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Principles of cross-modal competition: Evidence from deficits of attention

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How does the attentional system coordinate the processing of stimuli presented simultaneously to different sensory modalities? We investigated this question with individuals with neurological damage who suffered from deficits of attention. In these individuals, we examined how the processing of tactile stimuli is affected by the simultaneous presentation of visual or auditory stimuli. The investigation demonstrated that two stimuli from different modalities are in competition when attention is directed to the perceptual attributes of both, but not when attention is directed to the perceptual attributes of one and the semantic attributes of the other. These findings reveal a differentiated attentional system in which competition is modulated by the level of stimulus representation to which attention is directed.

Attention can be thought of as the selection of perceptually salient or behaviorally relevant stimulus representations from among multiple competing representations (Desimone & Duncan, 1995). Given this, in order to understand attention, it is essential to determine which representations are in competition with one another. One specific set of issues concerns the manner in which the attentional system orchestrates the processing of stimuli presented simultaneously to different sensory modalities.

Research in this area has been dominated, thus far, by the question of whether attention is modality specific or cross-modal. Another way of formulating the question is to ask whether or not stimulus representations from different modalities are in competition with one another for neural and representational resources. Evidence of competition among the modalities is taken as evidence of shared cross-modal resources, whereas lack of competition points to independent, modality-specific attentional processing. This question has been addressed in studies of neurologically injured and neurologically intact subjects, using both behavioral and neural-imaging techniques. Findings have indicated that it is not a question of either one or the other but, rather, that both modality-specific and cross-modal attentional mechanisms exist.

For example, modality-specific attention is implied by the fact that neurological damage can result in attentional deficits that affect one modality but not others. That is, individuals have been described as suffering from deficits of visual attention but not of tactile attention (Umiltà, 1995). In addition, with individuals suffering from attentional deficits affecting multiple modalities, rehabilitation of one modality does not lead to recovery in the other modalities (Làdavas, Menghini, & Umiltà, 1994). Convergent findings from research with neurologically intact individuals indicate that multiple stimuli presented in different modalities can be processed more easily than multiple stimuli presented within the same modality (Duncan, Martens, & Ward, 1997; Treisman & Davies, 1973; but see Gladstones, Regan, & Lee, 1989). Such findings suggest a considerable degree of attentional independence among modalities.

However, there are multiple sources of evidence for attentional interdependence among modalities (sometimes referred to as cross-modal, supramodal, multimodal, or amodal attention). Neural-imaging research reveals that attentionally demanding processing in one modality may lead to a reduction in neural activity in other modalities. For example, positron emission tomography has shown that subjects carrying out tactile discriminations exhibit a reduction in activation in primary visual areas (Kawashima, O'Sullivan, & Roland, 1995; Sadato et al., 1996). Similarly, attentionally demanding visual processing may result in a reduction in the amplitude of auditory evoked responses (Hillyard, Simpson, Woods, Van Voorhis, & Münte, 1984; Oatman, 1976), as well as in below-baseline levels of regional cerebral blood flow in primary auditory and somatosensory areas (Courtney, Ungerleider, Keil, & Haxby, 1996; Haxby et al., 1994). Attentional interdependence among modalities is also supported by behavioral studies with neurologically intact subjects that indicate that attention to a stimulus in one modality may either facilitate or interfere with directing attention to a stimulus in another modality (Bonnel & Hafter, 1998; Buchtel & Butter, 1988; Driver, 1996; Jolicœur, 1999; Massaro & Warner, 1997; Spence, Nicholls, Gillespie, & Driver, 1998; Treisman & Davies, 1973). Finally, certain neurological conditions make it difficult for subjects to

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attend to a stimulus in one modality (e.g., tactile) when it occurs in the context of another stimulus that is presented in the same modality (tactile) or even in a different modality (visual; Bender, 1952; di Pellegrino, Làdavas, & Farnè, 1997; Farah, Wong, Monheit, & Morrow, 1989; Làdavas, di Pellegrino, Farnè, & Zeloni, 1998; Mattingley, Driver, Beschin, & Robertson, 1997).

In sum, research to date supports an internal organization (differentiation) of the attentional system into distinct modality-specific and cross-modal mechanisms of attention. However, more detailed questions concerning further dimensions of differentiation within the attentional system and principles of modality-specific and cross-modal competition have not been extensively investigated. These questions constitute the focus of this report.

What determines a representation's competitiveness? The default position is that attention-based competition is governed largely, if not solely, by the representational strength (salience) or processing load (difficulty) imposed by the competing representations. We will refer to this as the *attentional load hypothesis*. According to this hypothesis, the more salient or attentionally demanding a stimulus representation, the more it will dominate the competition. If attention is viewed as a limited resource, this would imply that the more attentionally demanding a stimulus, the fewer the resources that will be available for other stimuli. This assumption makes predictions for subjects' abilities to process and/or ignore stimuli in tasks requiring either selective attention (Lavie, 1995; Rees, Frith, & Lavie, 1997) or divided attention (Lindsay, 1970; Moray, 1967; Shaffer, 1971).

