examples, see Myers, 1993; Sternberg, 1995).

Second, illusions can help psychologists to understand how the perceptual-cognitive system operates. Some illusions reveal general operating principles, such as the collaboration of bottom-up and top-down processes in perception. For example, analyses of the Müller-Lyer illusion suggest that bottom-up processes such as lateral inhibition and top-down processes such as the application of size constancy contribute about equally to produce the illusion (e.g., Coren, Porac, & Ward, 1984). In contrast, other illusions reveal the specific operating principles of certain mechanisms. For example, the Pulfrich effect involves placing a dark filter over one of an observer's eyes and swinging a pendulum in a plane parallel to the observer's

body; this creates an illusion in which the pendulum appears to be swinging in an ellipse toward and away from the observer. The primary mechanism that produces this effect is binocular disparity—a mechanism that is elicited by a slight delay in processing the pendulum by the dark-adapted eye (Emerson & Pesta, 1992; Gregory, 1973).

Third, visual illusions can affect people's perception as they interact with human-made displays in the real world. Much of the research on illusions in these everyday perceptual situations has emphasized designers' purposeful use of illusions. Examples include Rubens's use of the Poggendorff illusion in *Descent from the Cross* (Topper, 1984) and landscape painters' use of monocular visual cues to produce the perception of apparent depth (Coren & Girgus, 1978). Studies of displays that unwittingly include an illusion have been rare. One exception is Poulton's (1985) demonstration that a Poggendorff illusion exists in some line graphs and has its greatest effect in graphs with two calibrated y-axes.

The research reported in this paper provides another example of an illusion unwittingly included in everyday displays: the Müller-Lyer illusion in maps. Maps are complex visual displays that format information in a way that helps users solve navigational and spatial problems, including estimating distances. Maps directly relate display space to real-world space (Gillan & Lewis, 1994). However, map-makers often purposefully distort the representation of aspects of the space in order to reflect accurately other aspects (for examples, see Monmonier, 1991). In contrast to these intentional distortions, the presence of illusions might accidentally introduce an error into readers' perceptions of

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a map. Due to the convergence of line segments, maps often contain outward-going and inward-going wings that resemble elements of the Müller-Lyer illusion. Figure 1 shows examples of Müller-Lyer elements found in a part of a map of the Chicago area. We invite our readers to examine street maps and road atlases for other examples. If the Müller-Lyer elements in maps distort a map reader's perception of line lengths, then map readers might misestimate the distance displayed in a map.

Maps are complex displays containing many lines other than those framed by elements of the Müller-Lyer illusion. The Müller-Lyer illusion has principally been studied with backgrounds containing no distracting lines. The additional lines in the map might interfere with the effect of the Müller-Lyer elements and, as a consequence, reduce or eliminate the illusion in the context of a map. Previous studies have shown that certain variations in the display of the Müller-Lyer illusion can substantially reduce the effect (Coren & Girgus, 1978; Larsen & Garn, 1988; Sadza & deWeert, 1984; Wenderoth & Wade, 1981).

Consider how the lines in a map might affect two commonly discussed mechanisms for the Müller-Lyer illusion: lateral inhibition and the application of size constancy due to a misreading of the depth cues (e.g., Coren et al., 1984; Schiffman, 1996). The lateral inhibition hypothesis suggests that the lines forming an inward-going wing create an area of retinal inhibition that overlaps the central line, leading the viewer to perceive it to be shorter than it actually is. Likewise, an outward-going wing creates an area

of inhibition that affects the perception of the empty space beyond the central line, leading the viewer to perceive that line to be longer than it actually is. Additional map lines near and going through the Müller-Lyer elements (as in Figure 1) should produce their own areas of inhibition that might affect the perception of the wings and/or the line that they frame. Thus, this complex pattern of excitation and inhibition might be expected to influence the illusory effect induced by the Müller-Lyer elements, with the specific effect depending on the configuration of the map lines and their relation to the Müller-Lyer elements.

The size constancy hypothesis proposes that a line framed by outward-going wings looks like the corner of a room, whereas a line framed by inward-going wings looks like the outside edge of a building. In other words, the lines with their wings appear to be two-dimensional projections of three-dimensional space (Gregory, 1974). Because a room corner recedes away from the viewer, whereas a building corner projects toward a viewer, viewers misread the Müller-Lyer elements as indicating depth. As a consequence, the viewer applies size constancy to the central lines, resulting in an expansion of the line that appears to be far away (i.e., the line framed by outward-going wings) and a reduction in the length of the line that appears to be closer (i.e., the line framed by the inward-going wings). It might be reasonable to expect that if the Müller-Lyer illusion were embedded in a map and the viewer interacted with the display as if it were a map, the viewer would interpret the display and its various elements

Figure 1. Section of a map of the Chicago area in which numerous Müller-Lyer elements can be seen to frame road segments. For example, notice the double outward-going line near Island Lake.

as two-dimensional. Increasing the two-dimensionality of the display might decrease the likelihood of misreading inward- and outward-going wings as depth cues, thereby decreasing any misapplication of size constancy.

