Time-distance relations in shifting attention between locations on one's body

STEPHEN LAKATOS and ROGER N. SHEPARD
Stanford University, Stanford, California

Does the time to discriminate the presence or absence of a tactile stimulus depend on its distance from the bodily location to which one has been attending? Subjects were tested by the presentation of air puffs at four of eight possible locations on the body. In each trial of Experiment 1, (1) subjects attended auditorily to an announcement of one of the eight locations; (2) 2 sec later, a second location was announced and, simultaneously, air puffs were presented at a randomly selected four of the eight locations; (3) the subjects reported as quickly as possible on whether or not air puffs had been presented at the second-announced location. Overall, reaction times increased with the distance between the just-attended and the tested locations. Experiment 2 was undertaken to determine whether the operative distance was distance through the subject's body or directly through three-dimensional space. The subjects were tested as in Experiment 1, but with their arms or legs either side-by-side in front or spread out to each side. Reaction times then depended more on straight-line distance in space than on distance through the body.

Mounting evidence supports notions that regularities of perceptual processing reflect pervasive spatiotemporal constraints in the physical world (e.g., Gibson, 1979; Marr, 1982; Shepard, 1994). One quite general perceptual regularity (resembling the time-distance law of imagined spatial transformations surveyed by Shepard & Cooper, 1982) is the law of apparent motion first formulated by Korte (1915) and since known as Korte's third law (Koffka, 1931). In its modern form (e.g., as stated by Shepard, 1984), this law holds that the minimum stimulus onset asynchrony (SOA) yielding compelling apparent motion between two alternately presented stimuli increases with the distance along the path over which the spatial transformation between the two stimuli is experienced—whether in depth (Corbin, 1942, or Shepard & Judd, 1976) or over a curved path (Farrell, 1983; McBeath & Shepard, 1989; Shepard & Zare, 1983; Shiffrar & Freyd, 1990).

In more recent work (Lakatos & Shepard, 1993, in press), we have found that Korte's third law also accounts for time-distance relations in tactile and auditory circular apparent movement. The cross-modal generality of such a time-distance law suggests that sensory systems, despite differences in the proximal energy patterns incident upon them and despite differences in the characteristics of their neural transduction, have evolved to realize a common set of internal constraints (Shepard, 1994) and/or are all

subject to similar limitations on the physical rate of signal propagation or processing within the three-dimensional neuronal medium (Shepard, 1989).

In the two experiments reported here, we sought evidence for a general time-distance law, akin in spirit to Korte's third law for apparent movement (although not necessarily constrained by functionally similar mechanisms) that might characterize the allocation of attention between locations on the body. First, in shifting attention between spatially separated locations of the body at which the skin may be tactually stimulated, do such shifts require more time for more widely separated locations? Second, if there is such a dependence of time on distance, to what extent is the controlling distance the anatomical length of a path on or through the body, and to what extent is it an internal representation of the straight-line distance through external three-dimensional space? Third, for a given pair of body locations (e.g., left and right wrists), does the time required to shift attention from one to another also change in direct proportion to *changes* in the straight-line separation between them? We addressed this last question by testing different body postures in which the anatomically distant arms (or legs) are, in three-dimensional space, either extended far apart to the sides or brought close together in front. (We do not here pursue the further quantitative question of just what anatomical distance is most relevant—for example, distance of neural pathway or distance in the sensory "homunculus" in the cortex, which is differentially magnified for such more critical regions of the body as fingers, face, lips, and tongue; Penfield & Rasmussen, 1950).

With regard to the first question, chronometric studies of visual attention have indicated that both detection accuracy and response speed are correlated with the magni-

Portions of these results were reported at the 7th Annual Meeting of the American Psychological Society (Lakatos & Shepard, 1995). The research was supported in part by National Science Foundation Grant DBS-9021648 to R. Shepard, and in part by a CNRS postdoctoral fellowship to S. Lakatos. Correspondence should be directed to S. Lakatos, Department of Psychology, Washington State University, 14204 N. E. Salmon Creek Ave., Vancouver, WA 98686 (e-mail: lakatos@vancouver.wsu.edu).

A **B**

Figure 1. (A) The multiposition apparatus used to deliver air puffs to the different limbs of the body. (B) The eight body locations tested in Experiment 1. Subjects' arms and legs were positioned as shown.

tude of the required shift of attention (e.g., Posner, 1978). Moreover, such relations hold even under cross-modal cuing (Buchtel & Butter, 1988; Butter, Buchtel, & Santucci, 1989), suggesting that the cognitive mechanisms associated with spatial attention shifts are superordinate to the inputs converging from individual sensory modalities. If this is the case, then an attention-shift paradigm for the human body that employs location cues from a single modality (e.g., tactile) is anticipated to reflect the internal characteristics of a supramodal, rather than a unimodal, representation of the body.