Although there is considerable evidence that salience and processing load do contribute to competitiveness across a range of experimental paradigms (e.g., Duncan, 1987; Kleiss & Lane, 1986; Lavie, 1995), this does not rule out the possibility of additional competitive principles. For example, all theories of stimulus processing assume that a stimulus is processed through a number of stages of analysis or levels of representation, beginning with the most peripheral sensory levels and continuing through the processing of meaning. Given this, one possibility is that competition is modulated by the level of representation to which attention is directed. Consistent with this general notion of attentional differentiation, Wickens (1980, 1984) proposed a *multiple-resource model* in which attentional resources are dedicated to specific cognitive processes or structures. He specifically proposed distinctions between stages of processing (encoding/central-processing vs. responding), codes of processing (spatial and verbal), and modalities of input (visual and auditory) and output (vocal vs. manual). In our investigation, we examined this notion of a *structured* attentional system by specifically evaluating the hypothesis that attention-based competition between simultaneously presented stimuli is, at least in part, determined by whether attention is directed to the same or different representational levels for the competing stimuli. We were specifically concerned with evaluating the possibility that attention may be selectively directed to perceptual versus semantic representations. According to what we will refer to as the *levels-of-representation hypothesis*, competition should be greater when attention is directed to the same level of representation for multiple stimuli than when attention is directed to different levels of representation for multiple stimuli.

Relevant to the levels-of-representation hypothesis is Treisman and Davies's (1973) study, which specifically examined the relationship between modality and what the researchers referred to as *level of analysis* (comparable to our use of level of representation). In Experiment 2, they examined the ability of subjects to monitor for the presence of targets defined by either their physical attributes (the letters END or the sound "end") or their semantic attributes (animal names). Stimuli were presented in either the same or different modalities (visual and auditory), in divided versus focused attentional conditions. Treisman and Davies found that multiple stimuli in separate modalities were processed with greater accuracy and speed than multiple stimuli presented in the same modality, suggesting less competition between modalities than within (but see Wickens & Liu, 1988, for an alternative account of these findings). They also found that targets were identified more rapidly in the focused attention condition (in which subjects were required to monitor only one of the two stimuli presented) than in the divided attention condition (in which subjects were required to monitor both stimuli). The fact that there was a cost for dividing attention between two events both within and across modalities suggests a commonality of resources across modalities. Finally, Treisman and Davies did not find an interaction between target type (level of analysis) and across- versus within-modality monitoring. On the basis of this set of observations, these investigators concluded that there are modality-specific attentional capacities and, also, that there are limits to attentional capacity at both physical and semantic (or verbal) levels of analysis.

Treisman and Davies's (1973) results support the notion of both modality-specific and cross-modal attentional mechanisms. These investigators did not, however, examine the effects of competition when the modalities are monitored at *different* levels of analysis/representation. This question is central to what we have referred to as the levels-of-representation hypothesis and, thus, forms the focus of the present investigation.

Individuals suffering from the neuropsychological condition referred to as *extinction* provide a unique opportunity for investigating this question. As a result of damage to any of a wide range of neural structures, an individual may exhibit extinction such that a stimulus presented to the contralesional (CL) side of space can be detected when presented alone, but not when presented simultaneously with an ipsilesional (IL) stimulus (Posner, Walker, Friedrich, & Rafal, 1982). For example, an individual with right-hemisphere damage may have no difficulty detecting a single tap to either the IL (right) or the CL (left) hand but, when taps are presented to the right and the left hands simultaneously, will often miss the tap to the left hand. Extinction is assumed to be an attentional deficit because individuals exhibit intact sensory capacities in the affected modality (Rees et al., 2000). Extinction can be understood by assuming that the representation of a CL stimulus is less able than the representation of an IL stimulus to compete successfully for attentional selection.[1] Extinction occurs both intramodally, in response to multiple stimuli within a single sensory modality, and cross-modally, so that stimuli simultaneously presented in other modalities can serve to extinguish responses in the affected modality (Bender, 1952). For example, an individual may often fail to detect (may *extinguish*) a CL *tactile* stimulus when it is presented simultaneously with an IL *visual* event (see, e.g., di Pellegrino et al., 1997; Làdavas et al., 1998; Mattingley et al., 1997).

Cross-modal extinction, therefore, provides us with the opportunity to examine principles of multimodal processing by manipulating the manner in which attention is directed to competing stimuli. The severity of extinction serves as a convenient index of the competitiveness of the concurrent event. In other words, the competitiveness of a concurrent event is indicated by the degree of difficulty it creates for the processing of a stimulus presented in the impaired modality. In this investigation, we examined the performance of individuals suffering from somatosensory extinction in order to evaluate whether extinction is affected by the level of representation to which attention is directed. Specifically, we examined whether the degree of extinction to a CL tactile stimulus is influenced by whether attention is directed to the semantic versus the perceptual attributes of a competing visual or auditory stimulus.

INITIAL EVALUATION

The purpose of the initial evaluation was to establish that the subjects in the experiments suffered from cross-modal extinction and to determine which modalities were implicated. In the literature, there has been only a handful of reports of cross-modal tactile/visual extinction (e.g., di Pellegrino et al., 1997; Mattingley et al., 1997) and only one brief mention of tactile/auditory extinction (Bender, 1952).

