Dissecting Spatial Visual Attention

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I. Introduction and Background

The study of attention had a prominent place at the birth of psychology as a scientific discipline. Wundt devoted the first chapter of his *Einfuhrung in die Psychologie* (Introduction to Psychology) to attention. Wundt commented, for example, "If we practise letting our attention wander over the different parts of the field of vision while keeping the same fixation-point, it will soon become clear to us that the fixation-point of attention and the fixation-point of the field of vision are by no means identical" (p. 20, 1912/1973).

It has been recognized that there are at least two forms of spatial attention in vision. For example, Wundt (1902) commented that attention could be "involuntary" or "voluntary." A variety of distinctions have been made that more or less correspond to Wundt's distinction including goal-directed attention vs. stimulus-driven capture and endogenous attention vs. exogenous attention. The terms that are used to label these forms of attention are not important. The critical question is whether these two forms of attention involve the same or different mechanisms; and if they involve different mechanisms what are those mechanisms? Modern investigators have largely been unclear whether voluntary and involuntary attention are mediated by different mechanisms, or whether they are simply different means of controlling a single mechanism. Rather, most contemporary investigations have focused on the properties of different methods of summoning attention. The assumption is often made that involuntary attention has the same effect on perceptual processes as voluntary attention (Rauschenberger, 2003) and that they effect the same neural mechanisms (Gazzaniga, Ivry, & Mangun, 1998).

The research reported here challenges this assumption. Three separate behavioral paradigms demonstrate that voluntary and involuntary attention have different consequences. Furthermore, neural imaging (Esterman, Prinzmetal, DeGutis, Landau, Hazeltine, Verstynen, & Robertson, under review) and EEG studies (Landau, Esterman, Robertson, & Prinzmetal, under review) demonstrate that they involve different neural mechanisms. Voluntary attention enhances the perceptual representation so that the observer has a more veridical perceptual representation of stimuli in an attended location than in an unattended location (e.g., Lu & Dosher, 1998; Prinzmetal, 2005). Involuntary attention, on the other hand, does not enhance the perceptual representation, but rather works on a non-perceptual priming mechanism that only affects response time.

Although we are interested in the distinction between voluntary and involuntary attention in a variety of paradigms, an excellent way of separating voluntary and involuntary spatial attention is vision is the spatial cueing paradigm developed by Posner and his colleagues (Posner, 1980).

In the spatial cueing paradigm, subjects engage in either a simple target detection or target identification task. Before the target appears, a location is "cued" with, for example, a box changing color or brightening. A version of this paradigm is illustrated in Figure 1.

Insert Figure 1 about here

In this version, the task was to indicate which of two target faces was presented by pressing a button. The cue consists of one of the boxes getting thicker and turning red (dashed line in the figure). There are two kinds of trials. On valid trials, the cue indicates the target location. On invalid trials, it indicates a nontarget location. Eye movements are always monitored. Subjects are trained to not move their eyes and trials on which eye movements are made are eliminated from the analysis. The general idea is that subjects will "attend" to the cued location and that target detection or identification will be better on valid trials than on invalid trials.

Posner and his colleagues (e.g., Posner, Snyder, & Davidson, 1980) had subjects engage in various detection and identification tasks. The onset of the cue preceded the onset of the target by 1 second, and the cue was always informative of the target location. For example, 75% of the trials were valid, and 25% were invalid. Subjects were faster on valid trials than invalid trials in both detection and identification tasks. The notion was that the cue enabled subjects to voluntarily shift their attention to the cued location. When the target appeared in that location (valid trials), subjects were already attending to that location when the target appeared. On invalid trials, subjects had to switch their attention causing longer reaction times (RTs).

Jonides (1976, 1981) demonstrated how this task could be used to investigate voluntary vs. involuntary attention. With the experiment described in Figure 1, to study voluntary attention, the cue was made informative or predictive about the target location as in the Posner, et al. studies. In this situation it is strategically advantageous for the subject to voluntarily attend to the cued location. To study involuntary attention, the cue was made noninformative or nonpredictive as to the target location. Thus with two possible target locations, 50% of the trials are valid, 50% are invalid. Jonides found that both predictive and nonpredictive cues affected performance in RT experiments: subjects were faster on valid trials than invalid trials. Thus simple RT experiments do not discriminate voluntary and involuntary attention.

Posner and his colleagues used a central cues that was predictive of the target location, whereas Jonides often used a peripheral cue. For many years investigators believed that the main difference between these experiments was whether the cue was in central vision and symbolic of the target location or in peripheral vision and directly indicated the target location (e.g., Briand, & Klein, 1987). However, since that time, numerous investigators have found the peripheral nature of the cue is not necessarily critical for involuntary attention and some central cues can behave identically to cues in the periphery (Driver, Davis, Ricciardelli, Kidd, Maxwell, & Baron-Cohen, 1999; Lambert & Duddy, 2002; Langton, Watt, & Bruce, 2000; Ristic et al., 2002; Tipples, 2002). In order to engage voluntary attention in this paradigm, at least two factors must be present. First, the cue must be predictive of the target location. In all of the studies reported in this chapter, we compared predictive and nonpredictive cues, *ceteris paribus*. That is, we used the same task, stimuli, timing and cues so that the differences we found could only be attributed to the predictability of the cues.

Interestingly, different results can be obtained between predicive and nonpredictive cues even of the subjects are not aware of the proportion of valid trials (e.g., Decaix, Seíroff, & Bartolomeo, 2002; Bartolomeo, Decaix, & Siéroff, in press).[1] However, even with noninformative cues, differences in performance can be obtained by telling subjects that it is to their interest to attend to the cues or not (Jonides, 1981). Thus both probability and instructional manipulations can engage the voluntary attention mechanisms.

The second criterion for engaging voluntary attention is that the SOA must be sufficiently long, over about 200 ms. (Luck, Hillyard, Mouloua, & Hawkins, 1996). Involuntary attention has its effect almost immediately and then its effect dissipates with time (e.g., Wright, & Richard, 2000). The difference in time course of voluntary and involuntary attention is seen most clearly in the anti-cueing paradigm (Posner, et al., 1982; Sereno, & Holzman, 1996; Warner, et al, 1990). In this paradigm, a locationed is cues, as in the standard spatial cueing paradigm. However, there is a low probability that the target will be in the cued location, and a high probability that it will be in the opposite (uncued location). To illustrate this, in an unpublished study (Prinzmetal & Wang, 2005) we had 4 possible target locations around the fixation point (above, below, left and right). Subjects had to identify a target (the letter F or T) and there were two SOAs, 40 ms and 600 ms. On 20% of the trials, the target was in the cued location, but on 80% of the trials it was in the location opposite the cue. Subject averaged about 92% correct and the dependent variable is RT on correct trials (Figure 2). On the short SOA condition, subjects were faster when the target was in the cued (low probability) location. This effect represents involuntary attention. At the longer SOA, subjects are faster when the target appeared in the opposite location (also see, e.g., (Decaix, Seíroff, & Bartolomeo, 2002; Posner, Cohen, & Rafal, 1982; Sereno, & Holzman, 1996; Warner, Juola, & Koshino, 1990). The interaction shown in Figure 2 is significant ($F(1,15) = 3.15$, $p < .05$).

Insert Figure 2 about here

Hence, voluntary attention and involuntary attention clearly differ in their temporal properties. Involuntary attention is transient in nature and has its largest effect at short SOAs while voluntary attention has its largest effect at longer SOAs (also see Berger, Henik, & Rafal, 2005). The issue is whether they only differ in their time courses or whether then also different in their effect on behavior and their neural mechanisms. We argue that they have different effects. Voluntary attention enhances the perceptual representation so that there is more information about an attended object whereas involuntary attention does not effect perception, but rather primes responses to anything similar to the target in the cued location. Thus involuntary attention may have more to do with action systems than perceptual systems (Allport, 1989).

In the sections below, we illustrate 3 behavioral differences between voluntary and involuntary attention. We also demonstrate differences in cortical activation seen in fMRI and high frequency gamma EEG activity. In all of the experiments we either manipulate SOA or use an SOA that is sufficient to evoke both voluntary and involuntary attention. All of the experiments use a peripheral cue and hence evoke involuntary attention. In most cases, the important independent variable is whether the cue is informative of the target location or not. To study involuntary attention, the cue is made not predictive of the target location. To study voluntary attention, we make the cue predictive of the target location, thus adding a voluntary component.