In the experiments we now report, subjects were cued to two body locations in sequence. On most trials, the first and second location were identical in order to encourage the subjects to maintain attention on the first location. Upon being cued to the second location, subjects were asked to report as quickly as possible whether or not airjet stimulation was present at that second location. By testing eight body locations on both the arms and legs in this manner, we hoped to determine whether the time required to shift attention between locations increased with the distance between those locations and whether straight-line distance or distance along the body surface was the operative independent variable. Then in a second experiment, we tested subjects in two contrasting body

positions: with arms spread laterally and legs close together in front, or the opposite. If straight-line distance is indeed critical, then, for example, one should be quicker to shift attention from the left to the right wrist when the two are close together as opposed to far apart. Evidence for a representation of the body based upon a three-dimensional, Euclidean distance metric would seem to suggest that the representation of personal space, even if anatomically and perceptually distinct in terms of its inherent processing mechanisms, is nonetheless functionally equivalent to that of extrapersonal objects and events.

EXPERIMENT 1

Method

Subjects. Six male and 9 female graduate students from the Psychology Department at Stanford University served as subjects. All were paid for their participation.

Apparatus and Procedure. Subjects were tested individually in a 6 × 6 ft audiometric test chamber (IAC), using the apparatus shown in Figure 1A. A multiposition aluminum frame was fabricated to permit access to a number of body locations in different limb positions. The frame, which was secured to a height-adjustable steel chair, supported the extended arms of a seated subject. Eight nozzles (0.63 cm i.d.), which were attached to the frame by means of adjustable armatures, delivered air puffs to select locations along the body surface (see Figure 1B): (1) right wrist, (2) right arm,

(3) right thigh, (4) right calf, (5) left calf, (6) left thigh, (7) left arm, and (8) left wrist. The subjects were required to wear short pants and short-sleeved shirts so that the air jets could have unimpeded access to the skin at all eight locations. Before an experimental session, the distance between each nozzle and the skin surface was adjusted manually by the experimenter to approximately 3 cm. A set of eight manifold-mounted high-speed air valves (Neumatics 11SAD4) located outside the sound-attenuating test chamber directed air from pressurized tanks to the nozzles via 0.31-cm i.d. Tygon tubing. A Macintosh microcomputer activated the air valves through custom relay junctions. The steady-state air pressure measured at the nozzle was approximately 4 p.s.i. To mask possible auditory localization cues arising from activation of the airjets, a noise generator (Grason-Stadler, Model 455C) transmitted white noise to subjects' ears through Sony MDR-V7 headphones at a level of 75 dB SPL.

In accordance with a two-alternative forced choice (2AFC) paradigm, on each trial, subjects first heard a 250-Hz warning tone, followed 500 msec later by the name of one of the eight body locations announced over the headphones. The eight names had been recorded previously using an Emu Emacs Digital Sound Sampler and edited to a duration of 500 msec; each sound sample could be triggered independently by the computer. The subjects were instructed to focus their attention on this cued location as quickly as possible. A short time (800 msec) after the offset of the announcement of the first location, a second location was announced. To encourage subjects to attend to the first location, on 70% of the trials, the first and second locations were identical. On the remaining 30% of the trials, the second location was chosen at random from the remaining seven possibilities. Concurrent with the onset of this second announcement, four of the eight airjets began emitting air puffs at a rate of 8 puffs/sec. A single puff was produced by opening the corresponding air valve for 62.5 msec and then closing it for 62.5 msec. The locations of the four airjets to be activated on each trial were selected at random before that trial. The subjects' task was to switch attention to this second-announced location and to determine as quickly as possible whether or not it had received air stimulation. The subjects responded by using two foot pedals marked "stimulation" and "no stimulation," respectively. The air-puff sequence continued until the subjects made this response. The next trial followed 2 sec later.

Subjects completed five blocks of 300 trials each, spread across three experimental sessions on separate days (one block for the first session and two blocks each for the remaining two sessions). The sessions lasted approximately 1 h. Across all sessions, each subject underwent the same number of trials for each combination of attended and tested location. Prior to the first session, the subjects received a 15-min structured training sequence in which they were cued to each of the eight body locations in a prescribed sequence and under conditions in which the first and second locations were both identical and different.

Results

Reaction times (RTs) for all body-location pairings were pooled and averaged across subjects. A paired *t* test indicated no differences in RT between split-half subject groups [$t(55) = .368, p = .7144$]. Overall performance in the two-alternative forced choice task was high (95.6%). Since RTs for trials on which an error was made did not differ significantly from those on which a correct response was made, all judgments were included in the calculation of average RTs. (We assumed that subjects' mistakes were primarily attributable to occasional pedal-press errors.) Also, since computer recordings of RTs began with the onset of stimulation at the second location, we subtracted 500 msec (i.e., the duration of the announced lo-

cation) from each RT measure, under the assumption that subjects could know where to attend only after completion of the announcement. Table 1 shows average RTs for those trials on which the first and second locations were identical (comparable times for same-location pairs are also shown for Experiment 2). It is readily apparent that subjects were quicker to respond to stimulation on the arms than to stimulation on the legs; response to wrist stimulation was fastest of all. Moreover, subjects took longer, on average, to respond to locations on the left, as opposed to the right, side of the body. (Such chronometric differences may be related to differences in the lengths of the afferent neural pathways and to the size of cortical area devoted to the representation of individual body locations.)