EXPERIMENT 1

Experiment 1 examined the Müller-Lyer effect using actual maps. The Müller-Lyer elements selected for this experiment were representative of the typical Müller-Lyer illusion in that they consisted of a shaft and two accompanying wings. However, uncharacteristic of textbook versions of the illusion, the elements were not attached to two lines in parallel. Also, as is characteristic of lines found in actual maps, wing angles and line orientation varied among the stimuli. In order to increase the external validity of the experiment, no effort was made to control these factors. As such, the results of this experiment are based on subjects' interacting with unaltered Müller-Lyer elements found in real maps. An effect of those Müller-Lyer elements on the judgment of road segment distances would support the hypothesis that the Müller-Lyer illusion can cause map-reading errors in real-world contexts. In addition, for comparison purposes, a second group of subjects judged the length of lines framed by Müller-Lyer elements outside of the map context. For this group, we eliminated from the maps all of the lines other than the one to be judged and the Müller-Lyer elements that framed it. Thus, the map group and the nonmap group made judgments of identical lines. Any differences in the strength of the Müller-Lyer illusion between the groups would be attributable to the differences in the backgrounds. Subjects judged line length by means of magnitude estimation (Stevens, 1962).

Method

Subjects. Thirty undergraduate students at New Mexico State University volunteered as subjects to fulfill course requirements.

Stimuli. Stimuli were found on various state and close-up maps in the Rand McNally 1992 Road Atlas. Twenty-four road segments containing variations of Müller-Lyer elements served as experimental stimuli. The 10 stimuli with inward-going wings and the 14 stimuli with outward-going wings were actual unaltered road segments found in the maps. The maps were redrawn using a drawing software application (DeskPaint) and simplified by eliminating nonroad lines (e.g., county lines) and minor roads for the map group. The simplification was more substantial for the nonmap group with all lines other than the line to be judged and the framing Müller-Lyer elements being eliminated. Figure 2 shows examples of both a map given to the map group (Figure 2A) and the comparable stimulus given to the nonmap group (Figure 2B).

Because the purpose of the experiment was to examine the effects of naturally occurring Müller-Lyer elements in maps, the road segment line lengths (i.e., the shafts) varied unsystematically. The lengths of the shafts varied from 1.5 to 15 cm. Each map also contained a legend, located in the upper right corner of the display; the legend included a common standard line that measured 3.3 cm and had a modulus value of 9 miles.

All of the displays for both groups were presented on an Apple-Vision 14-in. monitor using a Macintosh Quadra 610 computer, by means of a program specially developed for this experiment with

Authorware authoring software. The Authorware program presented the displays to each subject in a different irregular order and recorded the distance estimate on each trial.

Procedure. The subjects received brief instructions on map reading, including the proper use of a legend (i.e., the standard and modulus). The subjects were told that they could examine the legend and use it in estimating distances as often as needed. They were instructed not to use any measuring devices but only to "eyeball" the stimuli. When a subject indicated that he or she fully understood the task, the trials began.

The subjects received one map display per trial and received each map display on two trials during the experiment, with the maps presented in a different order for each subject. On each trial, the subjects first received a display that contained the names of the street or town markers that bordered the road segment to be estimated. Then the subjects pressed a software-based button to show the map. Using the names from the previous display, the subjects located the referred-to road segment and estimated its length.

Results and Discussion

Figure 3 shows the functions relating magnitude estimates to the length of the road segments in the displays for both inward-pointing and outward-pointing wings for the map and nonmap groups. The subjects' estimates were related to the length of the legend and, as a consequence, were in miles as displayed on the map. Similarly, the actual road segment length in Figure 3 is shown in map miles (based on the scale from the legend of 9 map miles per 3.3 cm). Thus, if the subjects accurately estimated the road segment lengths, the linear regression slopes should be close to 1.0. The figure indicates that, for both groups, the slopes for the regression functions were below 1.0 when the lines were framed by inward-going lines, but the slopes for the regression functions were above 1.0 when the lines were framed by outward-going lines.

The regression functions shown in Figure 3 are similar for the map and nonmap groups. A hierarchical multiple regression analysis of the data using the general linear model¹ also indicated that the type of display (map vs. nonmap) had no appreciable impact on the estimates: The *F* values were less than 1.0 for the main effect of type of display and for all interactions between type of display and all other variables. The design of Experiment 1 provided sufficient power to detect nontrivial differences between the map and nonmap groups in their responses to the inward-going and outward-going wings. The power to detect a display type $\times$ wing type interaction at $\alpha = .05$ with the present experimental design was above .99 (Cohen, 1977); thus, the Type II error rate was less than .01. The power to detect a display type $\times$ wing type $\times$ length interaction at $\alpha = .05$ with the present experimental design was .93 (Cohen, 1977); thus, the Type II error rate was equal to .07.

For the map group, the regression analysis, estimated length = $a + b_1(\text{wing type}) + b_2(\text{line length}) + b_3(\text{wing type} \times \text{line length})$, found that the rate of increase in magnitude estimates across the various road segments depended on the type of wing framing the segment [line length $\times$ wing type interaction, $F(1,14) = 89.44$, $p < .0001$]. For the nonmap group, the regression analysis also

Figure 2. Examples of a display used with the map group (A) and the corresponding display used with the nonmap group (B). The subjects judged the distance from Thomasville to Valadosta.

showed that the rate of increase in estimates as the road segment length increased depended on the wing type [line length $\times$ wing type interaction, $F(1,14) = 53.06$, $p < .0001$].

The regression parameters showed that the effect of the wing type $\times$ length interaction was comparable for the two groups. The parameter estimates were similar (b values of .36 for the map group and .42 for the nonmap group), as were the standardized parameter estimates (β values of .20 and .18, respectively). The pattern of the analyses examining the effect of the type of display suggests that presenting Müller-Lyer elements in a map con-

text does not reduce the effect of the illusion. This finding does not mean that the display characteristics would never affect the Müller-Lyer illusion. For example, background lines that obscured the Müller-Lyer elements would probably reduce or eliminate the illusion. Rather, our conclusion is that the typical map displays used in Experiment 1 did not measurably reduce the strength of the Müller-Lyer illusion.

