EFFECTS OF SPATIAL ATTENTION ON TACTILE PROCESSING: A SPEED-ACCURACY ANALYSIS

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Abstract

Does attention to spatial cues affect tactile processing? Subjects received 60-Hz mechanical sinusoids at levels near 15 dB SL, delivered with equal probabilities to the left and right hands. Spatial attention was directed by a visual cue: an arrow that pointed left or right. The cue was valid (pointed in the direction of the hand that would receive the stimulus) on 75% of the trials, invalid on 25%. The subjects' task was to identify, as quickly as possible, the intensity of the stimulus – as low (press one pedal with left foot) or high (press another pedal with right foot). Latency operating characteristics (LOCs) for each subject quantified the trade-off between response time and accuracy. Seven of the eight subjects accumulated information more rapidly on valid compared to invalid trials (slopes of LOC were greater), thereby indicating the benefits of directed spatial attention.

Cues that provide information about the likely location of subsequent target stimuli can improve both detection and discrimination of the targets. For example, the spatial cuing paradigm of Posner and his colleagues (Posner, Snyder, & Davidson, 1980) has been used to show that response time (RT) is smaller when the cue is valid rather than invalid, that is, responding is quicker when the cue correctly predicts the location of the target stimulus. In this paradigm, average RT is commonly used to measure performance.

The use of RT to gauge performance is based on two assumptions: first, that superior performance is marked by faster (neural) processing of sensory information; and second, that average RT provides a valid representation of speed of sensory information processing. This approach rests, however, on a third, implicit assumption, namely, that both the time for decisional processes and the criterial amount of information required before responding is initiated are fixed. If this assumption is not correct – if decisional processes or response criterion varies across conditions, for example, differing when spatial cues are valid versus invalid – then to this extent one cannot attribute variations in RT to variations in speed of sensory information processing. An attentional cue might, for example, reduce the criterial amount of information needed to initiate a response, and therefore reduce RT, without affecting the 'quality' of the information or the rate at which the information accrues. The potential problems are exacerbated when accuracy is very high, as it may be difficult to discern any differences in accuracy across conditions.

To distinguish the rate of temporal processing of sensory information from decisional and criterial processes, Lappin and Disch (1972a,b) proposed the use of the latency operating characteristic (LOC). The LOC provides a measure – applicable in principle to individual subjects as well as group averages – of the way that discriminative performance improves as latency to respond (RT) increases. That is, the LOC represents the speed-accuracy trade-off. In doing so, the LOC essentially capitalizes on the way that accuracy (e.g., *d'*) as well as speed covary as the decisional criterion for response varies. Lappin and Disch (1972a) showed, for example, that stimulus probability does not affect the LOC. While varying stimulus probability might affect average RT, it would at the same time also affect average accuracy. Lappin and Disch formulated the function for the LOC as linear: $d' = m (\mathrm{RT} - k)$.

In this study, we ask a relatively simple question: Does directing spatial attention to one site or another on the body surface improve the processing of non-spatial dimensions of tactile targets presented to a validly cued location, relative to an invalidly cued location? There is considerable evidence implying that the two hands, or different fingers on the same hand, can serve as separate informational channels (e.g., Craig, 1985; Horner, 1992; Sathian & Burton, 1991; Whang, Burton, & Shulman, 1991). Nevertheless, there appear to be many conditions under which spatial attention is lacking or weak – or, more precisely, where benefits and/or costs of manipulating spatial attention are absent or small (e.g., Evans & Craig, 1991; Shiffrin, Craig, & Cohen, 1973; Sathian & Burton, 1991; Whang et al., 1991). Interpreting many previous studies of cued, endogenous (voluntary) tactile spatial attention (e.g., Bradshaw, Bradshaw, Pierson-Savage, & Nettleton, 1988; Butter, Buchtel, & Santucci 1989; Forster & Eimer, 2005). Honoré, Bourdeaud'hui, & Sparrow 1989; Pierson, Bradshaw, Meyer, Howard, & Bradshaw, 1991) is difficult, however, because these studies have generally failed to control or measure the possible role of variations in decision criterion.