Subjects

S.L.H. and G.A.S. are right-handed males who suffered cerebral vascular accidents (CVAs) 2 and 5 months, respectively, prior to the onset of this investigation. S.L.H. was a 76-year-old Ph.D. physicist with right anterior parietal, posterior frontal, and left occipital damage[2] that created reading difficulties and left hemiparesis (weakness on the left side of the body); his spoken language skills were excellent, and he suffered only minor visual field loss in the very far periphery of the left visual field. G.A.S. was a 70-year-old high school graduate and retired railroad employee with left occipital and parietal damage that created reading difficulties, right hemiparesis, a right visual field loss with foveal sparing, and mild spoken language impairments. Neither subject suffered from visual neglect or extinction.

Evaluation of Within- and Across-Modality Extinction

The subjects were tested in four stimulus conditions: (1) single CL tap, (2) single IL stimulus in one of three modalities (a tap, a visual finger flex [movement], or a brief tone), (3) double stimulation (a CL tap simultaneous with an IL competing stimulus in one of the three modalities), and (4) no stimulus. Unless otherwise indicated, the subjects were instructed to report the location of the stimulation by verbally responding "left," "right," "both," or "neither." These four conditions were presented randomly within blocks of 36 trials (8 CL, 8 IL, 16 double, and 4 none). The modality of the competing stimuli was held constant across trials within a block. All the tactile stimuli consisted of a light tap of the experimenter's finger, delivered to the subject's index finger(s). The subject was prevented from seeing the tactile stimulation by a cardboard cuff placed over the touched hand (Figure 1). On blocks in which no visual information was presented, the cuff was not used, and the subject was simply asked to close his eyes. Data were analyzed using a chi-square with a correction for continuity (Yates, 1934) and are reported for the subjects (S.L.H. and G.A.S.) individually.

We found that both subjects accurately detected IL tactile stimuli whether presented alone (96% and 98% cor-

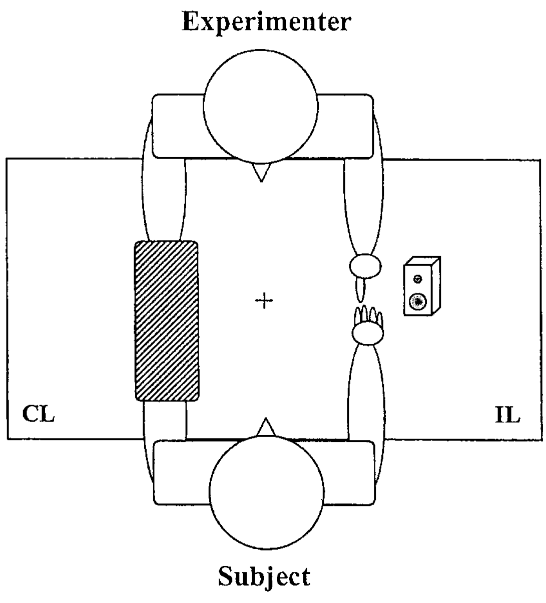

Figure 1. Diagram of the patient/experimenter setup. CL refers to the subject's contralesional side, and IL refers to the ipsilesional side.

rect for S.L.H. and G.A.S., respectively) or with simultaneous CL tactile stimulation (100% and 100% correct). Both subjects also accurately detected CL stimuli when presented alone (100% and 98% correct). However, as is indicated in Figure 2A, they both exhibited severe difficulty in detecting CL tactile stimuli when the stimuli were presented with simultaneous IL tactile stimuli (tactile/tactile conditions). Extinction severity was calculated as the difference in detection accuracy between trials in which a single CL stimulus was presented and trials in which a CL tactile stimulus was presented simultaneous with a competing stimulus. Tactile extinction affected S.L.H.'s left side [$\chi^2(1, N = 144) = 33.79, p < .001$] and G.A.S.'s right side [$\chi^2(1, N = 192) = 16.96, p < .001$].

Furthermore, Figure 2A indicates that both subjects also exhibited significant CL tactile extinction when the competing stimulus was visual [tactile/visual conditions; S.L.H., $\chi^2(1, N = 144) = 14.09, p < .001$; G.A.S., $\chi^2(1, N = 192) = 88.32, p < .001$] or auditory [tactile/auditory conditions; S.L.H., $\chi^2(1, N = 144) = 21.18, p < .001$; G.A.S., $\chi^2(1, N = 184) = 46.73, p < .001$].

Additional Extinction Evaluations

In addition to establishing the presence of within- and across-modality extinction, we also considered two other extinction-related issues.

First, we established that the cross-modal extinction effects were attentional, because we found that they were strongly modulated by instructions to *ignore* versus *attend* to the competing modality (analogous to the focused/divided attention conditions in Treisman & Davies, 1973). Although all other testing described in this paper was carried out under *standard* attend conditions, we found that when S.L.H. and G.A.S. were instructed to ignore the simultaneously presented auditory stimuli, CL tactile detection accuracy was 33% and 25% greater for S.L.H. and G.A.S., respectively.