Because RTs for same-location judgments varied according to location, such variations would also affect different-location conditions and introduce biases in the estimates of the time required to shift attention from one body location to another. Therefore, we employed same-location RTs as baselines to compute less biased measures of the attention-shift times for the different-location trials, using the following formula:

$$\text{Adjusted RT}_{(\text{loc } 1 \leftrightarrow \text{loc } 2)} = \frac{[\text{RT}_{(\text{loc } 1 \rightarrow \text{loc } 2)} + \text{RT}_{(\text{loc } 2 \rightarrow \text{loc } 1)}]}{2} - \frac{[\text{RT}_{(\text{loc } 1 \rightarrow \text{loc } 1)} + \text{RT}_{(\text{loc } 2 \rightarrow \text{loc } 2)}]}{2} \quad (1)$$

This equation states that the adjusted RT for shifting attention between different locations (i.e., from location 1 to location 2, or vice versa) is simply the difference between the average of the two unadjusted RTs for attention shifts between location 1 → location 2 and location 2 → location 1, respectively, and the average of the same-location RTs for the two locations. By effectively removing from the RT measure the average time required to respond to either of the two locations, a purer estimate of the attention-shift time is obtained. Table 2 presents the different-location RTs for all of the body-location pairs tested in Experiment 1.

Figure 2A shows the adjusted RTs for different-location judgments plotted as a function of the straight-line separation between locations. Results are plotted separately

Table 1
Average Reaction Times (in Milliseconds) for Same-Location Pairs (e.g., Right Wrist–Right Wrist) in Experiments 1 and 2

Same-Location Pair	Experiment	
	1	2
Right wrist	209.5	340.5
Right arm	263.3	360.0
Right thigh	289.5	415.2
Right calf	351.7	400.4
Left calf	372.7	490.1
Left thigh	317.0	445.3
Left arm	306.3	414.9
Left wrist	238.3	390.5

Table 2
Adjusted Reaction Times (in Milliseconds) for Location Pairs in Experiment 1
and for Pairs From Both Bodily Positions in Experiment 2

Different-Location Pair	Experiment 2					
	Experiment 1		Position 1		Position 2	
	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>	<i>M</i>	<i>SE</i>
Right wrist↔Right arm	284.0	27.4	303.2	23.8	320.5	25.4
Right wrist↔Right thigh	334.9	22.7	385.8	24.3	333.6	24.2
Right wrist↔Right calf	350.9	31.5	389.5	26.8	350.1	28.1
Right wrist↔Left calf	341.9	25.9	354.2	28.5	296.0	25.3
Right wrist↔Left thigh	309.7	27.9	337.4	28.6	318.5	27.6
Right wrist↔Left arm	258.5	21.5	322.9	24.2	318.6	25.9
Right wrist↔Left wrist	207.2	19.8	393.4	30.1	236.6	26.8
Right arm↔Right thigh	362.8	29.7	378.7	24.8	341.8	26.4
Right arm↔Right calf	389.4	34.9	365.4	27.8	361.4	31.6
Right arm↔Left calf	394.6	36.3	336.0	28.5	354.2	31.9
Right arm↔Left thigh	376.9	30.6	326.8	30.3	336.6	24.8
Right arm↔Left arm	247.3	26.1	290.1	26.8	264.6	29.4
Right arm↔Left wrist	267.6	22.3	282.4	25.5	313.2	30.0
Right thigh↔Right calf	307.5	25.9	297.4	27.2	337.3	29.9
Right thigh↔Left calf	314.8	27.3	291.9	24.1	325.4	27.6
Right thigh↔Left thigh	245.6	20.7	285.1	28.5	307.3	28.9
Right thigh↔Left arm	333.8	24.1	336.9	21.7	338.4	26.9
Right thigh↔Left wrist	330.6	22.3	330.6	26.6	295.6	27.1
Right calf↔Left calf	219.9	25.0	191.3	26.4	254.4	32.1
Right calf↔Left thigh	240.8	22.1	262.4	28.5	323.2	34.0
Right calf↔Left arm	369.8	27.8	356.9	31.3	346.6	33.2
Right calf↔Left wrist	365.7	26.2	297.8	23.8	319.2	29.7
Left calf↔Left thigh	321.5	24.8	336.2	27.2	310.2	30.9
Left calf↔Left arm	428.1	32.8	451.3	33.0	396.6	34.6
Left calf↔Left wrist	424.1	28.2	423.4	29.8	351.6	28.1
Left thigh↔Left arm	370.9	22.9	424.4	33.1	360.6	30.4
Left thigh↔Left wrist	383.7	27.3	417.3	30.8	348.5	30.7
Left arm↔Left wrist	323.4	25.8	361.8	27.8	326.6	31.8

