Spatial Vision, Vol. 18, No. 1, pp. 99–127 (2005)

Also available online - www.vsppub.com

Thresholds vary between spatial and temporal forced-choice paradigms: The case of lateral interactions in peripheral vision

MIGUEL A. GARCÍA-PÉREZ [1,*], ROBERT G. GIORGI [2], RUSSELL L. WOODS [2] and ELI PELI [2]

[1] *Departamento de Metodología, Facultad de Psicología, Universidad Complutense, Campus de Somosaguas, 28223 Madrid, Spain*

[2] *The Schepens Eye Research Institute, Harvard Medical School, 20 Staniford St., Boston, MA 02114, USA*

Received 7 March 2004; accepted 17 August 2004

Abstract—Psychophysicists use spatial or temporal two-alternative forced-choice (2AFC) paradigms interchangeably. Thus, experiments with the same general goal are carried out using one or the other paradigm by distinct or even the same research groups. For example, this situation has occurred both in studies on visual sensitivity in dyslexia and in studies on lateral interactions in peripheral vision. Conflicting results in either field (e.g. whether or not dyslexics have a visual deficit and whether or not peripheral detection is facilitated by the presence of flankers) appear to be resolved on the surmise that spatial and temporal 2AFC paradigms indeed produce different results. We designed experiments in which peripheral detection thresholds for Gabor patches (in the presence or absence of suprathreshold flankers) could be measured using completely equivalent spatial and temporal 2AFC paradigms so that any resultant difference can be unequivocally attributed to the effect of the paradigms themselves. The results showed that spatial 2AFC renders significantly lower sensitivity than temporal 2AFC when the target is presented along with suprathreshold flankers, but about the same sensitivity as temporal 2AFC when the target is presented alone. In the end, this resulted in statistically significant facilitation in peripheral vision only when measured with temporal 2AFC. Separate experiments at each of several peripheral locations revealed that the presence and magnitude of this effect varies not only with psychophysical paradigm but also with retinal locus.

Keywords: Lateral interactions; facilitation; peripheral vision; spatial 2AFC; temporal 2AFC.

1. INTRODUCTION

Hypotheses in vision research are usually tested with data reflecting the cross-condition stimulus levels at which visual performance reaches some fixed criterion.

*To whom correspondence should be addressed. E-mail: miguel@psi.ucm.es

A simple case is the measurement of contrast thresholds as a function of spatial or temporal frequency, where threshold is usually defined as the contrast at which the probability of seeing the stimulus is 0.5 and, hence, at which the probability is 0.75 of choosing the one alternative that actually displayed the stimulus in a two-alternative forced-choice (2AFC) paradigm. A psychometric function captures the underlying characteristic that visual performance expressed as probability of success in a task increases monotonically with stimulus level, which allows threshold measurement to be addressed with any of the statistical methods that were designed for the estimation of percent points on a response function.

Threshold estimation is ubiquitous in vision research and numerous *psychophysical methods* have been proposed to carry out that task (for reviews, see Leek, 2001; Treutwein, 1995). The quest for efficient psychophysical methods contrasts with the lingering use of methods that are known to be defective. For instance, García-Pérez (1998) showed that common settings for up-down staircases render biased estimators and that simple alterations of the setup solve these problems; yet, a look at the methods section of papers published during the last few years reveals that psychophysicists still use the flawed settings. Another case in point is Wichmann and Hill's (2001) demonstration that maintaining a fixed upper asymptote when fitting a psychometric function may bias slope estimates, a problem that can easily be circumvented by letting the asymptote be a free parameter. Again, a look at the methods section in papers submitted well after Wichmann and Hill's (2001) results were published reveals that asymptotes continue to be treated as fixed instead of free parameters. Provided that flaws such as those just discussed are avoided, several psychophysical methods could in principle be used to obtain an estimate of a given percent point on a psychometric function. In these conditions, the choice of method will not alter the results or bias the conclusions.