The hypothesis that motivated this experiment was that subjects would overestimate distances represented by lines framed by outward-going wings relative to inward-going wings when presented with these Müller-Lyer ele-

Figure 3. Mean magnitude estimates in Experiment 1 of the lengths of lines framed by inward-going wings and outward-going wings in map and nonmap displays. The solid and dashed lines show the best-fitting linear regression functions for the outward-going and inward-going wing types, respectively.

ments in a map. The significant interaction between line length and wing type and the regression slope parameters in the map group support that hypothesis.

Because we used versions of real-world maps, the lengths of the lines framed by inward-going wings tended to be longer than those framed by outward-going lines, and the line lengths framed by the outward-going wings covered a wider range. However, because the regression functions for the inward-going lines were based only on lines greater than 7 cm, they may not provide a good estimate of the per-

ceived length of short lines. Thus, in the subsequent experiments, the lengths of lines framed by inward-going wings equaled those framed by the outward-going wings.

The finding in this experiment that naturally occurring Müller-Lyer elements in a map produce misestimation of distances in that map raise three additional issues related to the generality of the effect. First, did the subjects overestimate the length of the lines framed by outward-going lines, underestimate the length of the lines framed by inward-going lines, or both? The regression slope para-

meter estimates in Figure 3 suggest that the subjects probably both overestimated lines framed by the outward-going wings and underestimated lines framed by inward-going wings. To further address this question, we used a control in Experiment 2 in which straight line "wings" framed the line segments. Second, although the subjects estimated perceived distances differently as a function of the framing lines in Experiment 1, they did not have to make any decisions or perform any actions based on those perceptions. People frequently undertake map reading in the real world as part of a decision-making task. Would the Müller-Lyer elements also influence decisions that might be based on the distance judgments? Experiment 2 also addressed this question. Third, in certain real-world settings, people will "eyeball" the maps (as they did in Experiment 1), but, in other settings, they might mark off distances with their fingers or even make use of rulers. Although it seems likely that making a precise measurement with a ruler would eliminate any effects of Müller-Lyer elements, would less precise measurement (e.g., finger marking) also eliminate these effects? In other words, how does a readers' behavior influence the Müller-Lyer illusion in maps? Experiment 3 examined the conditions under which people use eyeball estimates and the impact of the map readers' measurement behavior on the Müller-Lyer illusion in map reading.

EXPERIMENT 2

The three purposes of Experiment 2 were (1) to examine the effect of the Müller-Lyer illusion on people in a task that involved decision making based on reading a map rather than simple distance estimates, (2) to control for the differences in length between the lines framed by inward-going and outward-going wings in Experiment 1, and (3) to compare decisions made when subjects examined maps with inward-going and outward-going wings with those made when they examined maps with control wings.

To meet the first objective, we created a scenario in which we told subjects that they owned Cactus Jack's, a company that provides people with a desert hiking experience. One of the subjects' tasks was to decide the amount of water that hikers would need to take, on the basis of the assumption that a group of 10 hikers would need a total of 10 quarts of water per mile of hiking. Hikers who had to carry too much water would be weighted down, become fatigued (perhaps dangerously so), and either pay Cactus Jack's a discounted rate because they had an unpleasant experience or require money due to medical expenses. On the other hand, hikers who carried too little water would become dehydrated (perhaps dangerously so) and also either pay Cactus Jack's less money because of their unpleasant experience or be paid money to cover medical costs. Thus, the only way that the subject as company owner could get paid the full amount in this scenario

would be to estimate the amount of water accurately (within an allowable margin of error). Half of the subjects received feedback on each trial concerning the amount of money that they had made or lost, whereas the remaining subjects received feedback only at the end of the experiment. The feedback manipulation allowed us to examine whether performance feedback would affect any impact of the Müller-Lyer elements.

To meet the second and third objectives, we showed subjects the desert hiking trails on computer-displayed maps specially created for this experiment. Each map contained a target line that subjects were told was the hiking trail. We systematically varied the trail line lengths and the framing lines (straight, inward-going, and outward-going) but had the same trail line lengths represented under each of the framing conditions.

Method

Subjects. Thirty undergraduate students at New Mexico State University volunteered as subjects to fulfill course requirements.

Stimuli. Forty-five different maps, created for this experiment, were designed to resemble real maps (see Figure 4 for an example). Although each map contained many lines, one line was designated as the trail line. The trail line varied in length (2.2, 4.4, 8.8, 13.2, and 17.6 cm) and in the wings framing it (perpendicular, inward-going, and outward-going). The inward-going and the outward-going wings formed a 90° angle (i.e., 45° angles with the trail line), whereas the control wings formed a 180° angle (i.e., 90° angles with the trail line). The position of the trail line on the map and its orientation varied nonsystematically. Each map contained a legend in the upper right corner of the map 3.2 cm in length, which was labeled as "9 miles." Each of the 15 combinations of trail line length and framing line type were replicated three times in maps with different surrounding lines, for a total of 45 unique maps.

Apparatus. All trials were presented using software developed for this experiment with the authoring application, Authorware, and a Macintosh Quadra with an Apple AudioVision 14-in. monitor. The software presented the trials in an irregular order and recorded the subjects' estimates of the amount of water needed.