Note—Standard errors are derived from unadjusted reaction time scores.

for pairs occurring on the same side of the body (left or right) and those crossing the midline of the body. The separations in Figure 2A were determined by measuring all possible pairwise distances between airjets from the seated positions of 5 randomly chosen subjects. Average values for equivalent separations (e.g., left arm – right thigh and right arm – left thigh) were calculated in order to produce symmetrical separations for both the left and right sides of the body. As can be seen, attention shifts between locations on opposite sides of the body ($r = .81$) are faster on average than those between locations on the same side. Furthermore, subjects are faster in shifting attention between locations on the right side of the body ($r = .86$) than between locations on the left side ($r = .99$). Apparently, there is some processing penalty, perhaps in the form of mutual interference between same-side locations, that increases the time required for shifting attention, particularly for the left side. The increase in processing time appears to be on the order of 100–150 msec, although the time to shift on the right side appears to approach that of cross-midline locations as the separation grows larger.

Also apparent from Figure 2A is that RTs increased systematically with distance between locations. This increase is clearly revealed by the straight-line functions fitted to each of the three types of conditions in Figure 2.

(The three functions do not have a y -intercept of zero, suggesting that there still remains some fixed time constant associated with initiating an attentional shift of any magnitude.) Regression analyses for the three separate types of location pairs indicated statistically significant linear relations between RT and straight-line distance (Table 3). The pairs of dashed lines for each fitted function in Figure 2A represent 95% confidence intervals for the slope of each fitted line; all slopes differ significantly from zero. Apparently, within each condition, subjects required significantly more time to shift attention between locations when their distance of separation was large. The results suggest that a space–time relation governs shifts of tactile attention between locations on the body.

Although straight-line Euclidean distances between body locations correlated significantly with the adjusted RTs, we were curious to see whether a metric corresponding to distance along or within the body would provide a better fit to the data. Since, with the current paradigm, it would have been impractical to measure distances along the body surface between all location pairs for each subject, we computed rough approximations of bodily distances using the measured straight-line distances presented in Figure 2A: For example, we approximated the bodily distance between left and right wrists (locations 1 and 8 in Figure 1B) as the sum of the distances between the

Figure 2. Adjusted reaction times from Experiment 1 plotted as a function of either (A) the straight-line distance between successive stimulations of different body locations, or (B) distance along the body surface. Values are plotted separately for location pairs confined to either the left or the right side of the body, or those that cross the body midline. Dashed lines indicate 95% confidence intervals for the slope of the fitted functions.

left wrist and left arm, the left arm and right arm, and the right arm and right wrist, respectively (i.e., $\text{dist}[1 \rightarrow 8] = \text{dist}[8 \rightarrow 7] + \text{dist}[7 \rightarrow 2] + \text{dist}[2 \rightarrow 1]$ in Figure 1B). Similarly, the distance between the right wrist and right calf was computed as the sum of three distances: right wrist $\rightarrow$ right arm, right arm $\rightarrow$ right thigh, and right thigh $\rightarrow$ right calf. These approximations of bodily distances are plotted against RT in Figure 2B. As can be seen, correlations between these two variables decrease substantially, particularly for location pairs spanning the body midline ($r = .17$). Clearly, bodily distance between stimulated locations (as estimated by our course-approximation method) accounts for less of the variance in RTs than does straight-line distance.

In Experiment 2, we pursued the following question further: If spatial attention for different body locations is constrained by some form of time-distance metric, as the results from Experiment 1 suggest, does the critical time for an attention shift also depend on *changes* in the relative locations of these locations in three-dimensional space?

EXPERIMENT 2

Method

Subjects. Twenty-two students (8 female, 14 male) from Telecom Paris, a large technical university in Paris, France, received payment for their participation as subjects. They were recruited from a large introductory class on acoustics by the first author; none of them had ever taken part in a psychological experiment.

Apparatus and Procedure. The apparatus from Experiment 1 was retained intact, except that a Rocograf silent air compressor (Model 6-50S) was substituted for the compressed air tanks. The subjects were tested in a small anechoic room that was normally used for acoustic measurements. All supporting equipment involved in the experiment, including the compressor and air valves, was kept outside of this sound-attenuation chamber. The subjects were again asked to wear short-sleeved shirts and shorts for each session.

The experimental paradigm was as described for Experiment 1. The subjects again reported as quickly as possible as to whether the second of two cued locations had received air puffs. This time, however, the subjects were tested in one of two contrasting body positions, in counterbalanced order. In Position 1 (Figure 3A), subjects' arms were fully extended laterally, while their legs were kept close together in front. In Position 2 (Figure 3B), subjects' arms were placed in front with their wrists in close proximity (and elbows subtending approximately 140°), while their legs were extended laterally so that their knees and feet were separated by approximately 45 cm. Announced locations were recorded (edited to a length of 500 msec) using a native French speaker. (In French, the adjectives *left* and *right* follow, rather than precede, the noun; thus, "left thigh" was translated "cuisse gauche.") The percentage of trials for which the first and second locations were identical was reduced (from 70% in Experiment 1) to .59% to diminish fatigue by shortening the total number of trials required per session.