Second, we found that tactile/auditory extinction did not require IL presentation of the competing auditory stimulus (Figure 2B). Significant CL tactile extinction occurred whether auditory stimuli were presented ipsilesionally [S.L.H., $\chi^2(1, N = 120) = 9.90, p = .001$; G.A.S., $\chi^2(1, N = 168) = 40.84, p < .001$], centrally

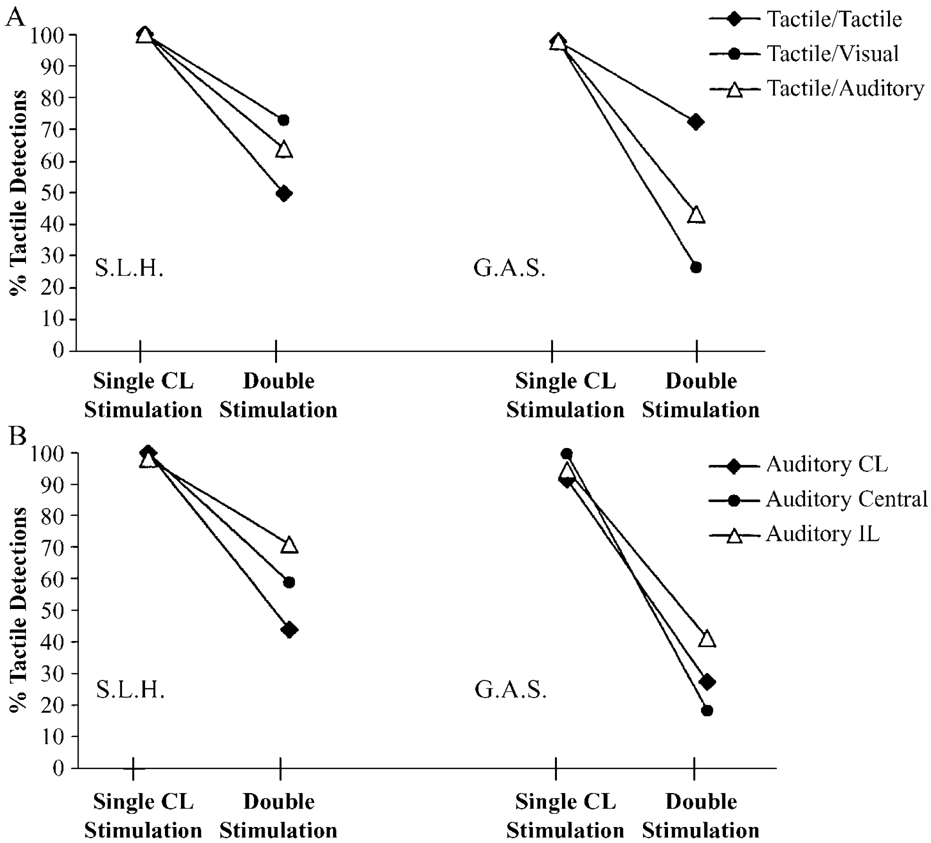

Figure 2. Initial extinction effects. (A) Percent correct contralesional (CL) tactile detection under conditions of single CL stimulation and double simultaneous stimulation for Subjects S.L.H. and G.A.S. Competing stimuli were tactile, visual, or auditory. (B) Percent correct CL tactile detection with single CL and double stimulation as a function of the location (CL, central, or IL) of a competing auditory stimulus.

[S.L.H., $\chi^2(1, N = 120) = 20.74, p < .001$; G.A.S., $\chi^2(1, N = 120) = 70.91, p < .001$], or contralesionally [S.L.H., $\chi^2(1, N = 24) = 5.00, p = .025$; G.A.S., $\chi^2(1, N = 144) = 51.69, p < .001$]. Extinction is typically evaluated only by presenting competing stimuli to the IL side; however, our findings indicate that extinction is not limited to situations involving lateralized competing events.

EXPERIMENT 1

The question that we were concerned with is whether or not attentional competition is modulated by the level of stimulus representation that a subject is attending to. To investigate this question, we examined whether competition among stimulus representations was affected by manipulating the level of representation (perceptual or semantic) to which attention was directed. According to the levels-of-representation hypothesis, competition should be greater when attention is directed to the same versus different levels of stimulus representation.

The subjects were always presented with a tactile stimulus in one of the following conditions: tactile stimulus to the CL hand, to the IL hand, or to neither hand. They were asked to report the location of the tactile stimulus by saying "left," "right," or "nothing." We assumed that this type of detection task requires attention to a perceptual level of representation. In addition, a simultaneous competing stimulus in another modality was presented on every trial. This dual-task paradigm allowed us to examine the degree of competition between the *competing* stimulus and the tactile stimulus in each of the conditions. Across blocks, we varied the manner in which attention was directed to the competing stimulus. Thus, two tasks were required on all the trials: (1) report the location of the tactile stimulus (a perceptual judgment) and (2) report on some attribute of the competing stimulus. In perceptual blocks, the subjects were instructed to make a perceptual judgment to a competing visual stimulus or an auditory stimulus; in semantic blocks, the subjects were instructed to report the semantic category of competing auditorily or visually presented words. Therefore, in perceptual blocks, the subjects were required to evaluate both tactile and competing visual or auditory stimuli at a perceptual level, whereas in semantic blocks, attention was directed to the perceptual level for the tactile stimuli, but to the semantic level for competing word stimuli. In this way, perceptual blocks constitute a same-level condition, and semantic blocks constitute the different-level condition.