II. Accuracy and RT

The inspiration for these experiments was a series of studies on the effect of attention on stimulus qualia (e.g., Prinzmetal, Amiri, Allen, & Edwards, 1998; Prinzmetal, & Wilson, 1997). For example, one set of experiments examined the effect of attention on phenomenal brightness and contrast (Prinzmetal, Nwachuku, Bodanski, Blumenfeld, & Shimizu, 1997). In these experiments, attention was manipulated in various ways and the dependent variables related to the accuracy of perception. In several cases, we failed to obtain an effect of attention using the spatial-cueing task unless there was location uncertainty (discussed below). However, all of these early experiments were designed around accuracy as the dependent variable and so we did not know whether we would have obtained the usual RT effects.

We carried out a series of experiments in which we first conducted the usually RT experiment in which subjects were over 90% correct and RT was the variable of interest (Prinzmetal, McCool, & Park, 2005a). In every experiment subjects were faster on valid trials than invalid trials, regardless of whether the cue was predictive of the target location (voluntary attention) or not (involuntary attention). In each of these experiments, the voluntary and involuntary attention conditions were run with different groups of subjects.

Having ascertained that we obtained the usual RT effects of Posner and colleagues, and Jonides, we ran accuracy versions of the same experiments. In the accuracy experiments, we made the discrimination difficult by changing some aspect of the stimulus. For example, in a face discrimination task shown in Figure 1, we morphed the faces to be more similar to each other. Subjects were instructed to take their time and be as accurate as possible. Immediate feedback was give when subjects erred.

Typical results for the face stimuli are show in Figure 3. The left panel shows the results of a RT experiment in which the face discrimination was easy, subject were quite accurate (>90% correct), and speed was emphasized (from (Landau, Esterman, Robertson, & Prinzmetal, under review). The right panel shows the results of a separate experiment in which the faces were morphed to yield a difficult discrimination and accuracy was emphasized. In each RT experiment, subjects were significantly faster on valid trials than invalid trials. In every accuracy experiment, subjects were more accurate on valid than invalid trials, but only when the cue was predictive of the target location (i.e., voluntary attention. When the cue was not predictive, there was no difference between valid and invalid trials in accuracy.

Insert Figure 3 about here

Prinzmetal, McCool, and Park (2005a) obtained this pattern of results, not only with faces as stimuli, but also with letter discrimination (e.g., was the target the letter F or T) and line orientation discrimination (horizontal or vertical). This pattern of results was obtained with and without post-stimulus masks (cf. Smith, 2000), on a white background or black background, and with SOA's from 0 ms. (simultaneous onset of cue and target) to 300 ms. Different cues were used including visual onsets and auditory cues from speakers located to the left and right of the subject (see Spence, 2001). In 19 experiments reported by Prinzmetal, McCool, and Park, we found the same pattern. In experiments designed around RT, subjects were faster on valid trials than invalid trials regardless of whether the cue was predictive or not. However, in experiments designed around accuracy, subjects were more accurate on valid than invalid trials only with voluntary attention (e.g., predictive cues).

A few previous investigators had found that subjects were more accurate on valid than invalid trials with nonpredictive spatial cues (e.g., Handy et al. 1996;

Dufour, 1999; Klein & Dick, 2002; Carrasco et al. 2004; Awh & Oh 2005). We were able to replicate each of these studies and demonstrate that the results were due to a factor confounded with involuntary attention. For example, Dufour (1999) did not monitor eye movements. We replicated his results, but when we monitored eye movements, the effect disappeared (Prinzmetal, Park, & Garrett, 2005b). Other results could be accounted for by other confounds (see Prinzmetal, Park, & Garrett, 2005b). Many of the results in the spatial cueing paradigm can be accounted for by location uncertainty (Luck, & Thomas, 1999; Shiu, & Pashler, 1994). Location uncertainty arises when there are several possible stimulus locations and subjects are uncertain as to which contains the target. The quality of the perceptual representation might be the same in both cued and uncued locations, but if subjects have a tendency to base their responses on information in the cued location they will be more accurate on valid trials (where target information is in the cued location) than on invalid trials (where target information is in the uncued location.)[2]

We have demonstrated that the results of Carrasco et al. (2004) could be accounted for my location uncertainty (Prinzmetal, Long, & Leonhardt, under review; also see P. Smith in this volume). The effect of location uncertainty can be very subtle. Consider a recent experiment by Awh and Oh (2005). Each trial began with a fixation point (see Figure 4A), followed by a nonpredictive spatial cue (Figure 4B), a stimulus that contained a digit (Figure 4C) and a mask (Figure 4D). The stimulus consisted of a cluster of 9 alphanumeric characters, the center character was a digit.

Insert Figures 4 and 5 about here

The task was to indicate which digit had been presented and there were 4 possible locations where the cluster of characters could appear. In previously unpublished data, we (Prinzmetal and Le, 2005) replicated Awh and Oh: Subjects were more accurate with valid than invalid trials (t(13) = 4.36, p< .05, see Figure 5, diamonds). Awh and Oh argued that since it was clear to subjects which of the 4 quadrants contained the target, there was no location uncertainty. However, given that with a brief exposure the perceived location of an object may different from the actual object (Prinzmetal, 2005) perhaps the dot help subjects know which item within the cluster was the digit. We tested this by replacing the dot cue with a box that surrounded the entire cluster of characters. The effect of the cue vanished, there was no significant difference between valid and invalid trials (t(13) = 0.20, see Figure 5, circles).

In summary, in every RT study that we have conducted, subjects are faster on valid trials than invalid trials regardless of whether the cue was predictive or not. In every study we have conducted designed around accuracy, with voluntary attention, subjects are more accurate on valid than invalid trials. However, across a large number of studies with only involuntary attention, we have not observed even one study where involuntary attention improved accuracy.

III. RT and Perceptual Difficulty

The results in the previous section demonstrate a dissociation between voluntary and involuntary attention across different dependent variables. We have conducted another series of experiments within RT where we varied the perceptual difficulty of the task (Prinzmetal, Zvinyatskovskiy, Gutierrez, & Dilem, under review). The preferential allocation of processing resources should have its greatest effect with a perceptually difficult task than a perceptually easy task. A perceptually easy task, one that can be accomplished without much "attention," should show a relatively small effect of an attentional manipulation. Thus in an experiment with predictive spatial cues, the effects of the cue (difference between invalid and valid RTs) should be larger with a perceptually demanding task than an easy task (e.g., Briand & Klein, 1987; Soetens, et al. 2003; cf. Johnston, et al. 1995).

We made the opposite prediction for involuntary attention: The effect of attention should be less with a perceptually difficult task. The effect of involuntary attention is transient, it decreases with time (e.g., Nakayama & Mackeben, 1989; Berger, et al., 2005). Hence, making the task perceptually difficult would increase the time before response selection and the transient benefit of the cue would have had time to dissipate. Thus we predicted that increasing perceptual difficulty would increase the effect of a predictive spatial cue (voluntary attention) but decrease the effect of a nonpredictive spatial cue (involuntary attention).

We have found this interaction in a number of studies (Prinzmetal, Zvinyatskovskiy, Gutierrez, & Dilem, under review). One of the experiments is illustrated in Figure 6. There were 4 possible target positions. One of the positions was cued with a box, 280 ms. before the target appeared. Subjects responded whether the display contained an F or T. For the easy task the target was surrounded by the letter O (e.g., OFO – left panel). This task is easy because the targets can be discriminated by a single feature (the "– "in the F). Hence, this task was called the feature condition. For the difficult task, the target was surrounded by the letter H (e.g., HFH – right panel). The targets cannot be discriminated by a simple feature, and subjects must correctly conjoin the features, a process that has shown to require attention (e.g., Treisman & Schmidt, 1982; Prinzmetal, et al., 1986). We call this the conjunction condition. For half the subjects, the cue was predictive of the target location (voluntary attention) and for half it was random with respect to the target location (involuntary attention). There were 12 subjects in each group.