Alongside the choice of a dependable psychophysical method, psychophysicists must also make a choice as to their *psychophysical paradigm*. The quickest ones, namely, adjustment and yes-no paradigms, are not deemed dependable in research settings and most researchers thus use a 2AFC paradigm that can still come in either spatial or temporal forms. In spatial 2AFC the target stimulus appears in one of two possible spatial locations during a single presentation interval; in temporal 2AFC the target appears usually at a fixed spatial location but in one of two consecutive temporal intervals. Arguments can be raised in favor and against the use of each of these paradigms with short presentation durations. For instance, spatial 2AFC could initially be preferred because it makes the experiment run at least twice as fast: There is only one presentation period in spatial 2AFC, compared to two periods plus an interleaved gap in temporal 2AFC. The drawback is that spatial 2AFC is naturally incompatible with co-spatial stimulus presentations, brings complications arising from visual inhomogeneity as well as the spatial inhomogeneity of display monitors (see García-Pérez and Peli, 2001; Metha *et al*., 1993), and seems to demand that subjects split attention between two peripheral locations while maintaining fixation elsewhere. Although temporal 2AFC will be free of all these problems insofar as the two temporal presentations are spatially coincident, it demands that the subject keeps in memory the stimulus that was presented in the first interval to compare it with the one presented in the second (e.g. consider a discrimination task in which the subject has to indicate which stimulus is, say, higher in contrast). Some experiments cannot be carried out except in either spatial or temporal form but, if the conditions leave room for a choice, one would expect that the choice between spatial and temporal paradigms does not affect the results. Yet, it seems that results obtained with either paradigm differ non-trivially, as discussed next.

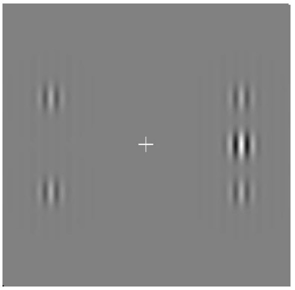
Peli and García-Pérez (1997) reported that one conspicuous difference between the sets of studies that had and had not found differences in contrast sensitivity between dyslexics and normals lay in the psychophysical paradigm that had been used. Specifically, dyslexics showed about the same sensitivity as normals when adjustment or yes-no paradigms had been used, but they showed less sensitivity under temporal 2AFC paradigms. This observation was later confirmed empirically by Ben-Yehudah *et al*. (2001). Peli and García-Pérez (1997) argued that dyslexics have been shown to have difficulties establishing temporal order and making sequential comparisons (Corkin, 1974; Eden *et al.*, 1995; May *et al.*, 1988) and, hence, they may make more errors than normals in a temporal paradigm. Peli and García-Pérez (1997; see also Stuart *et al.*, 2001) further showed that high error rates over the course of adaptive staircases masquerade as reduced sensitivity.

Although the apparent visual deficit of dyslexics might thus be regarded as a rare artifact arising from the use of an unsuitable paradigm, there is evidence that spatial and temporal paradigms also produce differences with normal observers. For instance, detection of a peripheral Gabor patch has been found to be facilitated by the presence of suprathreshold flankers in some studies (Polat and Sagi, 1994a), whereas no effect of flanker presence has been found in other studies (Williams and Hess, 1998; Zenger-Landolt and Koch, 2001). Giorgi *et al.* (2004) established that a conspicuous difference between the studies that had and had not found facilitation lay also in the use of a spatial or a temporal 2AFC paradigm, and they reported the results of an experiment in which the same observers showed statistically significant facilitation in temporal but not in spatial 2AFC.

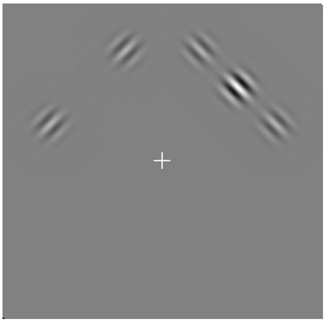
These results raise two interesting questions. One is whether spatial and temporal 2AFC consistently yield different estimates regardless of the particular stimulus and experimental conditions, and this is the question that we examine. The second question, namely, which of the paradigms (if any) portrays the actual threshold, is more relevant but also more difficult to address, and it may well be that the attentional and memory load that spatial versus temporal paradigms demand make each of them unsuitable for addressing distinct subsets of research topics. In any case, the reasons that this second question escapes examination are that (1) empirically, we cannot collect dependable data that would allow a comparison with ‘true threshold’ because all of our measured thresholds are suspect in these conditions and (2) formally, simulations cannot be carried out to address the issue in the absence of dependable and detailed quantitative knowledge of the particular effects of attention and memory (in spatial versus temporal presentations) on visual performance. Yet, the issue may be irrelevant from a practical point of view as long as thresholds obtained in spatial versus temporal paradigms keep a constant relation to each other and results obtained with spatial versus temporal paradigms in the same or different studies are not compared except to arrive at conclusions regarding differences in the outcomes of each paradigm. Since observing the latter admonition is entirely in the hands of practicing psychophysicists, the work reported in this paper set out to document the relation between thresholds obtained in identical conditions except for the spatial versus temporal arrangement of the 2AFC paradigm.