The subjects completed six blocks of 192 trials each during the course of two sessions on separate days. Three blocks each were devoted to the two body positions, and only one position was tested per session. As in Experiment 1, the subjects were given a short practice session to familiarize them with the task.

Table 3
Regression Analysis of Results for Experiments 1 and 2

Position	Comparison	<i>r</i>	<i>F</i>	<i>p</i>
Experiment 1				
—	Left side only	.99	350.8	.0001
	Right side only	.86	11.3	.0283
	Across midline	.81	26.6	.0001
Experiment 2				
1	Left side only	.88	11.2	.0287
	Right side only	.86	13.8	.0210
	Across midline	.77	20.4	.0005
2	Left side only	.93	11.8	.0262
	Right side only	.86	27.8	.0062
	Across midline	.46	3.7	.0758
Combined	Left side only	.87	22.4	.0008
	Right side only	.83	30.7	.0002
	Across midline	.67	24.3	.0001

Note—All comparisons are significant, with the exception of pairs spanning the body midline in Position 2.

Figure 3. The two contrasting body positions tested in Experiment 2. (A) In Position 1, subjects' arms were fully extended laterally and their legs were placed close together. (B) In Position 2, subjects' arms were extended forward, with a slight bend at the elbows, subtending approximately 140° . Legs were extended laterally with a distance of approximately 45 cm between the knees and between the feet.

Results

RTs were again pooled and averaged across subjects. A paired t test again indicated no differences in RT between split-half subject groups [$t(27) = -.032$, $p = .9748$]. Results for different-location pairs were tabulated separately for Position 1 and Position 2; those for same-location trials were combined across the two positions. Discrimination performance was slightly lower (92.8%) than in Experiment 1. RTs for both correct and incorrect responses were included in the averages because they did not differ significantly from one another. Average RTs for same location trials were approximately 50–150 msec longer than their respective complements in Experiment 1. It is not clear whether this is attributable to differences in the manner in which the body locations were announced in English and French or to some other factor. Nonetheless, the increase in RT is fairly small and stable across all of the eight tested locations.

Adjusted RTs for different-location pairs were again computed using Equation 1. Figure 4 shows adjusted RTs for Position 1 as a function of the distances between locations, with separate plots for pairs presented on the same (left or right) side, and those crossing the body midline. Interstimulus distances for Positions 1 and 2 were again obtained by measuring each distance for each of 5 randomly chosen subjects and averaging equivalent distances on the left and right sides of the body to obtain a bilaterally symmetric values. As in Experiment 1, subjects were faster on average to respond when the two locations were on opposite sides of the body ($r = .77$), and they were also

faster for pairs occurring on the right side ($r = .86$) than for those on the left ($r = .88$). Furthermore, RT increased significantly as a linear function of separation for all location pairs (dashed lines again indicate 95% confidence intervals for the function slope), confirming the findings

Figure 4. Adjusted reaction times for Position 1 (Experiment 2) plotted as a function of the straight-line distance between location pairs. Values are plotted separately for pairs confined to either the left or the right side of the body, or those that cross the body midline. Dashed lines indicate 95% confidence intervals for the slope of the fitted functions.

of Experiment 1 that a time–distance constraint holds for locations along the body. Similar trends can be seen in the results from Position 2 (Figure 5). Subjects again took longer to shift attention between locations that were farther apart. The somewhat greater overlap between points in Figure 5, as well as the substantially lower correlation for locations crossing the midline ($r = .46$, with the slope of the fitted function not significantly different from zero), may be explained by the reduced range of distances afforded by Position 2 (i.e., the distances between the various locations were much more similar in magnitude than those of Position 1).

The consistency between the RTs obtained in Positions 1 and 2 can be seen more clearly in Figure 6, where the two sets of results are plotted on the same scale. Correlations for the three subsets of data (left side only, right side only, and across midline) range from .67 to .87, indicating a strong consistency of RTs across the two positions. The straight-line fits suggest that on the average, subjects required approximately 11–12 msec to shift their attention 10 cm along a direct path between locations (this value is closer to 15 msec for locations on the left side of the body), a considerably shorter estimate than for Experiment 1 (approximately 20–30 msec). The reason for this difference is unclear. Given the word order difference between English and French, it is conceivable that the French subjects, having heard the location (e.g., “thigh”) first could have begun processing this information during the time between this utterance and the consequent modifier (i.e., “left” or “right”); American subjects, on the other hand, could be certain after the first utterance only that the location would be on either the right or the left side of the body.

Figure 5. Adjusted reaction times for Position 2 (Experiment 2) plotted as a function of the straight-line distance between locations. Values are plotted separately for pairs confined to either the left or the right side of the body, or those that cross the midline. Dashed lines indicate 95% confidence intervals for the slope of the fitted functions.