Consequently, in the present study we take a different tack. Instead of using average RT to gauge performance, we capitalize on the methodological and analytic approach of Lappin and Disch (1972a,b) to derive latency operating characteristics under conditions in which cues for spatial location are usually valid but sometimes invalid. In this study, the subject’s task is to identify each stimulus as weak or strong in amplitude, while stimuli may be presented to either the left or right hand. The question we ask is whether and how a spatial cue affects both speed and accuracy of responding to differences in stimulus amplitude.

Method

Subjects

Eight volunteers (aged between 20 and 40) including one of the authors participated. All subjects except the author were paid at an hourly rate for their participation.

Stimuli and Apparatus

Stimuli were 60-Hz mechanical sinusoidal vibrations, presented to the thenar eminence of the right or left hand. Stimuli were generated by a Tucker Davis Technology real-time processor (TDT, RP2.1), shaped to have rise and fall times of 25 ms and gated to a duration of 150 ms. Stimulus amplitude was controlled by programmable attenuators (TDT, PA5). Both the real-time processor and the attenuators in turn were controlled through computer software (RPvds and Matlab) operating through a Pentium 4 PC. The output signals activated two Brüel & Kjaer 4810 Mini Shakers, both mounted on triple beam balances to provide constant upward forces equivalent to resting masses of 40 g against the thenar eminence of the right and left hands.

The contactors of the shakers were 10 mm in diameter and touched the skin through 12-mm holes in the surface of a 0.5 cm thick table, the 1 mm gap helping to prevent lateral spread of vibration through the skin. Subjects were seated in front of a computer screen on the table located in a sound attenuated chamber. They were instructed to place one hand or both hands onto one contactor or both contactors. Subjects wore headphones that delivered white noise at about 80 dB SPL to mask both environmental sounds and any auditory cues generated by the shakers.

Procedure

The experiment had two parts: (a) a 3-down 1-up adaptive, forced-choice detection task that measured the absolute sensitivity of each subject's right and left thenar eminence to the 60-Hz signals; and (b) a spatially cued discrimination task that measured speed and accuracy of identifying signals as low or high in amplitude (amplitudes of the signals being tailored on the basis of absolute sensitivity) when the hand receiving the signal was validly or invalidly cued.

(a) Adaptive procedure. The detection threshold on the thenar eminence of each hand was measured using a 3-down 1-up adaptive, two-interval forced choice (2IFC) procedure (Levitt, 1971). On each trial, the subject was presented two observation intervals (indicated visually on a screen), one of which contained a vibratory signal; the subject reported which interval contained the signal by pressing one of two keys on a keyboard. Signal level was increased by 2 dB after a single correct response and decreased by 2 dB after three consecutive correct responses. Thresholds corresponding to a probability of 79% correct in 2IFC were obtained by averaging dB values across 10 reversal points.

(b) Spatially cued discrimination. Stimuli were two 60-Hz sinusoids, one weak and the other strong, differing in amplitude by 3 dB, set on average 15 dB above the thresholds measured in part (a), that is, set around 15 dB SL. Weak and strong vibrations were delivered with equal probabilities to the thenar eminence of both hands. On each trial, a visual fixation first appeared on the center of the screen, followed by a spatial cue (arrow) on the right-hand side of the fixation pointing to the right contactor or on the left-hand side of the fixation pointing to the left contactor.

The visual cues were valid on 75% of trials, that is, the arrow pointed to the side on which the vibrotactile stimulus was presented. On the other 25% of trial, the visual cues were invalid, the arrow pointing to the side opposite the stimulus. Subjects were instructed to respond as quick as possible within a window of time, pressing the left foot pedal with their left feet when the vibration was weak and pressing the right foot pedal with their right feet as the strong vibration signal occurred. Each subject received 15 blocks of 160 trials, with a time window varying randomly from 0.3 s to 1 s in steps of 0.05 s, preceded by one practice session with a time limit 0.8 s. Feedback was provided when the subjects' RT exceeded the window. Practice trials were also provided in each session to familiarize the subjects with the task and the time window before data collection began.