In brief, contrast detection thresholds were determined for stimulus conditions designed so as to be compatible with spatial and temporal paradigms. In the spatial paradigm the target stimulus appeared in one of two peripheral locations while the subject was fixating a cross on the center of the display. Because testing at these two peripheral locations might rightly render different thresholds owing to visual or display inhomogeneities, the threshold at each location was separately determined. Two temporal paradigms were also instated. In each, the stimulus always appeared at the same spatial location but in only one of the two temporal intervals. The two temporal paradigms differed only as to the location where the target was presented (which was one of the two locations involved in the spatial paradigm) and the two temporal paradigms ran in separate blocks of trials to prevent the temporal decision task from imposing also spatial uncertainty (as occurs in the mixed spatial and temporal paradigm of Solomon and Morgan, 2003). In the end, this design provided threshold estimates from spatial and temporal paradigms for the same stimuli at each of two locations in the visual field. With this design, threshold differences beyond random error reflect differential effects of the paradigms themselves. Because differences in the outcomes of spatial and temporal paradigms have been reported in studies of lateral interactions (Giorgi *et al.*, 2004), our design included all the necessary conditions in this context. This allowed us to determine whether spatial and temporal paradigms render different thresholds and whether this is so regardless of stimulus complexity (i.e. target alone versus target plus flankers).

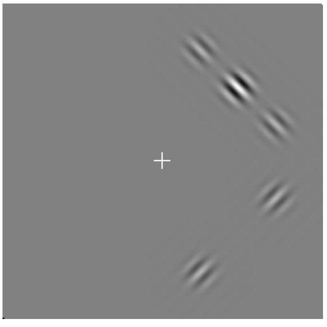
Three analogous experiments were carried out that differed only as to the position in the visual field of the two spatial locations involved, each of which was in all cases 4 deg away from fixation (see Fig. 1). In Experiment 1 (Fig. 1a), the positions were located in opposite directions along the horizontal meridian, thus representing the most distant locations that can be defined with the constraint that each of them is 4 deg away from the fovea. In Experiment 2 (Fig. 1b), the two positions were in the upper visual field, each orthogonal to the radius from fixation and 45 deg above horizontal, representing the closest locations that can be defined with the additional constraints imposed by the presence and size of flankers. In Experiment 3 (Fig. 1c), the two positions resulted from a mere 90-deg clockwise rotation around the fixation point, thus representing the same inter-location distance as in Experiment 2 but now involving only the right hemifield. This set of experiments allowed us to explore



(a) Experiment 1



(b) Experiment 2



(c) Experiment 3

Figure 1. Schematic diagram (not to scale) of the stimulus configuration in the target plus flanker condition of the spatial 2AFC paradigm in each of the three experiments. The target is shown in one of the possible spatial locations with maximum contrast and surrounded by 40%-contrast flankers (inaccurately portrayed in this nonlinear luminance rendition); the empty space between flankers in the other spatial location indicates where the target might be presented on other trials. The data that we are using for our comparisons of spatial and temporal paradigms comes from conditions in which the target was co-oriented with the flankers at the location where it was presented, which implies that target orientation covaried with spatial location in the configurations of Experiments 2 and 3. Sessions without flankers used the same target spatial locations and orientations indicated here. Temporal paradigms presented target and flankers in only one of the spatial locations shown here. The size of the fixation cross and the image area in this representation do not reflect those in the actual experiments. Gabor patches and distances between them within each configuration are drawn to size but the configurations are located here 2 deg away from the fixation cross instead of the 4 deg used in the actual experiments.

whether differences in the outcomes of spatial and temporal paradigms vary with stimulus complexity, with the distance between the two spatial locations, and with the involvement of one or two cerebral hemispheres.

2. METHOD

2.1. Apparatus and stimuli

All experiments were under computer control by a PC equipped with VisionWorks (Swift *et al.*, 1997). Stimuli were displayed on an EIZO Flex-Scan FX·E7 color monitor with a spatial resolution of 1024 × 600 pixels (horizontal × vertical), a luminance resolution of 2^{15} gray levels, and a frame rate of 122.7 Hz. The image area on the monitor spanned 40 cm horizontally and 23.4 cm vertically, which subtended 22.8 × 13.4 deg at a distance of 1 m. The voltage-to-luminance nonlinearity was compensated for via look-up tables arising from a calibration procedure that rendered a correlation of 0.9997 between actual and nominal luminance.