Insert Figure 6 about here

For the predictive group, there was a significant interaction such that the effect of attention was larger in the conjunction condition than the feature condition (Figure 7a). This result replicates Briand and Klein (1987) and Soetens, et al. (2003). For the nonpredictive group, there also was a significant interaction, but the results were in the opposite direction: The feature task had a significantly larger attention effect than the conjunction task (Figure 7b). The 3-way interaction between group, cue validity, and difficulty was significant. We twice replicated this finding with small procedural variations. Interpreting interactions in RT is difficult, but a strong aspect of these data is that there is no simple monotonic transformation that can lead to the pattern in Figure 7 (Loftus, 1978).

The results for the nonpredictive group were in contrast to those of Briand (1998) who reported that both predictive and nonpredictive peripheral cues led to the same results (i.e., the pattern in Figure 7a). We were able to demonstrate that Briand's results were due to the uncontrolled eye movements.

Insert Figure 7 about here

In summary, one would expect that a perceptually difficult task would demand more "attention" than an easy task. Hence the affect of a spatial cue (measured in RT) should be greater for an difficult task than a easy task. We found this effect only with predictive cues. With involuntary attention, we obtained the opposite effect: a larger cueing effect with the easy than the difficult task.

III. Characterizing Involuntary Attention

Voluntary attention is easy to characterize: It enhances the perceptual representation so that we have a more veridical view of objects that we are attending to than to objects we are not attending to. Voluntary attention leads to higher accuracy. The effect of voluntary attention is greater with a perceptually demanding task than an easy task.

The purpose of this section is to characterize involuntary attention. There are scant theories of involuntary attention that do not involve perceptual processes. Here we briefly describe such a theory, and preliminary test of the theory. The theory is part of the class of accumulator models (e.g., Grice, 1972; Smith, & Vickers, 1988). In particular, we use aspects of the "Leaky Accumulator model" of Usher and McClelland (2001, see P. Smith, this volume, for a similar use of accumulator models). The model we describe is to account for performance in a direct cueing experiment, with two targets and two possible stimulus locations. The model assumes that there are 4 accumulators: two accumulators sum evidence for targets 1 and 2 in the left display position and two accumulators sum evidence for targets 1 and 2 in the right display (see Figure 8). Unlike previous models, we assume that evidence for the alternative targets accumulates separately for each display position. The assumption is consistent to the claim that independent decisions are made for targets at each location. There is considerable evidence in support of this claim (Shaw, 1982). When evidence in anyone of the accumulators reaches a threshold, the subject responds.

Insert Figure 8 about here

When a location is cued (left location in this example), both target accumulators in the cued location are incremented (diagonal stripes in Figure 8). This activation "leaks" away with time, so that the effect of the cue is transient. When a target appears, evidence for that target/location accumulates on top of the cue-related activity. If the target appears in the cued location shortly after the cue, activation will reach threshold rapidly (valid trials, solid arrow, left panel). However, on an invalid trial, it will take longer for activation to reach threshold (dashed arrow, right panel). In the model, activation related to the cue (striped bars) is not information that enables one to discriminate the targets. Information represented by the arrows does discriminate targets. That is, the rate of accumulation of information indicated by the arrows is identical for *involuntary* attention. In contrast, voluntary attention does affect the rate of information accrual. In speeded experiments, the response is determined by which accumulator first reaches a threshold.

In the model, speed pressure is equivalent to lowering the threshold at which the subject responds. If the threshold is lowered sufficiently, activation from the cue may trigger a response. Hence one would expect more FAs when the nontarget (a stimulus subjects are suppose to **not** respond to) appears in the cued location than when it appears in the uncued location. This prediction is the opposite of what one would expect if the cue enhanced perception. If the nonpredictive cue enhanced perception, subjects should be more likely to correctly perceive the nontarget when it was cued, and this would lead to fewer FAs.

To test this model, we ran an experiment with nonpredictive cues (involuntary attention), a relatively short SOA (80 ms). There were two possible target positions, and on each trial, randomly one of them was cued with the appearance of a black square. There were two targets that consisted of vertical lines with a horizontal line either near top or bottom (see Figure 9). What made this experiment unique is that on 25% of the trials, we had nontargets, which consisted of a vertical line with the horizontal line in the center (Figure 9).

Subjects were to refrain from responding to nontargets. We put subjects under speed pressure, if they did not respond within 300 ms, a computer voice said "too slow." Under this speed pressure, on target-present trials, subjects made only 9% errors. However, on target-absent trials, they made 39% false alarms (FAs). We know that most of these errors were due to speed pressure, because in a control experiment without speed pressure, they made only 6% FAs. Also in both the control and main experiment, subjects were faster on valid trials than invalid target-present trials.

Subjects were significantly more likely to make FAs when the nontarget was in the cued location than when it was not, 41% vs. 35%, $t(11) = 3.15$, $p < .05$. Thus in a situation where the accumulator and perceptual enhancement make the opposite prediction, the results clearly supported the accumulator model.

Insert Figure 9 about here

The experiment demonstrates is that involuntary attention does not enhance the perceptual representation, but rather primes responses to any stimulus, similar to the targets, that appears in the cued location. In the version of the model presented here, the effect of the cue is to prime accumulators. Equivalent predictions would be made if we postulated that the effect of the cue was to lower the threshold for responding in the cued location. If the task was a simple target present/absent judgment, we would model it with a variant of signal detection theory and we would hypothesize a lower criterion in the cued location when subjects made errors because of speed pressure. The main difference between standard signal detection theory and the present formulation is that subjects are not making one decision, but rather an independent decision at each location (Shaw, 1982).

The accumulator model has a number of nice features. It is a possible account for a finding called contingent capture (e.g., Folk, Remington, & Johnston, 1992). Contingent capture is the finding that effectiveness of the cue is related to the extent that target and cue share stimulus features. We assume that the cue activates target accumulators in the cued position. Presumably, this is because the cue shares features with the target. For example, the target involves a sudden onset of black lines, and the cue was a sudden onset of a black frame.

Behavioral data demonstrates that voluntary attention enhances the perceptual representation such that subjects are more accurate in identifying targets to which they are attending – involuntary attention does not have this effect. In an RT task, the more perceptually demanding the task, the greater the attention effect. Involuntary attention by itself can show the opposite pattern of responses. Finally, involuntary attention seems to prime responses to any stimulus (similar to the target) that appears in the cued location. Hence its effect could be described as of priming motor responses, or lowering a decision threshold. Given these differences in behavior, we expected that there would be differences in neural mechanisms and these differences are explored in the next two sections.

IV. Functional Magnetic Resonance Imaging (fMRI)

The previous experiments with faces (Prinzmetal, McCool, and Park (2005a; Experiments 9, 10, 11; Figure 1 above) and the spatial cueing task were ideally suited for fMRI. Faces are known to selectively activate a portion of the fusiform gyrus, called the face fusiform area or FFA (e.g., Kanwisher, 2000). The FFA has been shown in block designs to be sensitive to task-relevant manipulations of attention (e.g., Beck, et al., 2001; Wojciulik, et al., 1998). We hoped that by using faces as stimuli, we could focus on a specific ventral processing area and overcome problems with previous fMRI studies of spatial attention.

Since the landmark PET study of Corbetta and colleagues (Corbetta, Miezin, Shulman, & Petersen, 1993) there have been dozens of function imaging studies of the spatial cueing task. A curious finding is that no spatial cueing study, using the paradigm where the cues precede the target by a few hundred milliseconds, has found evidence of spatially-specific activation.[3] For example, Corbetta et al. (2005) commented "A rather puzzling observation, one that has been replicated several times, is that preparatory signals … show weak evidence for spatial specificity during tasks that force subjects … to switch attention between locations" (p. 2052). In other words, heretofore, cortical activation in spatial cueing tasks has not shown spatial specificity! We hoped that by looking at a specific stimulus related processing area, we would find evidence of greater activation in the FFA contralateral to the target (face) location.