Procedure. The subjects received the instructions that described the scenario underlying the experiment. In addition, the instructions (1) told the subjects to determine the amount of water needed on the basis of 1 quart per mile for each of the 10 hikers in a group, (2) stressed the importance of making an accurate decision about the amount of water, and (3) described the benefits and costs of their decisions (an accurate decision paid off \$1,000, a slightly inaccurate decision paid off \$500, a moderately inaccurate decision cost them \$500, and a very inaccurate decision cost them \$1,000). In addition, the instructions asked the subjects to round their estimates to the nearest quart, since Cactus Jack's would only be able to provide quart containers. After they read the instructions, the subjects received three practice trials with one map per trial; the practice maps contained the straight line wings. On each practice trial, the subjects decided the amount of water needed. When a subject indicated that he or she fully understood the task, the trials began.

The subjects received one map per trial and received each map only once during the experiment, with the maps presented in a different order for each subject. On each trial, the subjects first examined a screen that provided the names of two map locations (e.g., "Estimate the water needed to travel from Lakeview to Iron Spring"). The subjects then pressed a software-based button on the screen labeled "Ready to see map," which took them to the screen containing

Figure 4. Example of a display used in Experiment 2.

the map. The subjects located the referred-to trail and, after determining the amount of water, pressed a software-based button labeled "Go to answer," which took them to the response screen. On the response screen, the subjects typed in the number of quarts of water needed and hit the Return key. Then, the subjects in the no-feedback condition ($n = 15$) simply had the screen display a button labeled "Continue." In contrast, the subjects in the feedback condition ($n = 15$) received feedback concerning their response. If a subject decided on the correct amount of water (10 times the number of miles between the two map locations identified, within ± 10 quarts), the feedback was "Good job! You estimated the correct amount of water." If the subject's response was ± 20 quarts different from the correct answer (note that responses were in multiples of 10), the feedback was either "Sorry, you estimated a little low. Your hikers will become a little thirsty" or "Sorry, you estimated a little high. Your hikers will become a little tired." If the subject's response was ± 30 quarts different from the correct answer, the feedback was either "Sorry, your estimate was very low. Your hikers are very thirsty" or "Sorry, your estimate was very high. Your hikers are fatigued." If the subject's response was ± 40 quarts (or greater) different from the correct answer, the feedback was "Sorry. Your estimate was extremely low. Your hikers are dangerously dehydrated," or "Sorry. Your estimate was extremely high. Your hikers are dangerously fatigued." In addition, the feedback display showed Cactus Jack's current financial status in the lower right corner. The subjects started the experiment with \$20,000.

After completing the 45 trials, the subjects filled out a seven-statement questionnaire concerning the usability of the system. All seven questions involved a response on a 7-point scale of agreement with a statement (1 = *strongly disagree*, 7 = *strongly agree*). Three statements concerned the map (ease of reading, accuracy of reading, and ease of understanding how to use maps), three statements concerned the computer displays (ease of reading, accuracy of reading,

and ease of understanding how to use the display), and one statement concerned the system as a whole (the system is a good way to present information needed).

Results and Discussion

Figure 5 shows the mean amounts of water that the subjects decided they would need as a function of the length of the trails and the type of wing framing that trail line in the map. As in Experiment 1, the graph shows length in terms of the mileage displayed on the maps. If the subjects accurately perceived the line lengths and selected 10 quarts of water per mile (i.e., 1 quart per mile for each of 10 hikers), then the regression slope parameter should be 10. Note that the slope parameter for the lines framed by the control wings is 10.5. In contrast, the slope parameters for the lines framed by Müller-Lyer elements depart markedly from 10 (12.3 for outward-going wings and 8.7 for inward-going wings). Also, the relation of the regression slope parameters between the outward-going and inward-going wing conditions in Experiment 2 resembles that for the map group in Experiment 1 (1.2 and 0.8, respectively).

The subjects' decisions about the amount of water needed increased as the length of the trail line segments on the maps increased [$F(4,56) = 688.82, p < .0001$]. Of particular interest for the hypothesis of this experiment, the wing type influenced the subjects' decisions about the amount of water needed [$F(2,28) = 4.84, p < .05$], and the rate of increase in the amount of water needed as a function of line length depended on the type of wing framing

Figure 5. Mean amount of water selected as a function of line length with map trail lines framed by inward-going, outward-going, or control wings in Experiment 2.

the trail line [line length $\times$ wing type interaction, $F(8,112) = 12.77$, $p < .0001$]. The presence of feedback about the accuracy of the decision concerning water had no effect on the subjects' decisions about the amount of water either as a main effect or in interactions with line length or wing type (all F s < 1.0).

Additional analyses compared each Müller-Lyer element with the control condition. Comparing the control condition with the inward-going wings yielded a significant interaction between wing type and trail line length [$F(4,56) = 17.85$, $p < .0001$]; comparing the control condition with the outward-going wings also yielded a significant interaction between wing type and trail line length [$F(4,56) = 14.62$, $p < .0001$]. Thus, in these maps, the outward-going wings increased the amount of water that subjects decided to take relative to a control condition, whereas the inward-going wings decreased the amount of water that the subjects decided to take relative to the control.

Although feedback had no effect on the subjects' decision about the amount of water needed, it had a pronounced

effect on the subjects' ratings of the usability of the map, display, and system. For every statement, the subjects in the feedback condition gave lower ratings (indicating lower agreement with the statement) than did the subjects in the no-feedback condition. Table 1 shows the mean ratings for both conditions for all questions, as well as the associated F and p values. Thus, the effect of frequent performance feedback was to reduce markedly the ratings concerning the usability of the map, display, and system. Since the feedback was frequently negative, the effect of feedback on usability ratings may have been because the subjects did not like hearing that they had made the wrong decision.