Figure 6. Plot of combined reaction times for Positions 1 and 2. Values are shown separately for pairs confined to either the left or the right side of the body, or those that cross midline. Dashed lines indicate 95% confidence intervals for the slope of the fitted functions.

A more direct comparison of performance between Positions 1 and 2 is shown in Figure 7, where the difference in RT between equivalent pairs of locations at the two positions is plotted as a function of the change in separation between the two locations across the two positions. The graph clearly shows that increases or decreases in RT are strongly correlated ($r = .79$) with concomitant increases or decreases in the distance between any given pair of locations. (The fitted line in Figure 7 passes directly through the origin, as it should if RTs change only with changes in separation.) The results displayed in Figure 7 represent clear evidence that a time–distance relation constrains the shifting of attention between body locations. For a given pair of locations, it appears to be the changing Euclidean distance in space between them, more than some sort of bodily distance, that determines the change in time required for an attention shift. This supports the theoretical notion of an analog representation of the body, in which physical distances are represented (somatosensory cortex) as equivalent psychological distances.

DISCUSSION AND CONCLUSIONS

In the two experiments reported here, we sought to determine whether a time–distance relation could be established for attention shifts between locations on the surface of the body. Subjects attending to one bodily location were asked to report whether they felt air-puff stimulation at a second location. Their RTs increased with the distance of the second location from the location to which they had been attending. This result suggests that the spatial processing mechanisms for attending to bodily locations are functionally similar to those responsible for encoding spatial transformations between external objects. In the

Figure 7. Graph showing changes in adjusted reaction time (Δ RT) for location pairs across Positions 1 and 2 as a function of changes in straight-line distance (Δ Separation) across these positions. Results indicate that reaction time approximates a linear function of the distance between a given pair of body locations.

case of both apparent movement and imagined transformations (Shepard & Cooper, 1982), the minimum time required to complete the internal transformation increases with the length of the path over which the transformation occurs. (The substantially shorter critical time in apparent motion, as opposed to mental transformation, may reflect the more automatic nature of the perceptual process in apparent motion, rather than a qualitative difference in the perceptual constraints invoked—cf. Shepard & Cooper, 1982.) The finding that attention to spatial and temporally separated stimulation along the body surface obeys a time–distance rule provides further evidence for the theoretical perspective that elementary constraints, such as the conservation of semirigid shape and motion within a locally Euclidean, isotropic world, are reflected not only in the representation of our environment, but also in the perception of our own bodies within that environment.

Our findings do not directly address the issue of whether shifts in attention across skin locations pass through intermediate positions, as an analog process would dictate. Since, on each trial, four separate locations were stimulated with the onset of the second announced location, subjects presumably could have attended to all four locations simultaneously, and could then have selected one location on the basis of a direct mapping of the verbal cue to the target location, for example; in such a case, an analog attention shift would not be required. The findings suggest that the duration of attentional processing is directly related to the magnitude of the attentional displacement in three-dimensional space.

The relevant distance in the results reported here appears to have both a bodily and an external spatial component. Subjects were quicker to respond when the two

relevant locations were on opposite sides of the body. This effect does not appear to be attributable to cognitive-linguistic factors (e.g., the making of the left–right distinction first in the case of “right thigh” $\rightarrow$ “left arm”), since the effect was also quite strong for the French subjects, for whom the word order of the location cuing was the reverse of that for the American subjects. Rather, the reduced RT may have had to do more with subjects’ increased ability to filter out irrelevant stimulation once attention had been focused on the second location on the opposite side. For example, if a subject focuses his or her attention on a particular location, and if the band-pass characteristics of the “spatial-attention” filter are fairly narrow (i.e., the person is attending only to the first announced location), then it may be more difficult to shift attention to another location on the same side of the body because of greater interference from stimulation at non-cued locations on that side (i.e., the filter would have to be narrower).

This possibility is bolstered by subjects’ postexperimental comments that they felt they were able to shift their attention equally rapidly between locations on the same side and those on different sides, but found it more difficult to determine whether locations on the same side of the body received air stimulation due to the potential presence of other activated airjets. Further support of a hemispheric component to bodily attention comes from recent positron emission tomography measurements of cerebral blood flow, which indicate that subjects’ anticipation of tactile stimulation results in reduced blood flow to both ipsilateral parts of the somatosensory cortex outside of the spatial target of the expected stimulus as well as to the contralateral part (Drevets et al., 1995); the reduction in flow, however, is greater for the ipsilateral side, suggesting that contralateral regions of the somatosensory cortex may be more readily activated by additional stimulation to a region on the opposite side of the body.