This design allowed us to make use of tactile extinction to evaluate the levels-of-representation hypothesis. We assumed that degree of tactile extinction would serve as an index of a stimulus's competitiveness. If competition is indeed affected by the level of representation to which attention is directed, we should observe more tactile extinction in the same-level condition than in the different-level condition.

Method

Subjects. The subjects were the same as those in the initial investigation.

Stimuli and Procedure. CL detection accuracy was examined for tactile stimuli presented simultaneously with competing stimuli that required either perceptual or semantic judgments. For each block, a tactile stimulus was presented to the CL hand, the IL hand, or neither. In addition, a competing auditory or visual stimulus was presented on every trial. Thus, *on every trial, across all conditions*, the subject was required to report the location of the tactile stimulus (left, right, or nothing) *and* perform a categorization task regarding some attribute of the competing stimulus. The subjects were required to produce their response to the categorization task first and then their response to the tactile detection task.

In same-level (perceptual) blocks, the subjects reported on a perceptual attribute of the competing stimulus. Two perceptual tasks, tones and colors, were used in separate blocks. For the tone task, on each trial, the subjects heard a centrally presented tone (~68 dB, ~760 msec) and were instructed to report whether the tone was high or low. For the color task, on each trial, S.L.H. was presented a colored square that subtended 1.4º of visual angle and was displayed in the center of a computer screen for 300 msec. He was instructed to report whether the square was green or yellow.

In different-level (semantic) blocks, auditory and visual words were used as the competing stimuli (in separate blocks for each modality). The subjects were required to report the semantic category (animal or body part) of a presented word. The auditory word stimuli were from a set of 12 single-syllable words; each word was spoken aloud by the experimenter at ~70 dB, and they ranged from 400 to 900 msec in duration. The visual word stimuli consisted of three-letter words from a set of 12 words; each word was presented visually at the center of a computer screen. The words occupied 2.9º–3.5º of visual angle and were presented for 300 msec.[3]

In a control task designed to provide information regarding the attentional load imposed by the competing stimuli, neurologically intact individuals were asked to make judgments to visual and auditory stimuli (tones, color patches, and visual and auditory words) identical to those used in the competing task with the neurologically impaired subjects. The subjects rated the attentional demands of each task on a 5-point scale and ranked them in order of their attentional demands. Eleven volunteers were recruited from the student population at Johns Hopkins University to participate. Statistical significance was evaluated using a sign test with $\alpha = .05$.[4]

Results and Discussion

The results clearly support the levels-of-representation hypothesis. For both S.L.H. and G.A.S., the perceptual judgments to competing tones [S.L.H., $\chi^2(1, N = 384) = 96.78, p < .001$; G.A.S., $\chi^2(1, N = 288) = 68.14, p < .001$] and color patches [S.L.H., $\chi^2(1, N = 96) = 14.21, p < .001$] produced highly reliable decrements in CL tactile detection accuracy (Figure 3). In striking contrast, CL tactile detection was excellent when attention was directed to the semantic attributes of competing word stimuli (Figure 3). There was a reliable difference between the same-level and the different-level conditions with competing tones and aurally presented words [S.L.H., $\chi^2(1, N = 380) = 74.10, p < .001$; G.A.S., $\chi^2(1, N = 96) = 11.97, p < .001$] and with competing color patches and visually presented words [S.L.H., $\chi^2(1, N = 288) = 68.14, p < .001$].[5]

However, given the default hypothesis that attributes differences in competitiveness to differences in atten-

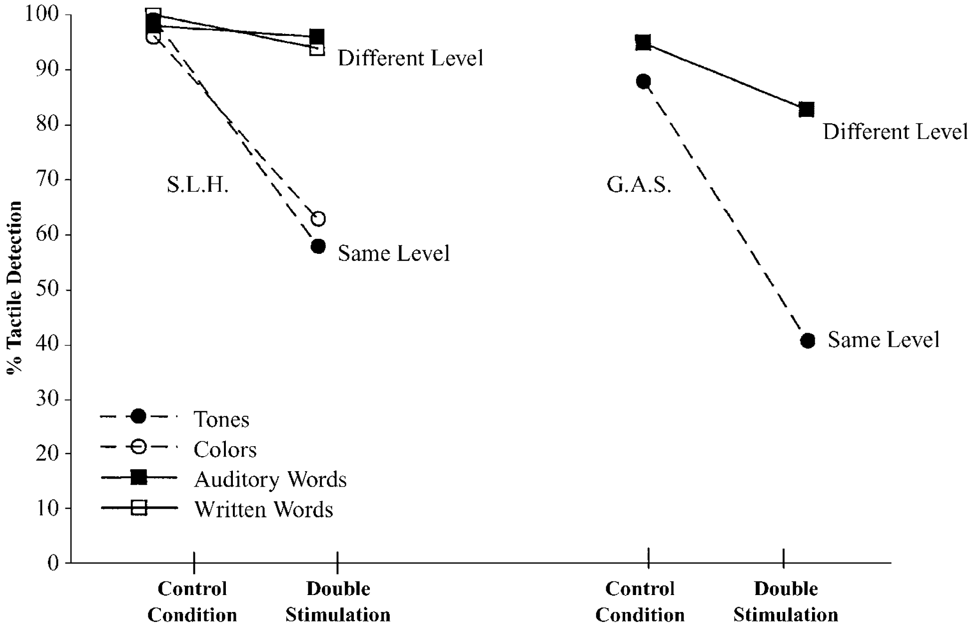

Figure 3. Effects on contralesional (CL) detection accuracy when the perceptual attributes of the CL tactile stimulus and competing tones or color patches were attended to (same-level condition), as compared with CL accuracy when the perceptual attributes of the CL tactile stimulus and the semantic attributes of a competing word were attended to (different-level condition).