One purpose of this experiment was to examine the effect of Müller-Lyer elements on map reading under more controlled conditions than were permitted with the real-world maps of Experiment 1. Specifically, would we observe the same effects if the line lengths were equivalent across the different types of wings, and would a control condition with straight line wings produce results in the middle of the inward-going and outward-going wings? The results of Experiment 2 provide further support that

Table 1
Mean Ratings of Agreement With Statements in the Posttest Usability Questionnaire in Experiment 2 for Feedback and No-Feedback Conditions

Statement Topic	Feedback Condition Mean Rating	No-Feedback Condition Mean Rating	F	$p <$
Map: Ease of reading	3.8	5.7	14.1	.01
Map: Accuracy	4.1	5.4	12.0	.05
Map: Comprehension	2.8	5.4	21.4	.01
Display: Ease of reading	4.5	6.0	7.5	.05
Display: Accuracy	4.6	5.9	4.1	.07
Display: Comprehension	2.6	5.9	23.4	.01
Information Presentation	3.1	5.6	46.0	.01

Müller-Lyer elements in maps can influence map-reading performance. A second purpose of Experiment 2 was to examine whether the subjects' type of response influenced the effect of Müller-Lyer elements on map reading: If the subjects had to make a decision based on their reading of a map, would the Müller-Lyer elements continue to have an effect? Both the main effect of wing type and the interaction between wing type and line length indicate that the Müller-Lyer elements in a map influence decisions that people make using those maps.

EXPERIMENT 3

Perception in a real-world context can be strongly influenced by the perceiver's behavior. For example, sound localization based on interaural differences in intensity and time creates a zone of confusion because those differences are the same for sounds at the same angle in front of or behind the hearer's ear or for sounds at the same angle above and below the ear. Likewise, sounds coming from any point on the median plane bisecting the hearer's body cannot be localized well because of the lack of interaural differences. However, hearers in the real world resolve any confusion by engaging in the simple behavior of turning their head (e.g., Schiffman, 1996). Touch provides additional examples of the subject's behavior influencing perception, with perception differing among (1) cutaneous touch in which the perceiver passively experiences an object, (2) haptic touch in which the perceiver actively feels the object by moving his or her hands over and around it, and (3) dynamic touch in which the perceiver grasps, lifts, and/or carries an object (see Turvey & Carello, 1995, for a review).

Because perception of maps is important in a real-world context, Experiment 3 focused on the ways in which map-reading behavior might moderate the effect of Müller-Lyer elements on distance estimation with maps. First, we wanted to observe people's map-reading behavior, particularly their use of measurement devices as a function of their task and the display hardware. Second, we wanted to determine whether the use of measurement devices influenced the effect of the Müller-Lyer elements on estimating distances. Experiments 1 and 2 showed that Müller-Lyer elements influenced perception of maps when people did not use any measurement devices (i.e., "eyeballing" the map). Not surprisingly, we hypothesized that using a precise measurement instrument, such as a ruler, would eliminate any effect of the Müller-Lyer elements. However, what would happen if subjects engaged in potentially less precise measurement behavior—for example, marking off distances on a map line by successive pointing with their fingers?

To examine map-reading behavior, we used two scenarios related to taking a trip. The scenarios were a within-subjects variable. In one condition, we told subjects that they were planning in advance of the trip and would be es-

timating distances as part of that plan. In the other condition, we told them that they were driving their car and had to estimate distances. We made precise measurement devices—including a ruler and a compass—available to subjects and instructed them to use whatever devices they would normally use in these conditions. We also had subjects view the maps on one of two media: one group had the maps displayed on paper, and the second group had the identical maps displayed on a computer.

We hypothesized that subjects would be reluctant to take their eyes off the road for an extended period of time while driving and so would be more likely to use "eyeball" measurement in that scenario. In addition, we predicted that subjects would be more comfortable touching a paper-based display than a computer-based display, and so "eyeball" measurement would be most prevalent with the computer and use of measurement devices would be more likely with paper maps. Accordingly, subjects should be most likely to use measurement devices when planning a trip using paper-displayed maps and most likely to eyeball when in the driving scenario using the computer-displayed maps.

Method

Subjects. Twenty-six undergraduate students at New Mexico State University volunteered as subjects to fulfill course requirements.

Stimuli. In general, the maps were similar to those described for Experiment 2 (see Figure 4 for an example). Of most importance, the wing types on the road segments of the maps were the same as those described for the inward-going and outward-going wings in Experiment 2. The two major differences in the displays in this experiment relative to Experiment 2 were (1) the road segment lengths were 0.7, 1.8, 2.7, 3.1, 4.7, 6.1, 6.7, 7.6, 8.8, 9.8, 10.8, 12.1, 12.8, and 14.1 cm and (2) the legend in the upper left corner of the display, which was labeled for the subjects to consider it to have a map length of 9 miles, was 2.9 cm in actual length.

Apparatus. For Group Computer ($n = 13$), all trials were presented using software developed for this experiment with the authoring application, Authorware, and a Macintosh Quadra with an Apple AudioVision 14-in. monitor. The software presented the trials in a random order and recorded the subjects' estimates of the distances. For Group Paper ($n = 13$), the maps were printed (using a laser printer on 8×10 in. sheets of paper) from the same graphic files as those used to develop the software for Group Computer.