The temporal course of stimulus presentation was basically a rectangular pulse of 90 ms (11 video frames) but this period was preceded and followed by a single frame at half the nominal contrast to mitigate transients. The total presentation duration was thus 107 ms (13 frames).

In Experiment 1, the target stimulus was a Gabor patch with a vertical carrier of 4 c/deg and a circular Gaussian envelope with a standard deviation of 0.18 deg (resulting in half-amplitude spatial-frequency and orientation bandwidths of 0.769 octaves and 30.2 deg, respectively). The stimulus was represented internally with 22.4 pixels per cycle of the carrier and was displayed with a mean luminance of 54 cd/m^2 that blended in with a uniform 54-cd/m^2 background covering the entire image area. The center of the monitor displayed a small cross (arm length × width: 0.11 × 0.03 deg; luminance: 88 cd/m^2) that the subjects fixated throughout the experiment. The target stimulus always appeared with its center 4 deg either to the right or to the left of the fixation cross.

In separate blocks within Experiment 1, the stimulus field either consisted of the target just described or included also two flanking Gabor patches of the same frequency, orientation, and size but with a fixed suprathreshold Michelson contrast of 0.4, which were located above and below the target and 1 deg (i.e. four wavelengths) away from it (see Fig. 1a). In blocks with flankers, these were present in each of the spatial or temporal intervals, as appropriate. Simultaneous presence of the flankers at a fixed contrast requires that some slots in the 255-entry display look-up table be reserved for these patches. Thus, the flankers were displayed with a total of 127 fixed gray levels whereas the target stimulus was also displayed with 127 gray levels that were drawn from a palette of 2^{15} levels to render the contrast required for the trial. To avoid differences in these respects between blocks with and without flankers, in the latter the target stimulus was also displayed with 127 gray levels only. For our comparison of the outcomes of spatial and temporal paradigms, we used this type of configuration in which the orientation of the target matched the orientation of the flankers at the location where the target was presented, and we will refer to them as *co-oriented* conditions.

The stimulus configuration in Experiments 2 and 3 differed from that in Experiment 1 only as to the location and orientation of the target and flankers (see Figs 1b and 1c). The peripheral locations for target presentation in experiment 2 lay along ± 45 deg meridia relative to upper vertical. In Experiment 3, the relative distance between the two spatial locations where the target might appear remained as in Experiment 2, but the entire configuration was rigidly rotated 90 deg clockwise around the fixation point so as to fall only on the right visual hemifield. For the spatial paradigm in Experiments 2 and 3, our software forced us to gather additional data for configurations in which the target was orthogonal to the flankers, and we will refer to these as *cross-oriented* conditions, but we did not use these data in our comparison of paradigms. In particular, in spatial 2AFC, the targets displayed on one of the spatial locations in Figs 1b and 1c were presented on the other location with the same exact orientation and, therefore, the target was co-oriented with the flankers on one location but cross-oriented with them on the other. To measure thresholds at each location with co-oriented targets, we had to implement two separate spatial sessions only differing as to the orientation of the target, as described in Section 2.2. Temporal sessions could be set up on each spatial location using co-oriented targets and flankers.

2.2. Procedure

The monitor was allowed to warm up for no less than half an hour before any session started. Binocular viewing with natural accommodation and pupils was used. Subjects sat 2 m away (1 m away in Experiments 2 and 3) from the display and their head was not restrained although they were asked to maintain a fixed viewing distance throughout the experiment. The room was dark except for the light from the display monitor. The background luminance and the fixation cross were present throughout the experimental session.

Data were collected with an adaptive method of constant stimuli governed by 1-up/1-down staircases with steps down of 0.2 log units and steps up of 0.4 log units. This up-down rule, with steps up that double the size of the steps down, places stimulus levels around the region where the probability of a correct response is 0.67 (Kaernbach, 1991), but the average-of-reversals estimator is unreliable with these settings (García-Pérez, 1998). Hence, data from all repeat sessions (see below) of a given condition were pooled and binned by contrast level to obtain percentages of correct responses that were then used to fit a psychometric function (see Section 2.3 below). Setting out to estimate the entire Ψ and not only the detection threshold allowed us to explore more thoroughly the differences in visual performance that may come from spatial versus temporal paradigms. As recommended by García-Pérez and Alcalá-Quintana (2004), two separate staircases were interwoven in each block which differed only by 0.1 log units in their starting points (−0.6 versus −0.5 log contrast), that is, half the base step size of 0.2 log units that was used in each staircase. Concerns have been raised about the capability of certain types of adaptive procedure to deploy trials over the broad range of stimulus levels that ought to be sampled to obtain dependable estimates of all the parameters of a psychometric function (see, e.g., García-Pérez and Alcalá-Quintana, 2004; Klein, 2001). The procedure that we have used is free of these problems (as will be evident by inspection of Figs 2 and B1).