Until very recently, there was no clear evidence, using fMRI, showing distinctly different neural systems for voluntary (endogenous) and involuntary (exogenous) attention. Three studies compared noninformative peripheral cues to informative central cues and found either no difference, or very little difference, in brain activation (Kim, et al, 1999; Peelen, et al., 2004; Rosen, et al, 1999). Two more recent studies (Kincade et al., 2005; Mayer, et al. 2004) found differences, but there were problems with these studies. First, both studies confounded voluntary and involuntary attention with other factors by comparing, for example, a central symbolic cue with a long SOA with a peripheral cue and short SOA. Using direct spatial cueing, we compared voluntary and involuntary attention cues using the same cues and temporal parameters. We only varied the proportion of valid to invalid trials.

We have completed an fMRI study using a task that is identical to that shown in Figure 1 (Esterman, Prinzmetal, DeGutis, Landau, Hazeltine, Verstynen, & Robertson, under review). We used the RT version, so that subjects were between 95% and 100% correct. Ten subjects participated in a practice session in simulated scanner and then where scanned the next day. Both the practice session and scanning session consisted of 3 blocks of 64 trials with a predictive cue and 3 blocks with a nonpredictive cue, with the order counterbalances across subjects. In the scanning session, the predictive and nonpredictive blocks of trials were separated by a separate task to independently locate each subjects FFAs. The only difference between the voluntary and involuntary attention sessions was the proportion of valid and invalid trials. In the voluntary attention session, on 75% of the trials the face appeared in the cued location. In the involuntary attention version, on 50% of the trials the face appeared in the cued location. The subjects were aware of the validity manipulation. We used an event-related design, where each event begins with the onset of the cue. During the task, 18 axial slices with full brain coverage were obtained every 2 seconds.

Insert Figure 10 about here

We found numerous areas where there voluntary and involuntary attention differed. Here, we will limit the discussion to the FFA because this structure has been related to the perceptual processing of faces. There was significantly greater activation in the FFA contralateral to the target. Hence, for a cueing effect, we examined processing in the FFA contralateral to the target face. The BOLD results, Figure 10, are plotted as a function the type of cue. For the predictive session, there was significantly more activation on valid trials. However, there was no difference in BOLD response between valid and invalid trials in the nonpredictive session. Both sessions yielded the typical RT effect. By examining a stimulus-specific perceptual area, we found cue-specific enhancement in brain activity. Thus in the voluntary condition, the cue modulated the FFA, but in the involuntary condition it did not.

V. Electroencephalograph (EEG)

The advantage of fMRI is that it has terrific spatial resolution. The analysis in Figure 10 is based on 15 voxels in each left and 15 voxels in each right FFA. The disadvantage is that there is poor temporal resolution. We do not know whether the activation shown in Figure 10 is due to the cue, the target, or some combination of the two. To obtain a good picture of temporal changes with voluntary and involuntary attention, we used same face stimuli that we used in the fMRI study and the same temporal parameters. Each of 19 subjects participated in two sets of 600 trials: in one set the cue was predictive and one set, the cue was not predictive. We also included ~15% of the trials with only the cue, and no face ("cue-only trials"). On these trials, subjects were to press a "face-absent" button. We included the cue-only trials to obtain a measure of the electrophysiological activity uniquely evoked by the cue (independent of the target). There were 64 electrodes.

Insert Figures 11, 12, and 13 about here

We conducted two different types of analysis. In the event related potential (ERP) analysis, electrical activity is averaged over all the trials of a specific type (e.g., valid, voluntary attention). In this analysis, there was a greater negativity on valid than invalid trials at about 170 ms after the face was presented (N170), but there were no differences between voluntary and involuntary attention and no interactions. Past research has found only very small differences in the ERP between voluntary and involuntary attention (Doallo, Lorenzo-López, Vizoso, Holguín, Amenedo, Bará, & Cadaveira, 2004, 2005).

Insert Figure 14 about here

ERPs only include information about phase-locked electrical activity under about 15 hz. Higher frequencies that are not time and phase locked are averaged out and do not influence the ERP. Previous research has found signatures of voluntary attention in higher frequencies, sometime called gamma-band activity

(Gruber, et al, 1999). Therefore, we conducted a fourier analysis of the electrical potential on every trial, and then averaged the power spectra for similar trial types.

The spectral analysis from one parietal electrode site (P8) is illustrated in two ways. The Figures 11-13 contains the full spectral analysis. In these figures, time is represented on the abscissa. The cue appears at 0 ms. on the figure. On valid and invalid trials, the target appears at 300 ms. Low frequencies are at the top on the figures, high at the bottom. The frequency amplitude is indicated with color. The dashed line indicates the onset of the target.

Figure 14 presents the spectral analysis in another format. The average power (log scale, baseline adjusted for each frequency) from 30 to 70 Hz is plotted as a function of the type of session (predictive cue, nonpredictive cues) and the type of trial (cue only, target present-valid, target present absent-invalid).

Both Figures 11-13 (full power spectrum) and Figure 14 (30 to 60 hz) illustrate an amazing correspondence between shifts of voluntary attention and gamma activity. On the cue only trials, beginning about 120 ms after the appearance of the cue, there is significantly greater activity in the 30-60 Hz range when the cue is predictive than when the cue is not predictive (Figure 11; Figure 14, left panel). This activity reaches its peak about 200 ms after the cue appears.

The results from the valid trials are shown in Figure 12 and Figure 14 (center panel). For both the predictive and nonpredictive session, there is activity in the 30-60 Hz range related to the target, about 120 ms after the onset of the target and peaking about 200 ms after the target appears (the target appears 300 ms after the cue, dashed vertical line in Figure 12). This activity is significantly less in the predictive session. This is reasonable, because if subjects have done cue-related preparatory processing in the predictive session (perhaps moved attention), there is less target processing to do (or its easier, because attention has been deployed to that location). In the nonpredictive session, there was little processing related to the cue and so there is more target processing to do.

Finally, the activity in invalid trials is shown in Figure 13 and Figure 14 (left panel). Here the relative magnitude of the target related activity reverses: Greater activation in the predictive cue session. This pattern is expected because in the predictive session, subjects have oriented attention to the cued location *but that is the wrong location*! They have to reorient attention to the target location.

Insert Figure 15about here

One interpretation of the gamma activity is that it is following shifts of voluntary attention. In the predictive session, subjects shift their attention when the cue appears, and this is seen in the gamma activity. There is almost no cue related activity in the nonpredictive session. When the target appears, in the nonpredictive session, subjects have to shift their attention to the target. With the predictive session, subjects have already done this, so that there is less gamma activity than in the nonpredictive session. On invalid trials, in the predictive session subjects have to reorient their attention leading to a large burst of activity.

There are various other interpretation of gamma activity (e.g., Tallon-Baudry, & Bertrand, 1999). However, whatever interpretation of the gamma activity, there are three significant differences between voluntary and involuntary sessions. Figure 15 is the average of 30-70 hz in a window XXX ms around the cue and target activities averaged over all electrode sites and subjects. On cue-only trials, there is significantly greater activity cue-related activity in the predictive than the nonpredictive session. When the target appears, there is significantly greater target related activity on valid trials for the nonpredictive session than the predictive session. This pattern reverses on invalid trials. Thus voluntary attention to the cue results in a different pattern of brain activity than involuntary attention.

VI. Conclusions

We have followed a "divide and conquer" strategy in understanding visual attention. We hypothesized that voluntary and involuntary attention involved different mechanisms. This distinction is not based on any logical consideration, but rather empirical dissociations between the two kinds of attention. We manipulated attention in the spatial cueing paradigm, using a peripheral cue.

When the cue was nonpredictive of the target location, any affects are involuntary since the there is no reason to allocate processing resources to the cued location. To study voluntary attention, we added voluntary component to the task by making the cue predictive of the target location.

The found several differences between voluntary and involuntary attention manipulated in this way. Both affects RT, but only voluntary attention affects accuracy as long as subjects are not under speed pressure, there is no location uncertainty, and there are no confounds, such as eye movements (Prinzmetal, et al. 2005a). In a pure RT experiment, we found that manipulations of perceptual difficulty can have the opposite effect for voluntary and involuntary attention (Prinzmetal, Zvinyatskovskiy, Gutierrez, & Dilem, under review). With a predictive spatial cue, increasing difficult increased the cueing effect, but with a nonpredictive cue, increasing difficult decreased the cueing effect. In an fMRI study with faces as stimuli, we found voluntary attention enhanced activity in the FFA (a face-specific processing area), but involuntary attention did not. In gamma EEG activity, there were three clear differences between predictive and nonpredictive cue sessions.