Procedure. The subjects in each medium group received both task scenarios, with 6 subjects in each group receiving the planning scenario first and 7 subjects in each group receiving the driving scenario first. In the planning condition, they were told to judge the distances as if they were at home planning a trip that they would take subsequently; in the driving condition, the subjects were told to judge the distances as if they were in a car en route to their destination on a trip, and they had to look at a map while driving. The subjects had a transparent plastic ruler, a plastic compass, pens, pencils, and paper available to them on every trial. Neither the experimenter nor the instructions prompted or encouraged the use of any measurement device; rather, the instructions simply told the subjects to judge the distances as they normally would under each scenario condition.

Each subject received 28 maps in both of the scenario conditions: one map for each of the 14 road segments framed by inward-going

Figure 6. Frequency with which the subjects in Experiment 3 used eyeball estimates, finger pointing, finger pinching, or ruler-based measurements as a function of task scenario (driving vs. planning) and map presentation medium (computer vs. paper).

wings and the 14 road segments framed by outward-going wings. Thus, the subjects received 56 maps in total. The subjects in the paper group received all of their maps on paper. On each trial, the subjects would be given the names of two locations that would be on the map, then would turn to the map, find the locations, and judge the distance using magnitude estimation by typing in the estimated distance into a computer file. The maps were presented in a different irregular order for each subject. The subjects in the computer group received their maps presented on the Apple AudioVision monitors by means of the Authorware program, which controlled a different irregular order for each subject and recorded the subject's distance judgments.

Results and Discussion

Map-reading behavior. The subjects' behavior while reading the map was categorized and recorded on each trial by a double-blind observer. The observed categories of behavior were (1) measuring distance with a ruler, (2) using the index finger to mark off successive segments on the map line (point), (3) using the index finger and thumb spread apart to mark off successive segments on the map line (pinch), and (4) using no external measurement devices (eyeball). Despite having other potential measurement devices—a compass, pencils, and paper—available, no subject used any of them for measuring. Figure 6 displays the proportion of trials that subjects selected a behavior as a function of medium and scenario.

All of the map-reading behaviors were sensitive to some aspects of medium and scenario. Because the data involved frequency counts, the analysis used the logistic regression model, $\text{behavior} = a + b_1(\text{medium}) + b_2(\text{scenario}) + b_3(\text{medium} \times \text{scenario})$ (see Pedhazur, 1997). (Scenario was centered, with drive = .5, and plan = -.5; medium was centered with computer = .5, and paper = -.5.) Due to zero frequency counts for finger pinching in three of the four medium-scenario conditions, only eyeball, pointing, and ruler use was analyzed. The use of eyeball-based estimation was significantly affected by medium, scenario, and their interactions: eyeball = $1.2 + 2.3(\text{scenario}) + 2.8(\text{medium}) + 1.6(\text{scenario} \times \text{medium})$, with Wald chi squares of 98.4 (for scenario), 148.5 (for medium), and 12.0 (for the interaction) (all $ps < .001$). The use of pointing was significantly affected only by the medium $\times$ scenario interaction: pointing = $-3.1 - 0.4(\text{scenario}) - 0.3(\text{medium}) - 5.2(\text{scenario} \times \text{medium})$, with Wald chi squares of 1.0, 0.8, and 49.8 ($p < .0001$), respectively. The use of the ruler was significantly affected by the scenario and the medium, but not by the interaction: ruler = $-2.2 - 3.4(\text{scenario}) - 2.3(\text{medium}) + 1.1(\text{scenario} \times \text{medium})$, with Wald chi squares of 103.3 ($p < .0001$), 49.1 ($p < .0001$), and 2.7 ($p > .10$), respectively.

The results show that presenting maps by computer to the subjects in the driving scenario elicited eyeball esti-

Figure 7. Mean magnitude estimates in Experiment 3 on trials in which the target line on the map was framed by inward-going or by outward-going wings as a function of the measurement behavior on that trial: eyeball estimation, estimation in which the subjects used their hands (i.e., finger pointing or finger pinching), and estimation using a ruler.

mates on almost every trial. Presenting maps on paper to the “driving” subjects still elicited primarily eyeball estimates but resulted in some use of measuring devices, primarily using a hand. The subjects in the driving scenario rarely used the ruler. In the planning scenario, the subjects looking at the map on the computer continued to make eyeball estimates primarily, with a small amount of pointing or use of the ruler. In contrast, when the subjects looked at the map on paper to plan a trip, they used the ruler on most trials, with the remaining judgments based almost exclusively on eyeball estimates.

Road segment length estimates. Figure 7 shows the road segment length judgments from trials in which the subjects made eyeball estimates, trials in which the subjects used their hands in making estimates (by pointing or finger pinching), and trials in which subjects used a ruler

in making estimates. As in the figures for Experiments 1 and 2, Figure 7 shows the length variable in terms of mileage on the map based on the legend. Thus, accurate estimates of perceived mileage plotted as a function of map mileage would result in a regression slope parameter close to 1.0. Of all of the regression lines in Figure 7, only the slope for the estimates on trials in which the road segments were framed by outward-going wings when the subjects eyeballed the maps shows a marked departure from 1.0. When the subjects estimated by eyeball, the slope on trials in which the road segments were framed by inward-going wings was not as far below 1.0 as we observed in Experiments 1 and 2. Partly as a consequence, in Experiment 3, the difference between the slopes of the regression functions for the outward-going and inward-going conditions was smaller than in Experiments 1 and 2.