tional load, it is important to evaluate the attentional load imposed by the competing stimuli in same-level versus different-level conditions. Given the results obtained, one concern could be that a greater attentional load is imposed by the color/tone tasks of the same-level condition than by the semantic categorization task of the different-level condition. An adequate test of the levels-of-representation hypothesis requires that the load imposed by the competing stimuli be equivalent across conditions or, if anything, that it be less for the same-level condition.

The results of the control study carried out with neurologically intact individuals provided an independent measure of the load imposed by the different competing stimuli. Recall that the subjects carried out the competing tasks and then both rated and ranked them in terms of their attentional demands. The results reveal that the subjects judged the attentional demands of the perceptual judgment tasks to be significantly lighter than those imposed by the semantic categorization tasks (tones vs. auditory words, $p < .0005$; color patches vs. visual words, $p < .05$). Thus, the competing perceptual tasks required in the same-level condition were judged to be less demanding than the competing semantic tasks in the different-level condition. This biases the results *against* the levels-of-representation hypothesis and, thus, serves to increase confidence that the obtained results do, indeed, constitute evidence in its favor.

In sum, for both S.L.H. and G.A.S., CL tactile detection accuracy (assumed to require attention to a perceptual level of stimulus representation) was severely affected when the subjects were required to monitor the perceptual attributes of a competing stimulus in another modality, but not when they were required to monitor the semantic attributes of the competing stimulus. This occurred despite the fact that monitoring the perceptual attributes was judged to be simpler and less demanding than monitoring the semantic attributes.

EXPERIMENT 2

The results of Experiment 1 cannot be explained by appealing to cognitive load alone. However, we wanted to guarantee that there were no other differences between the same- and the different-level conditions that could account for the observed differences in extinction severity. Recall that in Experiment 1, words were used as competing stimuli in the different-level condition and color patches or tones were used in the same-level condition. To rule out the possible contribution of stimulus differences, we conducted a second experiment in which we used words (visual or auditory) as competing stimuli for *both* perceptual and semantic judgments. In Experiment 2, identical stimuli were for same- and different-level conditions. In perceptual blocks, the subject (S.L.H.) was instructed to detect a tactile stimulus and to simply report the presence/absence of a visual or an auditory event. In this way, the perceptual task (detection) performed with the competing stimulus was even simpler than that in the first experiment (green/yellow or high/low tone judgments). Different-level blocks requiring semantic judgments were unchanged.

Method

Subject. S.L.H. (described in the Initial Evaluation section) participated in this experiment.

Stimuli and Procedure. The competing stimuli differed from those in Experiment 1 in that both perceptual and semantic judgments involved *identical* stimuli—auditorily or visually presented words. The different-level trials were identical to those in Experiment 1: The subject categorized word targets as animals/body parts and detected the presence or absence of a CL tactile stimulus. In contrast to Experiment 1, however, the perceptual task of same-level blocks merely required detecting the presence of a word stimulus. On the same-level trials, the subject was told to report any stimuli presented including a CL tactile stimulus and/or a centrally presented word (auditory in some blocks, visual in others). On same-level trials, the subject was asked simply to state "touch," "word," "both," or "neither" for each trial.

Results and Discussion

The results reveal that the same competing word stimulus had strikingly different *extinguishing* consequences for detection of a CL tactile stimulus, depending on whether attention was directed to the competing word's perceptual or semantic attributes (Figure 4). A comparison of CL detection accuracy between the same-level conditions and the different-level conditions revealed a substantial difference in extinction for both auditory stimuli ($N = 248$, $p < .001$) and visual stimuli ($N = 104$, $p < .001$).

As in the first experiment, the attentional requirements of processing the competing stimuli were evaluated by 5 subjects in a control experiment. These subjects rated the perceptual task (simple detection) to be easier than the semantic categorization task for both auditory ($p < .05$) and visual ($p < .05$) stimuli.

Experiment 2, therefore, replicated the findings of Experiment 1, showing that directing attention to different levels of processing with multiple stimuli produces less extinction than does directing attention to the same level of processing. Experiment 2 also allowed us to rule out the possibility that the findings of Experiment 1 resulted from differences in the stimulus attributes of the competing stimuli in same- versus different-level conditions.

GENERAL DISCUSSION

We found that in individuals suffering from somatosensory extinction, the ability to detect a CL tactile stimulus is severely affected when attention is directed to the *perceptual* attributes of a competing stimulus, although the ability to detect the CL stimulus is largely unaffected by directing attention to the *semantic* attributes of the competing stimulus. These findings have implications for our understanding of both the neuropsychological consequences of damage to the parietal lobes and the structure and mechanisms of attention.