Given that there are separable mechanisms for voluntary and involuntary attention, what are these mechanisms? Several different mechanisms have been proposed for voluntary attention, many of them are equivalent to the "more samples" hypothesis proposed by Luce (1977). This hypothesis could be implemented in neural hardware in many different ways (see Prinzmetal, 2005). The consequence of the more samples models is that voluntary attention should increase the accuracy of perception for attended objects.

Involuntary attention has been a bit of a puzzle. How can a mechanism affect RT, yet not accuracy? The accumulator model, presented above, is one suggestion. In effect, the cue primes responses to any stimulus appearing in the cued location that is similar to the target. A prediction of this theory is that when put under speed pressure, observers should make more FAs (false alarms) to nontargets presented in the cued than uncued location(s). If involuntary attention enhanced perceptual processing, there should be fewer FAs for nontarget in the cued location. The results were consistent with the accumulator model.

Having dissected visual attention in the spatial-cueing task, one might wonder whether further divisions would be useful. Involuntary attention is accounted for by the accumulator model. However, there is another theory of involuntary attention, which might be called the queuing or the serial-selection theory (Rauschenberger, 2003). The idea is that all target locations are perceptually encoded to the same extent, but a post-perceptual selection mechanism processes the result of perceptual processes in a serial manner (i.e., there is a queue), usually beginning at the cued location. This theory can account for the RT effects because a target in the cued location will be processed before a target in the uncued location. Furthermore, if there is no location uncertainty, there is no reason for the cue to affect accuracy.

Note that the queuing theory does not account for the false-alarm effect reported above. However, there might be situations where part of the involuntary attention effect can be accounted for by the queuing theory. In the experiment reported in section III above, the nontarget locations were blank. In effect, the display-size was one and the search component was minimal. A serial selection or queuing mechanism may play a role in experiments with distractors in the nontarget locations (Remington & Folk, 2001). Thus its possible that there may be more than one mechanism that subsumes involuntary attention effects and these might be empirically dissociable.

Is there more than one mechanism of voluntary attention? In fact many regions of the brain contain cells that behave in a manner than could account for attention effects (Colby, 1991). One question that we have is whether there is a difference between the mechanism involved when subjects are aware or unaware of the cue-target contingencies. It may be that there are little differences behaviorally between aware and unaware conditions (e.g., Decaix, et al., 2002; Bartolomeo, et al., in press), but there may be neural differences (see e.g., Hazeltine, Grafton & Ivry, 1997). We now have powerful fMRI and EEG methods to study voluntary attention, and these may be useful for exploring different kinds of attention.

One of our ultimate goals is to understand the mechanisms of attention. We will not be very successful in achieving this goal if do not have the correct taxonomy of attention. Dividing voluntary and involuntary attention is a first step in achieving this understanding.

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[1] One might argue that "voluntary" is not an appropriate term when the effects can be obtained without awareness of the probabilities of valid and invalid trials. The reason we use the terms "voluntary" and "involuntary" attention is that they were first used by Wundt (1902), well before terms such as endogenous and exogenous (Posner, 1978). In this chapter, we used the terms with a precise operational definition based on whether the cue provides information about the target location or not.

[2] Note that location uncertainty could also account for accuracy effects with voluntary attention, as in Prinzmetal et al., 2005a. However, they designed their stimuli so that there was no uncertainty as to which location contained the target.

[3] Note that this is in contrast to numerous studies that use sustained attention to a particular location (e.g., Hopfinger, Buonocore, & Mangun, 2000).

Dissecting visual attention figures

Figure captions

Figure 1. A example of the spatial-cueing task. One of two target faces was briefly presented. The task was to indicate which face was presented. The target was preceded by a cue, which consisted of one of the frames turning red (shown as a dashed black frame).

Figure 2. Results from an anti-cueing experiment. There were 4 possible target locations. A cue in one location indicated that the target would appear in the opposite location with a probability of .8, and in the cued location with a probability of .2.

Figure 3. Results from typical RT and accuracy experiments. Subjects had to discriminate faces. In the RT experiment, accuracy was over 90% correct. In the accuracy experiment, the faces were morphed to make the discrimination difficult and subjects were urged to take their time and be as accurate as possible.

Figure 4. The stimuli used in the replication of Awh and Oh (2005). The trial begins with a fixation point (A), followed by a cue (B), a stimulus (C), and a mask (D).

Figure 5. The results of the replication of Awh and Oh (2005). The dot cue indicated a specific location in the cluster of items reducing spatial uncertainty, the box cue surrounded all of the items.

Figure 6. The stimuli used by (Prinzmetal, Zvinyatskovskiy, Gutierrez, & Dilem, under review).

Figure 7. The results of (Prinzmetal, Zvinyatskovskiy, Gutierrez, & Dilem, under review).

Figure 8. The accumulator model on a valid and invalid trial. The striped boxes indicated cue-related priming. The arrows indicate target related activity.

Figure 9. The targets and nontarget used to test the accumulator model.

Figure 10. Activation in the FFA contralateral to the target face.

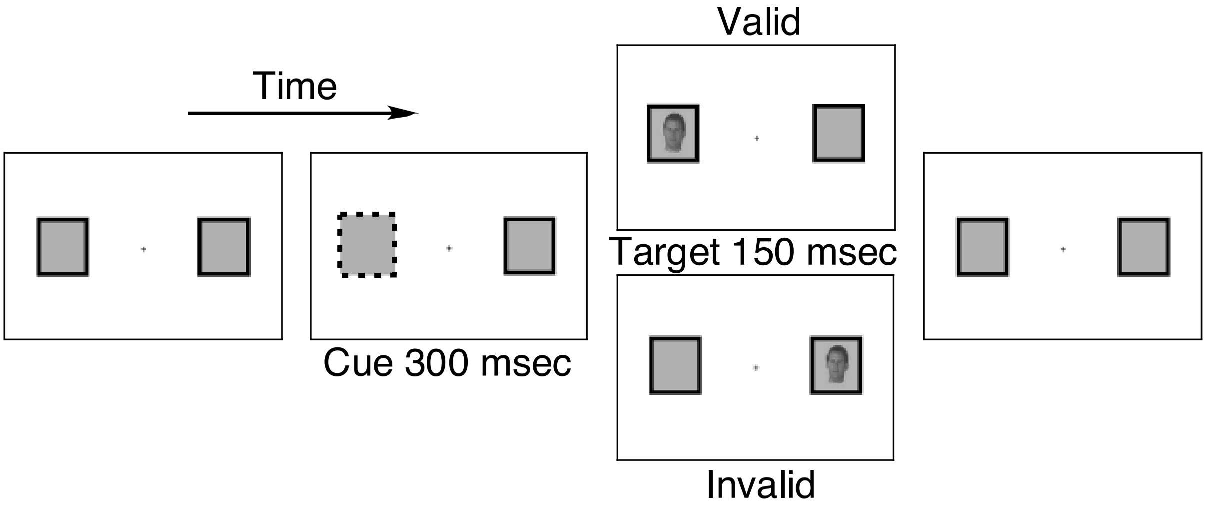
Figure 11. Time-frequency plot for cue-only trials.

Figure 12. Time-frequency plot for valid trials.

Figure 13. Time-frequency plot for invalid trials.

Figure 14. Frequency average over 30 to 70 hz.

Figure 15. The power averaged over all electrode sites and subject from 30 to 70 hz. and a temporal window XXX ms wide centered around cue related activity for cue-only trials and target related activity for valid and invalid trials.