Staircases under the temporal paradigm were set up to run until 50 reversals had been completed; staircases under the spatial paradigm were set up to complete 100 reversals. The reason for a larger length of the latter staircases is that trials from them had to be separated into two subsets (those in which the target had appeared on one location and those in which it had been presented on the other) to fit a psychometric function separately at each location. The increased number of reversals was not accompanied by an increase in duration compared to the temporal staircases because each spatial trial consumes less than half the time of a temporal trial.

A spatial trial consisted of a 107-ms presentation period signaled by a beep and in which the target appeared either at location A or at location B, newly decided at random with equiprobability on each trial. A temporal trial consisted of two 107-ms co-spatial presentations (either on location A or on B, invariant within a block) in only one of which was the target displayed, again newly decided with equiprobability on each trial. The two temporal intervals were marked by beeps of different pitch and separated by a gap of 820 ms (100 frames). In either case the subject's task was to indicate by a key press the location (in spatial 2AFC) or interval (in temporal 2AFC) in which the target had been presented, guessing at random when necessary. If subjects had missed a trial for whatever reason, they could use a third key to ask for the trial to be discarded and repeated (not necessarily immediately afterwards). The session was self-paced, as the next trial did not start until the subject had responded.

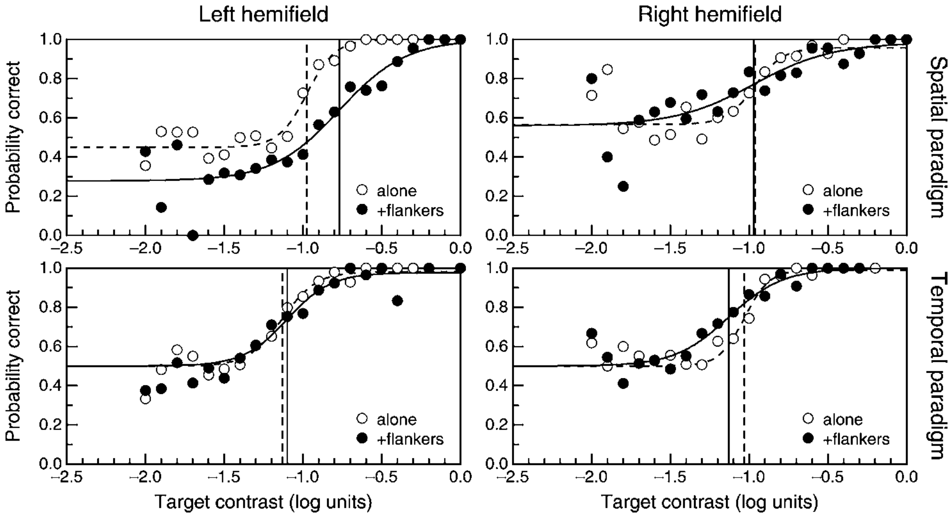
Each subject completed the full set of conditions of Experiment 1 in 12 sessions, four involving each of the three paradigms (spatial, temporal on location A, and temporal on location B). The four sessions of each type were mere repeats. A session consisted of two blocks of trials (one for the target alone and one for the target plus flankers), the length of each block being variable owing to the nature of the up-down staircases that were implemented. Each block consisted of two interwoven staircases covering interlaced lattices as described above. Spatial staircases set to finish after 100 reversals took between 175 and 246 trials to complete; temporal staircases set to finish after 50 reversals took between 85 and 135 trials to complete.

Experiments 2 and 3 were completed analogously except that the spatial paradigm required twice as many sessions. The reason for this is that the VisionWorks application that we used (called CSF; see Swift *et al.*, 1997) does not allow altering the orientation of the target according to the location where it is to appear. Note in Fig. 1a that the requirement of co-orientation allows the target to be displayed with the same orientation (vertical) at either spatial location in Experiment 1, but the same requirements dictate that the orientation of the target be 90-deg offset at the two spatial locations for Experiments 2 and 3 (see Figs 1b and 1c). Hence, two analogous sets of spatial sessions were programmed that differed only in the orientation of the target, each of which was set as appropriate for co-orientation at one of the two spatial locations involved. Each subset of sessions thus provided the data that were relevant to estimate the psychometric function in co-oriented configurations at only one of the locations plus another set of data (at the location in which the target is cross-oriented with respect to the flankers) that was not relevant to the goals of the present study but that are nevertheless reported for completeness in Appendix A.