Results and Discussion

For each subject, RTs on all trials (that is, RTs when responses were both correct and incorrect) were first rank ordered separately for the valid and invalid cue conditions. The ranked trials for each condition were then partitioned into equally sized bins. To maximize the number of trials per bin and to keep the similar resolution of differences in RT, each bin contained 150 trials for invalid cues and 450 trials for valid cues. Assuming a linear relation between *d'* and RT, we fitted straight lines to the LOCs; slopes and intercepts for each subject are given in Table 1. Two examples of LOCs from two subjects for valid and invalid trials are also shown in Fig 1. From the scatter plots of accuracy versus RT, we found that accuracy often first increased to a maximum as RT increased, then fell as RT further increased, indicating the possible introduction of another processing mechanism. Consequently, we fitted straight lines to the LOCs up to the point of maximal accuracy.

For seven of the eight subjects, slopes (*m*) of the LOC were greater on the trials having valid compared to invalid spatial cues. In general, the average (± se) slope, *m*, for the valid cue condition was 5.96 ± 0.73, which is significantly greater than average slope of

Table 1. Slopes (*m*) and intercepts (*k*) of the latency operating characteristics (i.e. speed accuracy trade-off functions), assuming a linear relation between *d’* and RT, $d' = m\,(\mathrm{RT} - k)$. Values of *m* and *k* were determined for each subject separately when the spatial cues were valid and when the cues were invalid. The slope, *m*, has units of accuracy/time (*d’*/s), whereas the intercept, *k*, has units of time (s).

	Valid cue		Invalid cue	
Subject	*m*	*k*	*m*	*k*
S1	4.76	0.24	3.72	0.26
S2	4.46	0.26	4.39	0.23
S3	5.82	0.23	2.08	0.07
S4	5.27	0.27	2.08	0.13
S5	6.87	0.26	4.63	0.21
S6	5.76	0.16	7.57	0.24
S7	4.15	0.25	2.10	0.23
S8	10.59	0.30	5.02	0.25
Mean	5.96	0.25	3.95	0.20
SE	0.73	0.01	0.67	0.02

3.95 ± 0.67 for the invalid condition ($t = 2.97$, $p < 0.02$). The difference in slope implies that the rate of gain of vibrotactile information was greater on valid trials than invalid trials: attention increased rate of accrual of accurate tactile information. In addition, the average intercept, *k*, did not differ significantly across the two conditions ($t = 1.60$, $p < 0.15$). Thus, it is possible that, regardless of whether the spatial cue is valid or invalid, it takes the same amount of time for vibrotactile processing before the level of performance accuracy exceeds