Damage to the parietal lobes has long been associated with deficits of attention, specifically with neglect and extinction (Posner et al., 1982). The results we report extend this understanding in a number of ways. First, we add to the handful of reports of tactile/visual extinction that have been described in the literature. Second, we describe two cases of tactile/auditory extinction, where there has been, to date, only one brief mention of this phenomenon (Bender, 1952). Third, we report, for the first time, clear evidence that the extinguishing effects of competing stimuli are not uniform but, rather, dependent on the manner in which attention is directed to the competing stimuli.

With regard to our understanding of attention, we find that the competitiveness of a stimulus does not arise merely by virtue of processing it, since in these experiments, all the *competing* stimuli were successfully processed (categorized or detected); instead, we find that competitiveness is determined by the manner in which attention is directed to the competing stimulus. Further-

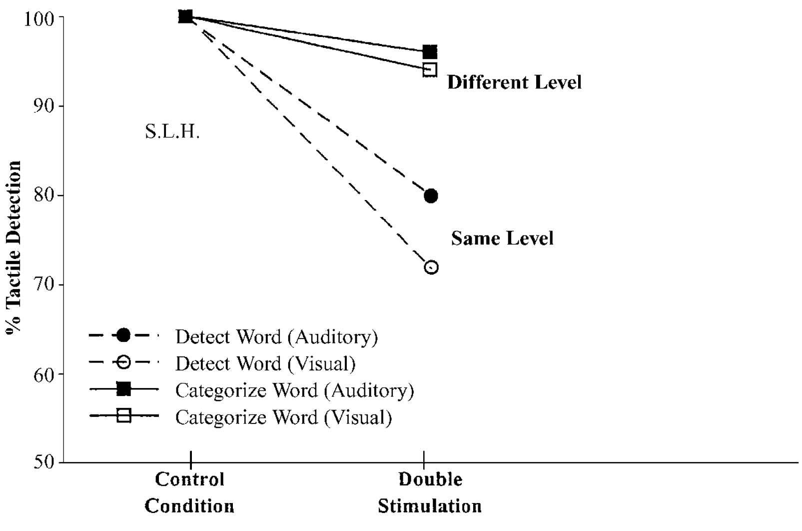

Figure 4. Effects on contralesional detection accuracy of attending to the same level versus a different level, using word stimuli as competing events (S.L.H. only).

more, the fact that extinction was present in the context of the relatively light demands of perceptual detection conditions and was largely eliminated under the cognitively more demanding semantic judgment conditions is incompatible with the view that attentional competition is governed solely by the strength of the attentional demands imposed by the competing events. Thus, an attentional load hypothesis alone cannot account for these findings. Instead, the fact that cross-modal extinction was present when perceptual judgments were required of both stimuli reveals that different principles of attentional competition apply when representations compete for selection at the same versus different levels of processing. These findings reveal an attentional system in which stimulus representations do not compete indiscriminately with one another; rather, they reveal an attentional system that is differentiated, not only by modality, but also according to level of representation.

It is worth noting that although it is certainly far from clear whether the perceptual/semantic distinction is the best characterization of the difference between the levels of representation that are attended in these experimental tasks, it is fairly clear that the spatial/verbal distinction proposed in other work (e.g., Wickens, 1980, 1984) would not be a more appropriate one. Although our semantic conditions may very well be appropriately characterized as *verbal*, the perceptual conditions requiring simple detection or color or tone categorization do not correspond to spatial judgments. It is clear that extensive research will be required to establish the precise characterization of the relevant representational levels; these may turn out to include, but not be limited to, perceptual, spatial, verbal, and/or semantic levels.

One concern regarding our findings is that the differences we observed in the magnitude of CL extinction in the same-level (perceptual) versus the different-level (semantic) conditions derived not from selective attention to different levels of representations, but from a difference in the times at which perceptual and semantic representations are computed. According to such a hypothesis, in the same-level condition, perceptual representations of the tactile and competing visual (or auditory) stimuli were computed (and therefore attended) virtually simultaneously, producing extinction effects. In contrast, extinction was largely absent in the different-level condition because, in that condition, the perceptual information required for the CL tactile detection task was computed earlier than the semantic information required for responding to the IL stimulus. This *timing offset* account is unlikely to be correct, given what is known about differences in sensory processing times in the different modalities (e.g., Andreassi & Greco, 1975). Thus, stimuli that are presented to a subject simultaneously in different modalities are not actually processed simultaneously at a perceptual level. For example, a visual stimulus presented at the same time as a tactile one will be perceived to have been presented later (Spence, Shore, & Klein, 2001). Similarly, visual and auditory stimuli that are presented simultaneously are perceived to have been presented at different times (Stone et al., 2001). However, despite these differences in the onset of perceptual processing for stimuli from different modalities, our results show that simultaneously presented stimuli produce strong extinction effects in the same-level condition. The occurrence of extinction in the same-level condition with stimuli that are, presumably, *perceptually offset* makes it more difficult to argue that timing offsets per se could account for the virtual elimination of extinction in the different-level conditions.[6] Interestingly, Treisman and Davies (1973) empirically examined the possibility that synchronous versus asynchronous arrival times could account for the differences they observed in the processing of multiple stimuli in the same versus different modalities. They did so by introducing an average asynchrony of one sixth of a second between paired auditory words in the semantic monitoring task. They reasoned that if asynchronies in the cross-modality condition allowed for superior processing, then introducing asynchronies in the within-modality condition should lead to improved performance. However, they found no evidence that this degree of asynchrony made the task any easier.