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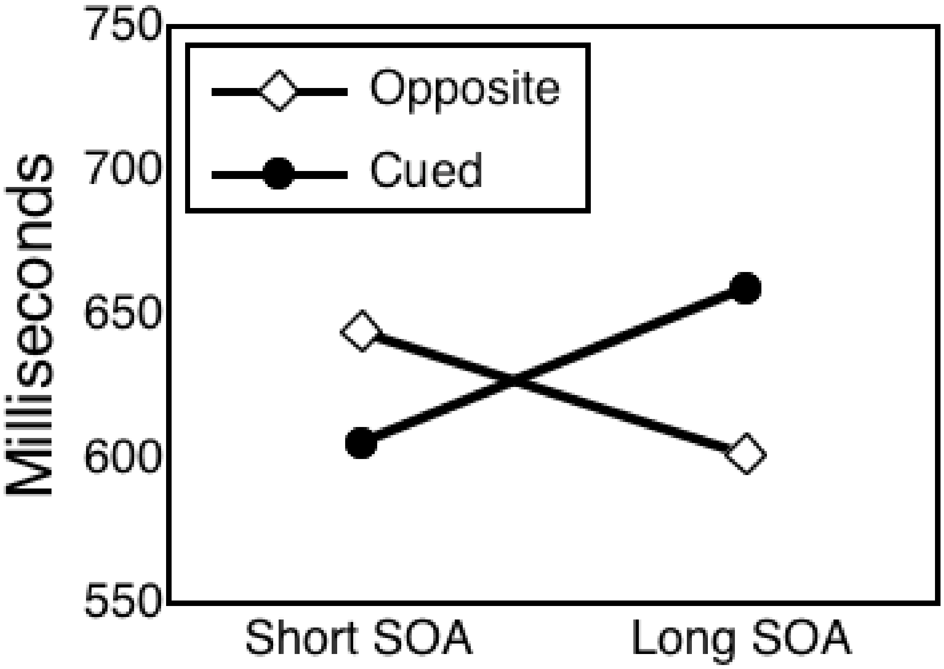

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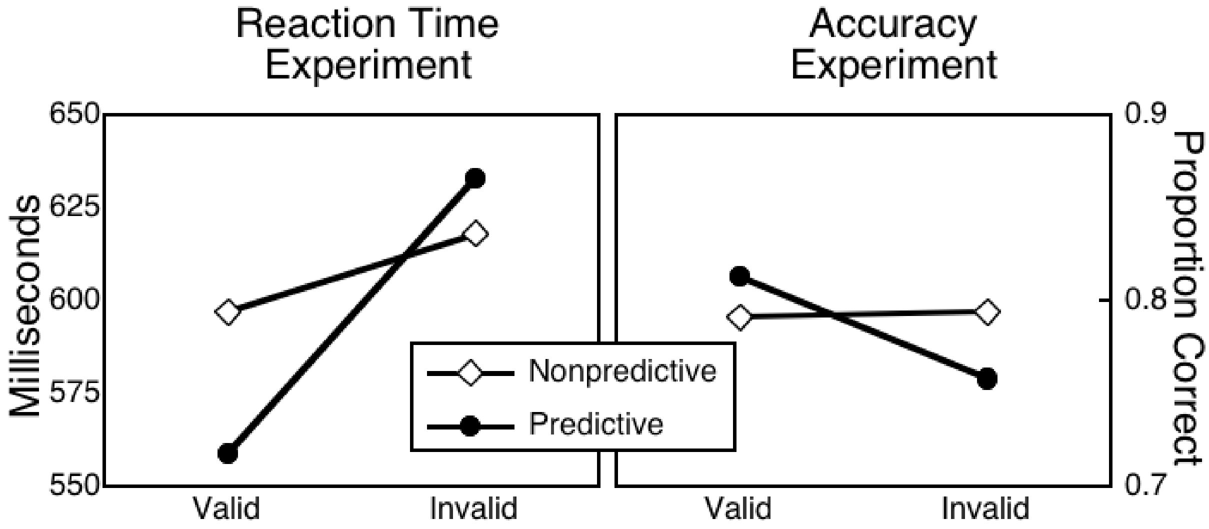

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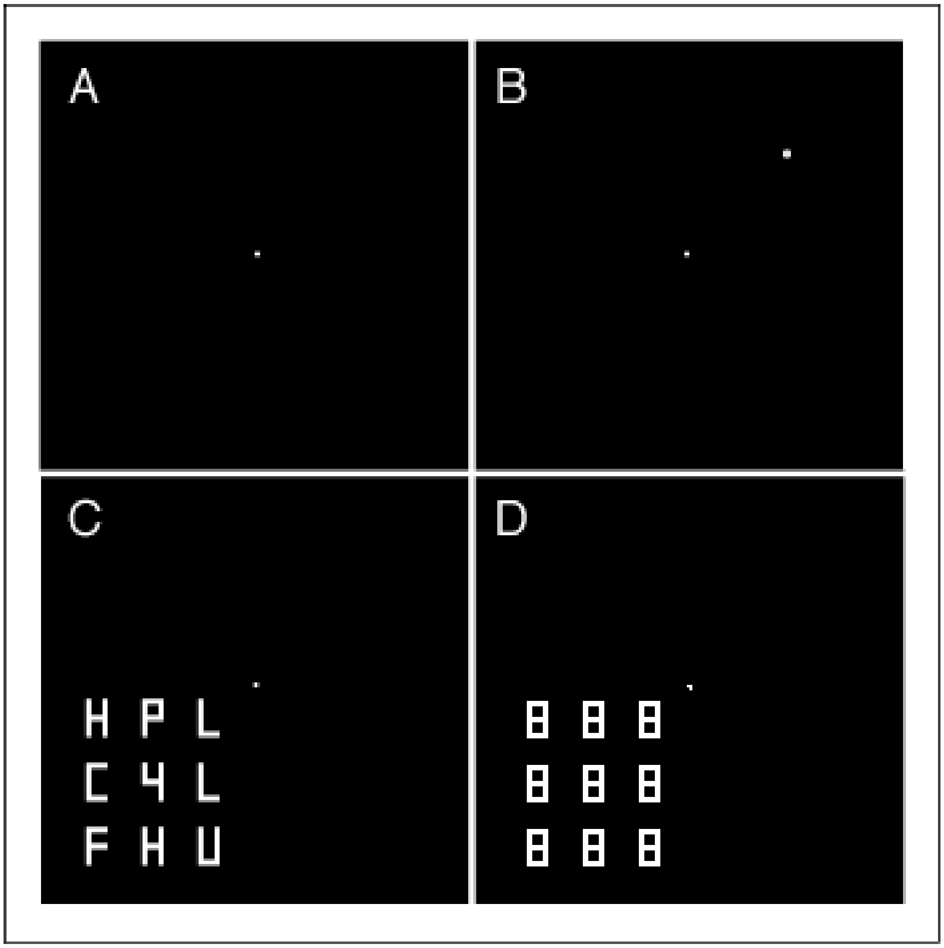

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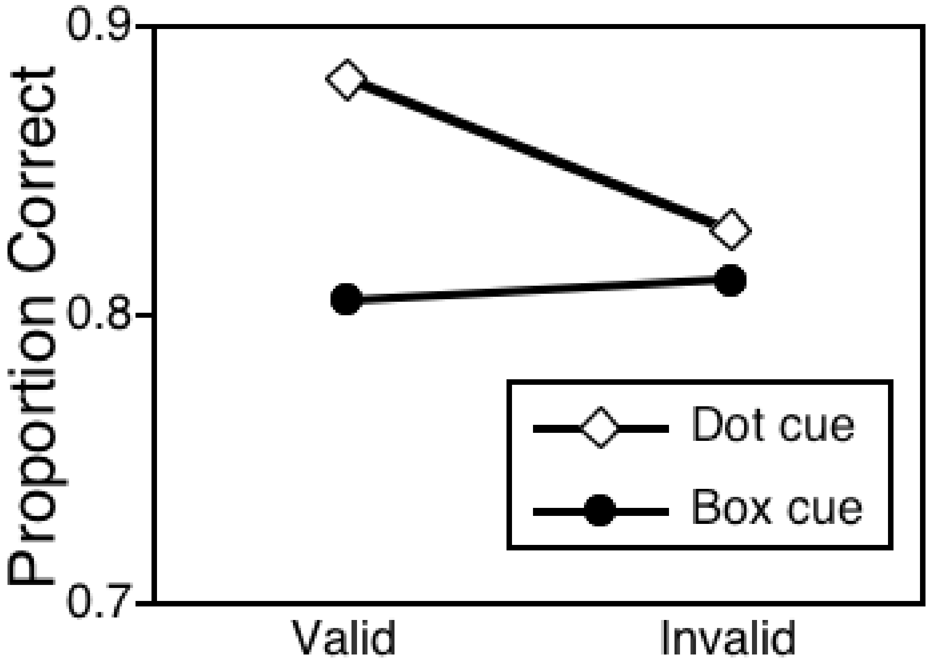