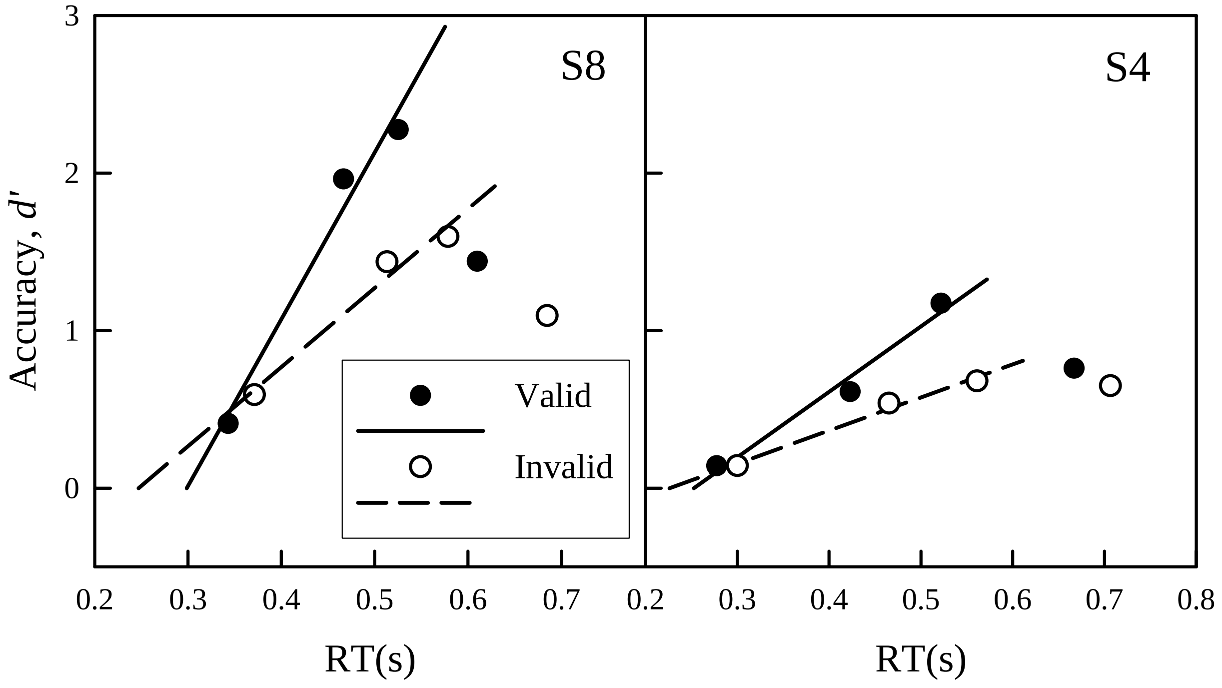

Fig. 1. Examples of LOC functions for valid trials (solid circles, solid lines) and for invalid trials (open circles, dashed lines) from two subjects.

chance (threshold). But because the slopes of the LOCs differ, the benefits of cueing, in terms of RT, increases as the level of desired accuracy increases. Thus, for example, to reach a level of accuracy equal to *d'* of 1.0, valid spatial attentional cues provide a benefit of about 40 ms. Directing spatial attention by means of spatial cues therefore serves, relatively speaking, to benefit performance on a speeded choice task.

These results imply that spatial attention engendered endogenously (in this case, by a visual cue) can modify the rate of tactile information processing. These data do not however, address the underlying mechanism. Results of several earlier studies suggest that tactile spatial attention can be modulated by, or perhaps even controlled by, proprioception (Bradshaw et al., 1988; Honoré et al. 1989; Pierson et al., 1991; Spence, Nicholls, Gillespie, & Driver, 1998). It is possible, for example, that the spatial cues provided to the subjects by the visual stimuli in the present experiment induced the subjects to shift their eyes or head toward the hand being cued, and that the effects of cued attention result, indirectly, from changes in posture or the associated proprioceptive signals.

Recent findings by Forster and Eimer (2005) imply that directing spatial attention can exert both costs and benefits to tactile performance. Those investigators compared behavioral measures (RTs) and neural measures (event-related potentials) under conditions in which the cues could be valid, invalid, or neutral (uninformative). With regard to RTs, costs (increase in RT on invalid trials versus neutral trials) were greater than benefits (decrease in RT on valid trials versus neutral trials). When they examined the somatosensory ERP, however, Forster and Eimer observed equal costs and benefits to the N140 component, but mainly costs at longer ERP latencies. If all of the components of the somatosensory ERP do indeed reflect processes involved in tactile behavioral performance, then it would be interesting to further investigate how benefits and costs contribute to ERPs for the early and later portions of the behavioral LOC, which may reflect different underlying neural mechanisms as indicated earlier in this section. In this regard, it could be especially informative to measure ERPs under behavioral and psychophysical conditions similar to those of the present experiment. This would make it possible, at least in principle, to correlate changes in ERPs with changes in performance corresponding to different points along the LOC.

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