We performed separate statistical analyses of the estimates of line length as a function of the map-readers' behavior. Each analysis examined the effect of the two independent variables—the physical length of the road line and the wing type—and their interaction. As in Experiments 1 and 2, the Müller-Lyer elements significantly affected judgments when the subjects eyeballed the maps. On eyeball estimate trials, the subjects made significantly higher estimates when the road was framed by outward-going wings than when it was framed by inward-going wings [$F(1,12) = 23.88, p < .0001$], and the slope of the regression function relating road length to the subjects' estimates was greater for the lines framed by outward-going wings than for those framed by inward-going wings, resulting in a line length $\times$ wing type interaction [$F(13,156) = 1.95, p < .05$].

For the analysis based on other measurement behaviors, we combined the trials with pointing and those with finger pinching. Both responses involved use of the hand as a measurement instrument, and too few subjects used finger pinching to permit an accurate analysis of those trials alone. When the subjects used their fingers for pointing or pinching off the distance or used a ruler, the wings had no effect on distance estimates [for the main effect of wing type, $F(1,7) = 2.84, p > .05$ (on pointing/pinching trials), and $F(1,9) = 3.99, p > .05$ (on ruler-measured trials); for the wing type $\times$ line length interactions, $F(13,21) = 1.14, p > .05$ (on pointing/pinching trials), and $F(13,102) = 1.61, p > .05$ (on ruler-measured trials)].

The hypotheses that motivated this experiment focused on people's behaviors in a map-reading task as a function of the task scenario and display medium and the impact of those behaviors on the effect of Müller-Lyer illusion elements. Concerning subjects' behaviors in the judgment task, we hypothesized that (1) they would shift from eyeball estimation to device-based measurement (using their hands or an external device) as they moved from a driving scenario to a planning scenario and (2) the group that received computer-presented maps would tend to use eyeball estimation, whereas the group that received paper-based maps would tend to use the available measurement devices. We hypothesized that the impact of these behaviors would be that the use of measurement devices would reduce or eliminate any effect that Müller-Lyer elements might have on distance judgments. The results largely support these hypotheses.

The subjects strongly tended to use eyeball estimation under three of the four task-medium conditions—driving and computer, driving and paper, and planning and computer. Moving from computer to paper decreased the frequency of use of eyeball estimation; in the case of the driving scenario, the hand-based measurement techniques showed marked increases, but ruler use did not increase substantially. The planning scenario resulted in markedly more use of measurement devices, with the ruler being the predominant tool for planning a trip with a paper map. Although these results were predicted and are both inter-

pretable and sensible, some caution in generalizing the results is warranted. The subjects were not really driving and did not have a full array of possible measurement devices.

GENERAL DISCUSSION

The three experiments in this paper provide the following findings concerning the Müller-Lyer illusion and map reading: (1) In both real-world maps and experimental displays that simulated maps, converging lines that produce outward-going wings resulted in overestimation of distances, and lines that produce inward-going wings resulted in underestimation of distances (Experiments 1 and 3); (2) the Müller-Lyer elements affected decisions related to distance judgment (Experiment 2); (3) the map context neither decreased nor increased the effect of Müller-Lyer elements significantly (Experiment 1); (4) the subjects' measurement behavior with maps was a function of their task and the display medium—subjects in a driving scenario looking at a computer-displayed map appear to have a strong tendency to use eyeball estimation, whereas subjects in a trip planning scenario looking at a paper-displayed map appear to have the strongest tendency to use external devices, particularly a ruler (Experiment 3); and (5) the effect of the Müller-Lyer illusion on distance judgment depended on the subjects' measurement behavior with the maps—use of either a ruler or a finger to “mark off” distances eliminated the effects of the illusion (Experiment 3), but eyeball estimation of distance was influenced by the illusion (Experiments 1–3). Thus, the present research provides additional evidence that real-life displays that inadvertently contain illusions will affect users' perception. These experiments go beyond previous such research (Poulton, 1985) to identify certain boundaries on the conditions under which the Müller-Lyer illusion affects map reading. As Experiment 3 suggests, Müller-Lyer elements are likely to be a factor when quick estimates are required and/or when map readers may be reluctant to touch the display with a measurement device.

Why do certain manipulations of the physical features of the display of the Müller-Lyer illusion decrease the size of the illusion (e.g., Coren's, 1970, use of dots at the end points of the wings and the vertices of the wings and center line), whereas other manipulations have little or no impact (e.g., presenting the illusion embedded in a map in Experiments 1–3; see also Hanowski, 1993, and Schmidt & Gillan, 1996)? A simple answer might be that manipulations that disrupt the psychological mechanisms underlying the illusion should diminish the effect of the illusion proportionally to the degree of disruption. In contrast, manipulations that do not disrupt those underlying mechanisms would have no impact on the size of the illusion. In other words, the size of the illusion might be a linear combination of the activation of the various underlying mechanisms. Coren and Girgus (1978) used this approach in their multimechanism analysis of the Müller-Lyer illusion (see also McClellan, Bernstein, & Garbin, 1984). Thus,

by this explanation, placing the Müller-Lyer illusion in the context of a map appears not to affect any underlying mechanisms.