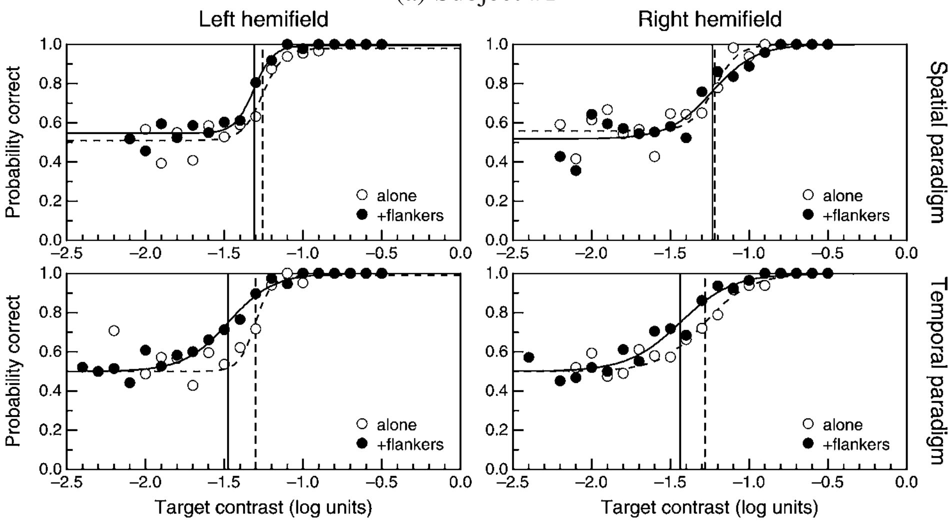
2.3. Data analysis

Data from each subject were analyzed separately. All responses (classified as correct or incorrect) bearing on each of the eight conditions in a given experiment (factorial combination of spatial versus temporal paradigm, location A versus location B, and target alone versus target plus flankers) were pooled and binned by contrast level, and a separate psychometric function Ψ was fitted to each data subset using a procedure described in Appendix B, thus yielding eight Ψs per subject (see Fig. 2). Each fit is based on data from 400–500 trials across the four repeat sessions.

Data from temporal paradigms were fitted assuming a fixed guessing rate $\gamma = 0.5$, as is usual in 2AFC paradigms. Data from spatial paradigms had to be fitted with the guessing rate γ regarded as a free parameter. The reason for this does not lie in the paradigm being spatial but rather in that responses to stimuli presented at each of the alternative locations were segregated and Ψ fitted to each subset separately. Alcalá-Quintana and García-Pérez (2004b) have shown that response biases leading a subject to use one of the response keys more often than the other upon guessing at random have no effect on the shape or parameters of Ψ when stimulus presentation is randomized and data from both locations/intervals are used together (as we actually did in the temporal paradigms) but when the data are segregated by presentation location (whether spatial or temporal) and separately analyzed as we did in the spatial paradigms, each subset is differentially affected by this response bias. A propensity to respond A instead of B upon guessing at random increases the number of correct guesses on location A at the expense of those on location B. At the same time, the overall rate of correct guesses across locations will still be about 50% if presentation location has been appropriately randomized. Alcalá-Quintana and García-Pérez (2004b) showed that, when there is a response bias, the Ψs for segregate presentation locations only differ in their guessing parameter γ in 2AFC detection tasks, and this is the reason that we allowed γ to be a free parameter when fitting Ψ in these cases. Even we were surprised at how much bias an experienced (but naïve) subject demonstrated in our study (see