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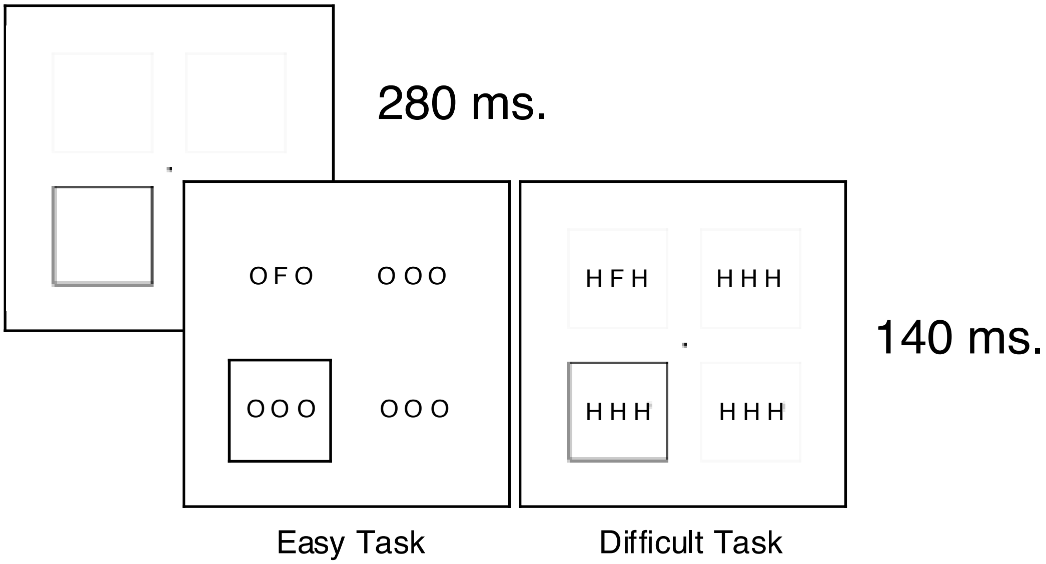

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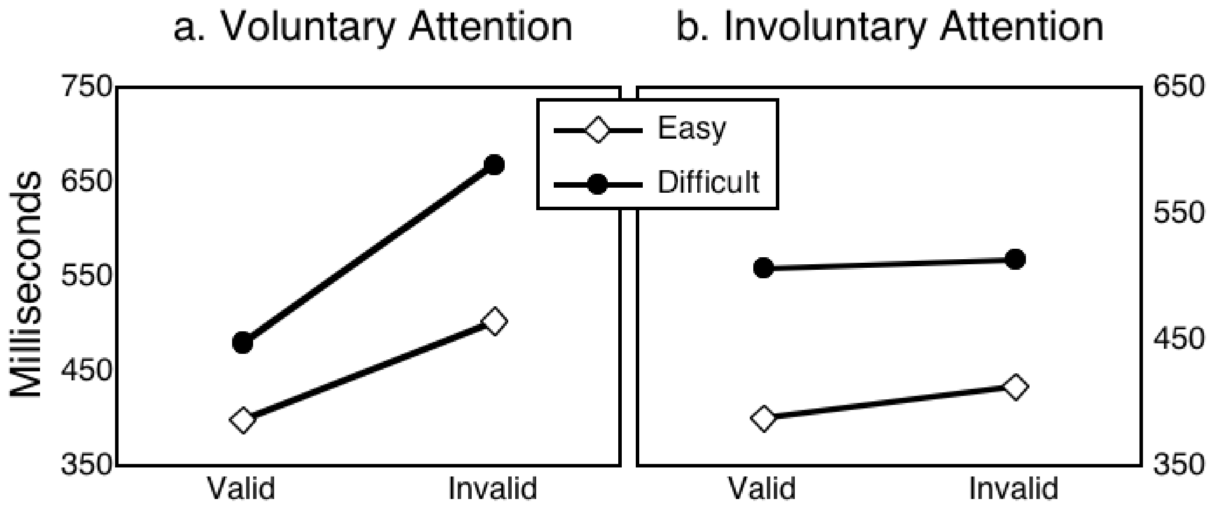

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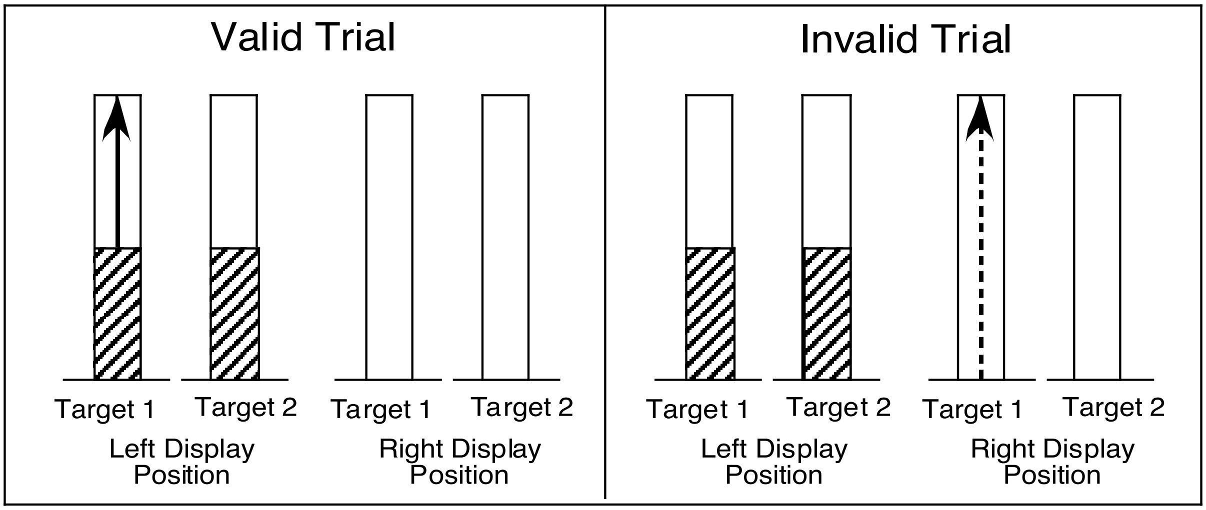

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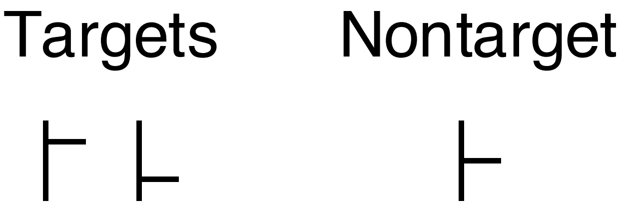

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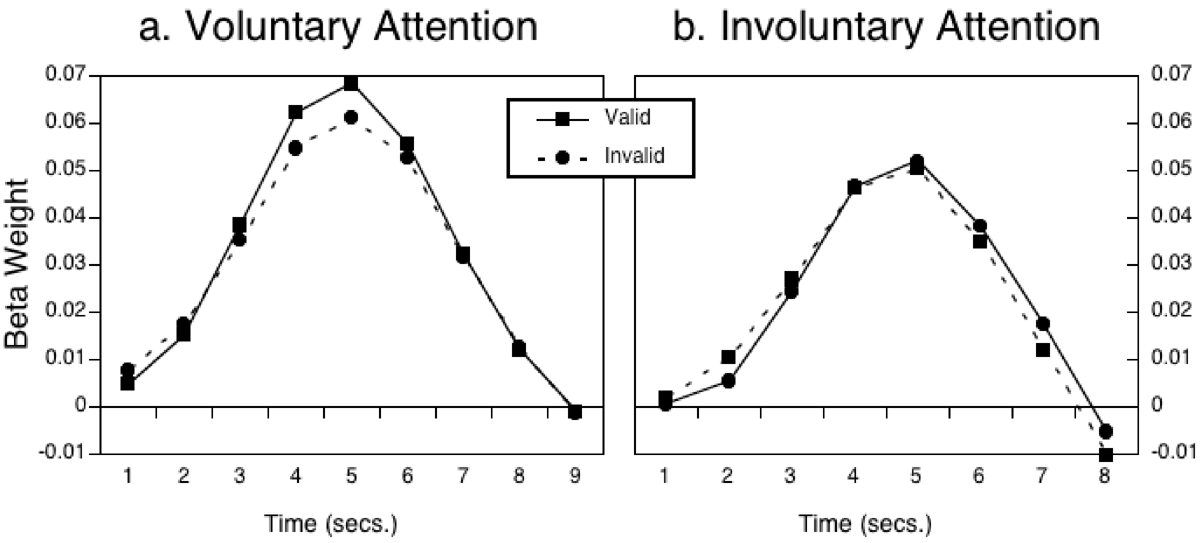