An analysis of the map-reading task suggests a different approach to a multimechanism model of the Müller-Lyer effect. The subjects who used maps in these experiments appeared behaviorally to accept that they were engaged in a map-reading task and that the maps were typical two-dimensional spatial displays. Mechanisms based on misreading of depth cues (Gregory, 1974) or on misperception of three-dimensional shape cues (Nijhawan, 1991) would seem to be good candidates to be disrupted when subjects engage in such a two-dimensional task. In addition, the robustness of the Müller-Lyer illusion across a variety of versions and display conditions might make one consider alternatives to the simple linear model. Physical features that permit the effect of the Müller-Lyer elements, in addition to the map lines in the present experiments, include outward-going and inward-going wings with no central line, lines with a circle at both ends with one line bisecting each circle and the other line touching the edge of each circle, line drawings of children either facing each other or looking in opposite directions (see Schiffman, 1996), and three-dimensional objects (e.g., Nijhawan, 1991). In addition, even those physical displays that have been shown to reduce the illusion (e.g., Coren, 1970; Nijhawan, 1991) still have produced some degree of misestimation of length. One alternative to the purely linear model suggests that the underlying mechanisms combine linearly to produce a mental representation of length but that the transformation from that representation to behavior is nonlinear (e.g., that a very low threshold of activation will induce the behavioral manifestation of the illusion). Thus, presenting the Müller-Lyer illusion in a map context might disrupt the activation of the underlying psychological mechanisms, but their combined effect would still have been above the threshold for the illusion. Those display manipulations that show an effect on the strength of the illusion must affect several mechanisms, reducing the overall activation to subthreshold levels. In other areas of perception, instances of such models (e.g., Spence's, 1940, work on continuity in discrimination learning, and Massaro's, 1987, application of the fuzzy logical model of perception to speech perception) have supported the model by examining different behavioral indices of the underlying psychological process, with certain behaviors showing a linear function and others showing nonlinearity. To address this model explicitly for the Müller-Lyer illusion, research will need to vary the Müller-Lyer elements systematically and measure the perceived length using several different measures, such as magnitude estimation, magnitude production, aimed pointing, and choice.

Another explanation that is consistent with the robustness of the Müller-Lyer illusion is that the underlying psychological mechanisms combine nonlinearly (see Smith & Thelan, 1993, and Thelan & Smith, 1994, for examples of nonlinear dynamic systems models). A nonlinear model would not require that all of the mechanisms be ac-

tivated for the illusion to be perceived or to influence behavior. Thus, in some situations, a given mechanism (e.g., lateral inhibition) may play an important role in producing the Müller-Lyer illusion, whereas, in other situations, it may be completely absent, with no disruption to the illusion. Thus, the map context might disrupt some mechanisms, but other mechanisms would have to be sufficiently activated to produce the illusion.

In addition to manipulating the stimulus features of the Müller-Lyer illusion, researchers have manipulated the task characteristics, including the subjects' response (using choice, magnitude estimation, magnitude production, and pointing), the distribution of attention (Coren & Porac, 1983), and practice with the stimuli (Schiano & Jordan, 1990), with many of the manipulations affecting the size of the illusion. The finding that the subjects' estimation behavior also affects the illusion was not surprising. However, we did not expect that the use of finger pointing as a measurement instrument would eliminate the illusion as effectively as the use of a ruler. Perhaps the subjects were very precise in marking off distances by pointing. However, previous research that has shown that pointing behavior is affected by Müller-Lyer elements (Elliott & Lee, 1995; Gentilucci, Chieffi, Daprati, Saetti, & Toni, 1996) suggests that pointing might not be as accurate as measuring with a ruler with the stimuli used in Experiment 3. Alternatively, engaging in the behavior of pointing may have increased the subjects' attention to the center line relative to the wings, consequently eliminating the illusory effects of the wings.

Phillips (1979) noted that errors made by map readers, due to poorly designed maps, may be inconvenient, costly, or even dangerous. Situations in which the Müller-Lyer illusion in a map would be most dangerous would be those that (1) called for rapid decisions or in which the map reader could not use a measurement tool, (2) required accurate distance judgments within about 20% (approximately the size of the difference in estimates between the control line and lines framed by inward-going and by outward-going wings), and (3) in which a misestimation could lead to injury or death. Examples of such situations might include hikers estimating the amount of resources required for a hike (the situation modeled in Experiment 2), hikers trying to reach a location before dark, and white-water rafters estimating the distance to the next rapids or waterfall.

The danger people face in other situations (e.g., a driver of a car under normal driving conditions or a person walking around town) may not be significantly increased if he or she has misestimated a distance by 20%. Rather, people in such situations would more likely face inconvenience or increased cost. However, estimation errors could also influence a map reader's trust or confidence in a display technology. If a reader expects a map to provide an accurate representation of a certain location, and the map has imbedded illusions that distort the reader's perception, then the map reader may make mistakes and, consequently, receive negative feedback. The result of the error and feedback may be decreased trust or confidence in the dis-

play. Experiment 2 showed the powerful influence of feedback on a user's evaluation of a computer-based map. Any loss of trust or confidence such as that described above may be especially great if the map display technology were novel (e.g., an in-vehicle navigation system for cars). Rather than attributing an estimation error to the perceptual features of the map, new users might attribute it to the technology (Hanowski, Kantowitz, & Kantowitz, 1994).

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NOTE

1. We analyzed the data using hierarchical multiple regression for two reasons. First, multiple regression provided a statistical control for line length differences between trials with inward-going wings and trials with outward-going wings that were inherent in the maps. Second, the hierarchical analysis allowed us to examine the effects of the main effects in the absence of the higher level interaction terms and then to examine the effect of the interactions while statistically controlling for the contributions of the lower level effects (e.g., Cohen & Cohen, 1983).

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