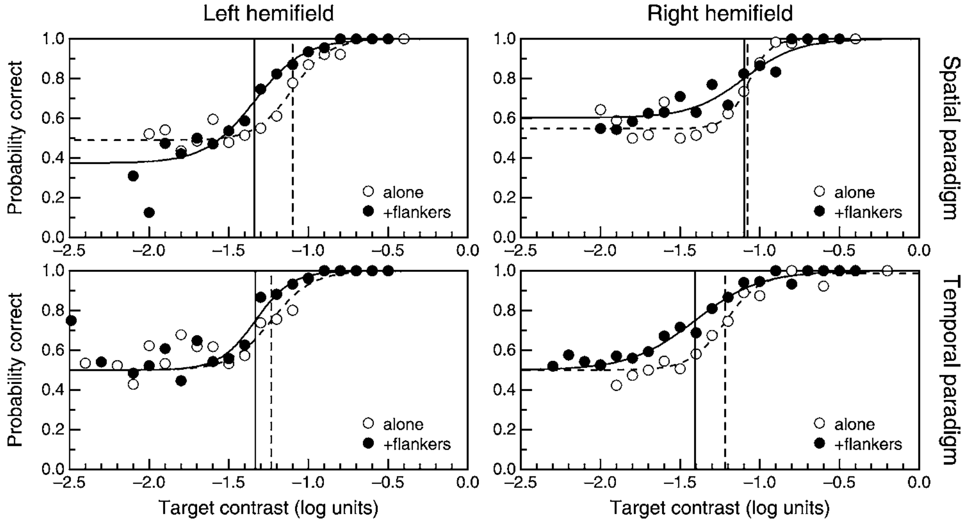


(a) Subject #1

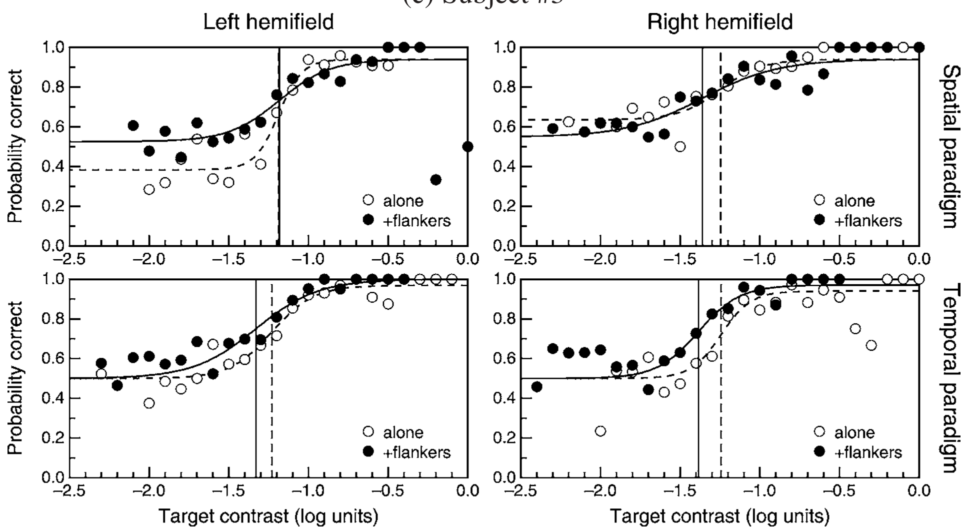


(b) Subject #2

Figure 2. Actual data (percent correct at each contrast level) and fitted psychometric function for each subject in each condition of Experiment 1. Parts (a) to (d) separately represent results for subjects #1 to #4. In each panel, open circles represent detection results for the target alone and the dashed curve is the best-fitting logistic psychometric function; solid circles represent detection results in the presence of flankers and the solid curve is the best-fitting psychometric function. Data points are omitted for low contrast levels at which fewer than twenty responses had been collected. Vertical lines (dashed or solid, as appropriate) indicate the location of threshold defined as the midpoint of the range of the applicable psychometric function. Left and right columns respectively represent results from the left and right visual fields; top and bottom rows respectively represent results from the spatial and temporal paradigms.



(c) Subject #3



(d) Subject #4

Figure 2. (Continued).

Fig. B1 in Appendix B). To reflect comparable performance levels across conditions yielding different lower asymptotes, threshold θ must be defined as the point at which the probability of a correct response is halfway between the lower and upper asymptotes of Ψ.

These analyses thus provided three or four parameter estimates for Ψ in each condition: the spread σ (see García-Pérez, 1998), the lapsing rate λ, and the threshold θ; for segregate data from spatial paradigms, the guessing rate γ was the fourth estimated parameter. Besides these summary parameters, the entire Ψ

was also available for an inspection that could tell whether threshold differences are spurious or reflect clear differences between the underlying curves.

Quantitative comparisons of means across conditions (Sections 3.1, 3.2, 4.1, 4.2, 5.1, 5.2, and 5.4) were carried out using two-tailed matched-sample *t*-tests. Ninety-five percent confidence intervals for means (Sections 3.3, 3.4, 4.3, and 5.3 and Appendix A) were computed through the method that is dual with the two-tailed one-sample *t* test, namely, adding to and subtracting from the sample mean the value of $t_{n-1,0.975}\tilde{s}_x/\sqrt{n}$, where n is the size of the sample, $t_{n-1,0.975}$ is the 97.5th quantile of a t distribution on $n-1$ degrees of freedom, and $\tilde{s}_x$ is the sample standard deviation.