Following completion of the two experiments reported here, we learned of a tactile discrimination experiment by Rosenbaum, Hindorff, and Barnes (1986), which appears in some ways to be quite similar to our experiments. Their subjects had to indicate as quickly as possible whether a single vibrotactile stimulus had occurred at a specified target site or at one of five distracter sites (from a fixed set of six possible sites—left or right palm, forearm, or upper arm). Applying multidimensional scaling to the matrix of obtained RTs for all possible pairs consisting of a target and a distracter from the six possible sites, Rosenbaum et al. recovered the approximate spatial configuration of those sites, implying a generally monotonic relationship between RT and distance between the sites to be discriminated. Their subjects, like ours, were quicker to respond when the two relevant locations were on opposite sides of the body. Moreover, in their second experiment, Rosenbaum et al. (like us) also tested two contrasting arm positions (parallel extension in front or separated extension to the sides).

In some respects, however, the results reported by Rosenbaum et al. appear difficult to reconcile with ours. Al-

though they reported (as we have) that RT increased with distance between locations, given the differences between their task and ours this is not clearly a point of agreement. We interpreted our task as requiring a shift in attention, with a shift over a greater distance expected to require more time. But their task, which required a discrimination as to whether a single stimulus had occurred at one location or another, appears to be of a type that would ordinarily be expected to require more time when the two locations were closer together and, hence, be less discriminable (e.g., see Shepard & Podgorny, 1986). Indeed, they reported that discrimination times did tend, if anything, to be longer between homologous parts of the two arms and, also, when the subject's arms were closer together (rather than shorter under this condition, as in our second experiment). These two findings support the notion that the times measured in their experiment were primarily times required for discrimination rather than for transformation or attention shift. In short, the relationship of their results to ours remains to be fully clarified.

Findings recently reported by Reed and Farah (1995) may also have a bearing on some of the issues addressed by the experiments we have reported here. Those researchers found evidence that movement of one's own body could facilitate attention to the corresponding parts of another body (contrary to their initial expectation of interference). In contrast, by comparing the accuracy of memory position for both body position and the position of an abstract configuration of blocks in the context of a secondary task (i.e., arm and leg movement), they found no interaction between body movement and the visual perception of block configuration. The results from both sets of studies led the authors to conclude that the body schema represented a form of spatial processing that was functionally distinct from object perception. Support for the notion of a body schema also comes from clinical cases involving severe representational neglect of one side of the body coupled with the absence of any impairment in the representation of external spatial relations for that side (e.g., Guariglia & Antonucci, 1992). There may have been some evolutionary advantage to the emergence of separate personal and extrapersonal space (e.g., to permit independent, and presumably more efficient, monitoring of ecologically relevant vs. irrelevant spatial information). This distinction, however, merely begs the question of whether time-distance relationships within the body schema are similar to those of other external objects and events, or whether they are body specific.

In conclusion, we find it striking that processing time should increase with distance between stimuli in a way similar to that for imagining a spatial transformation (as in "mental rotation"—Shepard & Cooper, 1982), for apparent motion (as expressed by Korte's third law), and for shifts of attention (as reported, e.g., by Posner, 1978; Rosenbaum et al., 1986; and the present study), and should do so whether the stimuli are presented visually, auditorily, or tactually (Lakatos & Shepard, 1993, in press; and the present study). Such a time-distance constraint may have arisen through natural selection as an adaptation to

corresponding constraints holding throughout the biologically accessible external world, and/or it may be the manifestation of corresponding constraints that apply directly to any physical system—including, therefore, the brain. A constraint of this sort, which appears particularly relevant for the time-distance relationships considered here, would be a constraint on the speed of signal propagation or processing in any neuronal or information-processing medium. In the cases of mental transformation, apparent motion, and attention shift, alike, natural selection would presumably have favored completing the connection or transformation as rapidly as possible rather than attempting to simulate some sort of average speed of transformation in the external world—if indeed there is such a thing (Shepard, 1984, 1989, 1994).

At the same time, for purposes of anticipating events and planning actions in the external world, the biological processing medium may have evolved a structure or effective internal metric that is functionally isomorphic to the relevant aspects of the external world. In this way, we might reconcile the two possibilities and explain why imagined transformations and apparent motions conform with the abstract principles of kinematic geometry for three-dimensional Euclidean space (Shepard, 1984, 1994). There may also have been selection for multiple representational media for multiple purposes. In vision, for example, we can take either of two perceptual stances—we can perceive the top of a table viewed from one end as having strictly parallel sides or we can experience the far end as subtending a smaller visual angle than the near end. The former type of judgment has been selected by the need to assess actual distances in the external world; the latter type of judgment has been selected by the need to be able to point our fingers (or our eyes) at objects or features from a particular point—hence confronting us with the fact that we move an arm through a smaller angle in pointing successively at the two farther corners of the table top than in pointing successively at the two nearer corners.

In the case of switching attention between different locations at which tactile stimulation may be present, too, it is possible that different mind sets might favor relying on representational media that correspond more to locations with respect to the body's surface or on representational media that correspond more to external three-dimensional Euclidean space. The evidence from our Experiment 2 suggests that both types of representations may play a role. Further experimental work, perhaps using techniques of the sort we have used here, may permit an eventual characterization of the spaces through which attention shifts.