Another related *timing* concern might be that in the semantic condition, the subjects *strategically deployed* attention to the IL stimulus at a different time than they did to the CL stimulus. This also seems unlikely because, if the subjects were able to control the timing of attentional deployment, they should have done so in all the conditions, not simply in the different-level conditions. In sum, although a definitive answer to questions regarding the importance of timing may ultimately require extensive parametric manipulation of stimulus onset asynchronies and the use of other experimental techniques, there are, at present, good reasons to suppose that it will be difficult to account for the findings we have reported without assuming that attention can be selectively directed to different representational levels.

In attempting to integrate the findings we have reported here with the evidence of modality-specific and cross-modal attentional mechanisms reviewed in the introduction, we begin to see the outlines of an attentional system in which modality-specific attentional processes are followed by cross-modal (or supramodal) attentional mechanisms that are specific to perceptual and semantic levels of representation. As Treisman and Davies (1973) suggested, multiple stimuli (from either the same or different modalities) are in competition at supramodal perceptual and semantic levels when subjects monitor multiple stimuli at one of these levels. Our results extend these findings by providing evidence that the attentional mechanisms or capacities of the perceptual and the semantic levels are sufficiently independent that one level can be monitored with limited consequences for the other.

These conclusions suggest that when an individual is faced with events in different modalities, stimulus representations at perceptual and semantic levels may be attended in a noncompetitive manner. In contrast, it seems that competitive principles apply to control access to perceptual attention and selection. In this way, the brain favors attentive perceptual processing of a stimulus in one modality, albeit at some expense to stimuli in other modalities. These behavioral findings are consistent with the previously mentioned observations that attentionally demanding processing in one modality leads to a reduction in neural activity in cortical areas corresponding to other modalities.

It is important to note that neither this work nor other work on cross-modal attention addresses basic questions concerning the underlying mechanisms that give rise to the cross-modal attentional effects that have been reported. One possibility is that cross-modal effects result from direct modality-to-modality connections that may be either facilitatory or inhibitory (Spence & Driver, 1996). Another possibility, however, is that the cross-modal perceptual and semantic attentional capacities we have described correspond to supramodal (or amodal) levels of representation that are independent of modality (Driver & Spence, 2000). Adjudicating between these hypotheses is not straightforward and will clearly require considerable empirical and theoretical work.

In conclusion, we have reported on the results of an investigation of the tactile detection abilities of two neurologically injured subjects suffering from tactile attentional deficits. This work clearly reveals that the competitiveness of a stimulus is not determined solely by its perceptual and semantic properties, but also by the manner in which attention is directed to those properties. These findings contribute not only to our understanding of cross-modal attention, but also to broader issues of attention, cognitive load, divided attention, and the psychological refractory period (Norman & Bobrow, 1975; Pashler, 1994; Pashler & Johnston, 1998). In this context, our conclusions raise a number of questions. Do the same principles apply to multiple events within the same modality? Are the modalities symmetrical with respect to their competitiveness, or do certain modalities have a competitive advantage in attentive perceptual processing? How are levels best characterized? Under what conditions will these competitive principles be revealed in neurologically intact subjects?

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NOTES

1. The reasons for the failure of the CL stimulus to be attended are as varied as are current conceptualizations of attention; thus, extinction has been attributed to a disruption of CL spatial representations (Bisiach & Luzatti, 1978), a failure of attentional disengage/engage mechanisms (Posner, Cohen, & Rafal, 1982), loss of competitive weighting (Desimone & Duncan, 1995), disruption of hemispheric attentional gradients (Kinsbourne, 1987; see also Heilman, Watson, & Valenstein, 1987), and so forth.

2. This left-hemisphere damage may have been caused by an earlier undiagnosed infarct.

3. Stimulus durations were approximately matched within modality (e.g., tones and spoken words) across conditions (same vs. different level) so that any differences between the conditions could not be attributed to differences in stimulus duration or intensity. In Experiment 2, the use of identical stimuli across same- versus different-level conditions eliminated this concern altogether. However, the fact that the stimuli were not matched across *modalities* precludes comparisons of the magnitude of extinction effects across modalities of competing stimuli.

4. There are a large number of methods that could be used for assessing attentional or cognitive load, none of which is without interpretative difficulties. Therefore, although subjective report has a number of obvious limitations, it is a measure that has been used fairly extensively, and some researchers have argued strongly for its appropriateness (Sheridan, 1980).

5. The same results were obtained in a similar experiment in which subjects were asked to read, rather than semantically categorize, competing word stimuli.

6. This is not to suggest that timing is entirely irrelevant; if stimuli are presented offset by several seconds, we would expect a reduction in extinction regardless of the task. It is also conceivable that the offsets created by differences in sensory processing times are just enough smaller than those that might be created by differences in computation time for perceptual and semantic representations to account for the results we have reported. An examination of the extinguishing consequences of small-magnitude timing offsets is quite complex and would require further experimentation, employing techniques such as event-related potentials that might allow for an independent assessment of sensory processing (or cortical arrival) times.

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