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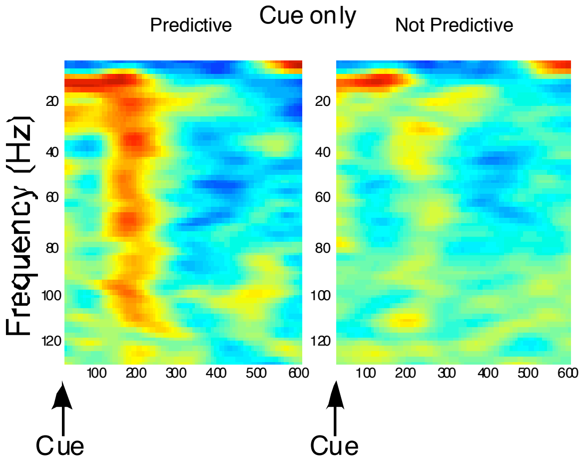

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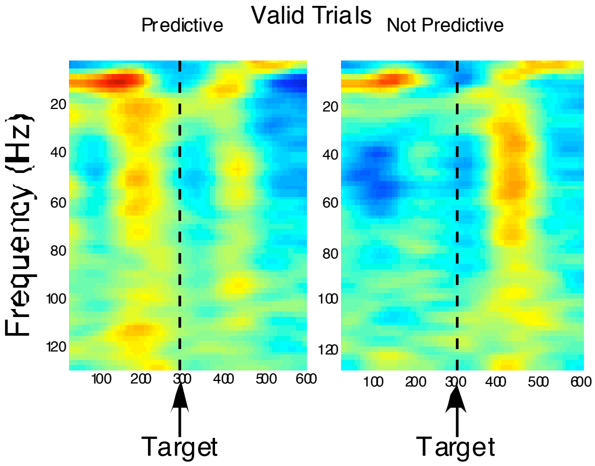
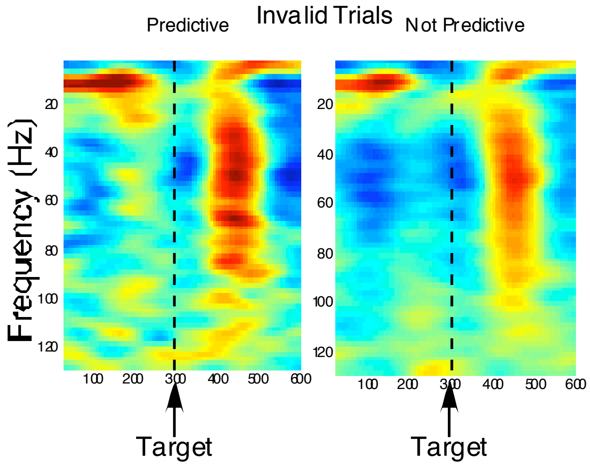


Figure 12. Time-frequency plot for valid trials.



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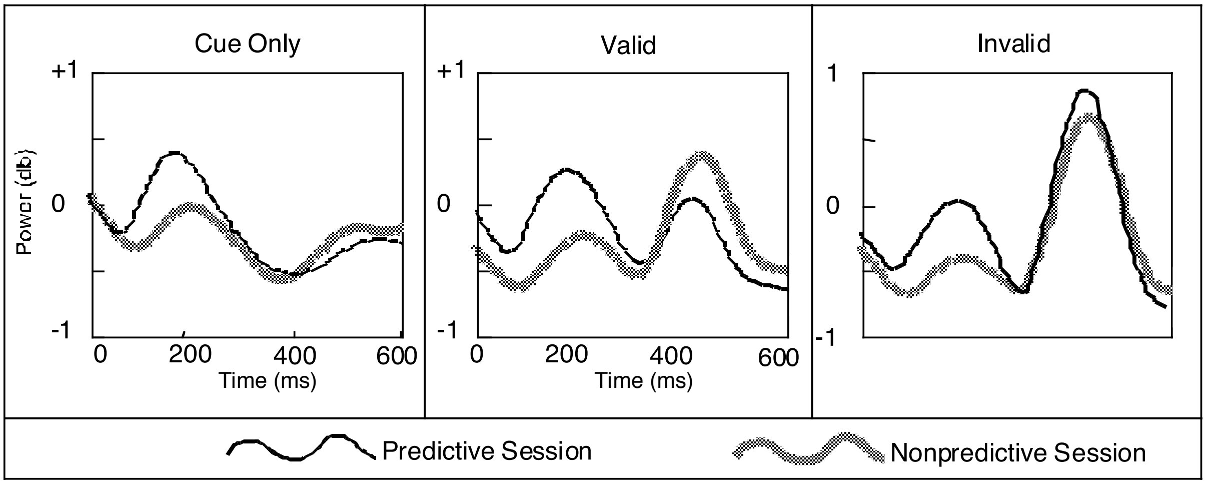

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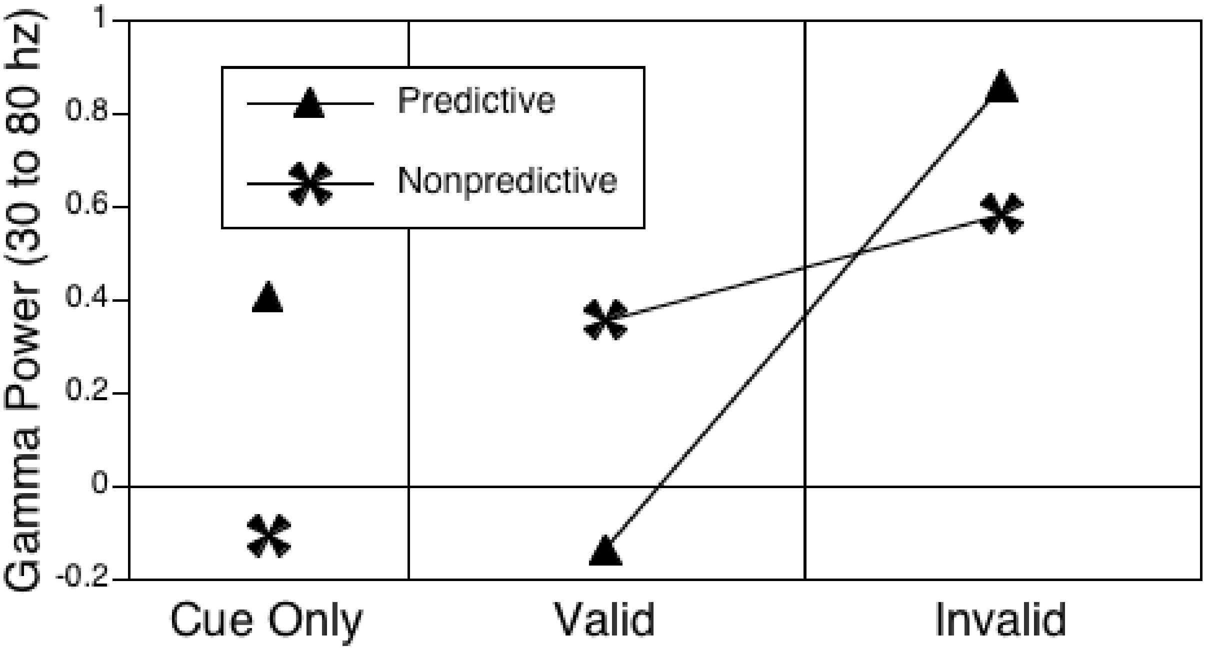

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