REFERENCES

- BUCHTEL, H. A., & BUTTER, C. M. (1988). Spatial attention shifts: Implications for the role of polysensory mechanisms. *Neuropsychologia*, 26, 499-509.
- BUTTER, C. M., BUCHTEL, H. A., & SANTUCCI, R. (1989). Spatial attention shifts: Further evidence for the role of polysensory mechanisms using visual and tactile stimuli. *Neuropsychologia*, 27, 1231-1240.

- CORBIN, H. H. (1942). The perception of grouping and apparent motion in visual depth. *Archives of Psychology*, No. 273.
- DREVETS, W. C., BURTON, H., VIDEEN, T. O., SNYDER, A. Z., SIMPSON, J. R., & RAICHLE, M. E. (1995). Blood flow changes in human somatosensory cortex during anticipated stimulation. *Nature*, **373**, 249-252.
- FARRELL, J. E. (1983). Visual transformations underlying apparent movement. *Perception & Psychophysics*, **33**, 85-92.
- GIBSON, J. J. (1979). *The ecological approach to visual perception*. Boston, MA: Houghton Mifflin.
- GUARIGLIA, C., & ANTONUCCI, G. (1992). Personal and extrapersonal space: A case of neglect dissociation. *Neuropsychologia*, **30**, 1001-1009.
- KOFFKA, K. (1931). Die Wahrnehmung von Bewegung [The perception of motion]. In A. Bethe et al. (Eds.), *Handbuch der normalen und pathologischen Physiologie* (Vol. 12, Part 2, pp. 1166-1214). Berlin: Springer-Verlag.
- KORTE, A. (1915). Kinematoskopische Untersuchungen [Cinematographic investigations]. *Zeitschrift für Psychologie*, **72**, 193-296.
- LAKATOS, S., & SHEPARD, R. N. (1993, November). *Time-distance relations in visual, auditory, and tactile apparent motion*. Paper presented at the 34th Annual Meeting of the Psychonomic Society, Washington, DC.
- LAKATOS, S., & SHEPARD, R. N. (1995, July). *Time-distance relations in shifting attention between locations on one's body*. Poster presented at the 7th Annual Meeting of the American Psychological Society, New York.
- LAKATOS, S., & SHEPARD, R. N. (in press). Constraints common to apparent motion in visual, tactile, and auditory space. *Journal of Experimental Psychology: Human Perception & Performance*.
- MARR, D. (1982). *Vision*. San Francisco: W. H. Freeman.
- MCBEATH, M. K., & SHEPARD, R. N. (1989). Apparent motion between shapes differing in location and orientation: A window technique for estimating path curvature. *Perception & Psychophysics*, **46**, 333-337.
- PENFIELD, W., & RASMUSSEN, T. (1950). *The cerebral cortex of man: A clinical study of localization of function*. New York: Macmillan.
- POSNER, M. I. (1978). *Chronometric explorations of the human mind*. Hillsdale, NJ: Erlbaum.
- REED, C. L., & FARAH, M. J. (1995). The psychological reality of the body schema: A test with normal participants. *Journal of Experimental Psychology: Human Perception & Performance*, **21**, 334-343.
- ROSENBAUM, D. A., HINDORFF, V., & BARNES, H. J. (1986, November). *Internal representation of the body surface*. Paper presented at the 27th Annual Meeting of the Psychonomic Society, New Orleans.
- SHEPARD, R. N. (1984). Ecological constraints on internal representation: Resonant kinematics of perceiving, imagining, thinking, and dreaming. *Psychological Review*, **91**, 417-447.
- SHEPARD, R. N. (1989). Internal representation of universal regularities: A challenge for connectionism. In L. Nadel, L. A. Cooper, P. Culicover, & R. M. Harnish (Eds.), *Neural connection, mental computation* (pp. 103-104). Cambridge, MA: MIT Press, Bradford Books.
- SHEPARD, R. N. (1994). Perceptual-cognitive universals as reflections of the world. *Psychonomic Bulletin & Review*, **1**, 2-28.
- SHEPARD, R. N., & COOPER, L. A. (1982). *Mental images and their transformations*. Cambridge, MA: MIT Press, Bradford Books.
- SHEPARD, R. N., & JUDD, S. (1976). Perceptual illusion of rotation of three dimensional objects. *Science*, **191**, 952-954.
- SHEPARD, R. N., & PODGORNÝ, P. (1986). Spatial factors in visual attention: A reply to Crassini. *Journal of Experimental Psychology: Human Perception & Performance*, **12**, 383-387.
- SHEPARD, R. N., & ZARE, S. L. (1983). Path-guided apparent motion. *Science*, **220**, 632-634.
- SHIFFRIN, M., & FREYD, J. J. (1990). Apparent motion of the human body. *Psychological Science*, **1**, 257-264.

(Manuscript received August 21, 1995;
revision accepted for publication June 16, 1996.)