2.4. Subjects

Four experienced psychophysical observers with normal or corrected-to-normal vision participated in the study. The first three subjects were authors and, thus, were aware of the design and goals of the study; the fourth subject was naïve in all these respects. Prior to their participation, all subjects read and signed an informed consent form that had been approved by the Institutional Review Board in accordance with NIH regulations.

3. RESULTS OF EXPERIMENT 1

Figure 2 shows the results of Experiment 1 for each subject at each location under each paradigm and flanker condition. Within Figs 2a to 2d, the top and bottom rows respectively represent results for the spatial and temporal paradigms; the left and right columns represent results for the left and right visual hemifields. Open circles and dashed curves represent actual data and best-fitting Ψ for detection of the target alone; solid circles and solid curves reflect data and Ψ for detection in the presence of flankers. For clarity, the detection threshold in each condition has been indicated by a vertical line (dashed or solid, as appropriate) in each panel. The relative horizontal location of these vertical lines across and within panels is relevant to address three issues, because

– if there were no difference between left and right visual fields, the location of each vertical line would be about the same in the two panels in each row;
– if there were no difference between spatial and temporal paradigms, the location of each line would be about the same in the two panels in each column;
– if the presence of flankers made no difference, solid and dashed vertical lines in each panel would lie at the same location; if flankers had a facilitatory effect on detection, the solid line would be on the left of the dashed line; and if the presence of flankers impaired detection, the solid line would be on the right of the dashed line.

Each of these issues is addressed next, but first note that differences of 0.1 log units or larger in the location of solid and dashed vertical lines in each panel generally reflect observable differences in the entire location of the applicable psychometric functions, and that these psychometric functions, in turn, describe well the monotonically increasing pattern of the data (except, naturally, at the lower range of contrasts). Therefore, threshold differences of 0.1 log units or larger between the two conditions portrayed in each panel are not spurious. They are also similar to differences reported in extant studies on lateral interactions (Giorgi *et al.*, 2004; Polat and Sagi, 1993, 1994a, b; Williams and Hess, 1998; Woods *et al.*, 2002; Zenger-Landolt and Koch, 2001).

3.1. Differences between left and right hemifields

Figure 3a summarizes the results presented in Fig. 2 in a way that is appropriate for assessing differences in thresholds between left and right hemifields. The pair of thresholds that define the coordinates of each data point involve the same subject and paradigm. The horizontal coordinate of a solid (alternatively, open) circle is the abscissa of the solid (alternatively, dashed) vertical line identifying threshold in the presence (alternatively, absence) of flankers in one of the left panels of Fig. 2 (i.e. thresholds in the left hemifield), whereas the vertical coordinate is the abscissa of the same line in the corresponding right panel (i.e. thresholds in the right hemifield). Were there no difference in threshold between hemifields, data points would lie along the diagonal identity line. This is indeed the case, although open circles (for target alone conditions) are tightly packed around the diagonal whereas solid circles (for target plus flanker conditions) are more broadly distributed around it. In neither case can a systematic deviation from the diagonal be observed. This is easily noted by inspection of the dashed and solid line segments drawn parallel to the diagonal. Each segment depicts the average difference between right-hemifield and left-hemifield thresholds from each subset of data (dashed line for open circles and solid line for solid circles), which amounts to 0.017 log units for the target alone conditions (open circles and dashed line) and −0.023 log units for the target plus flanker conditions (solid circles and solid line). Neither value is significantly different from zero at a 0.05 level ($t_7 = 1.069$ and -0.445, respectively).

3.2. Differences between spatial and temporal paradigms

Figure 3b shows a different cross-section of the same data. Here the axes reflect spatial versus temporal paradigms and the pair of thresholds that define the coordinates of each data point involves the same subject and spatial location. Thus, the horizontal coordinate of a solid (alternatively, open) circle is the abscissa of the solid (alternatively, dashed) vertical line defining threshold in one of the top panels of Fig. 2, whereas the vertical coordinate is the abscissa of the same line in the corresponding bottom panel. Again, accumulation of the data along the diagonal identity line would indicate that spatial and temporal paradigms render analogous thresholds. Quite on the contrary, all data points cluster noticeably below the diagonal, revealing that temporal paradigms render lower thresholds than spatial

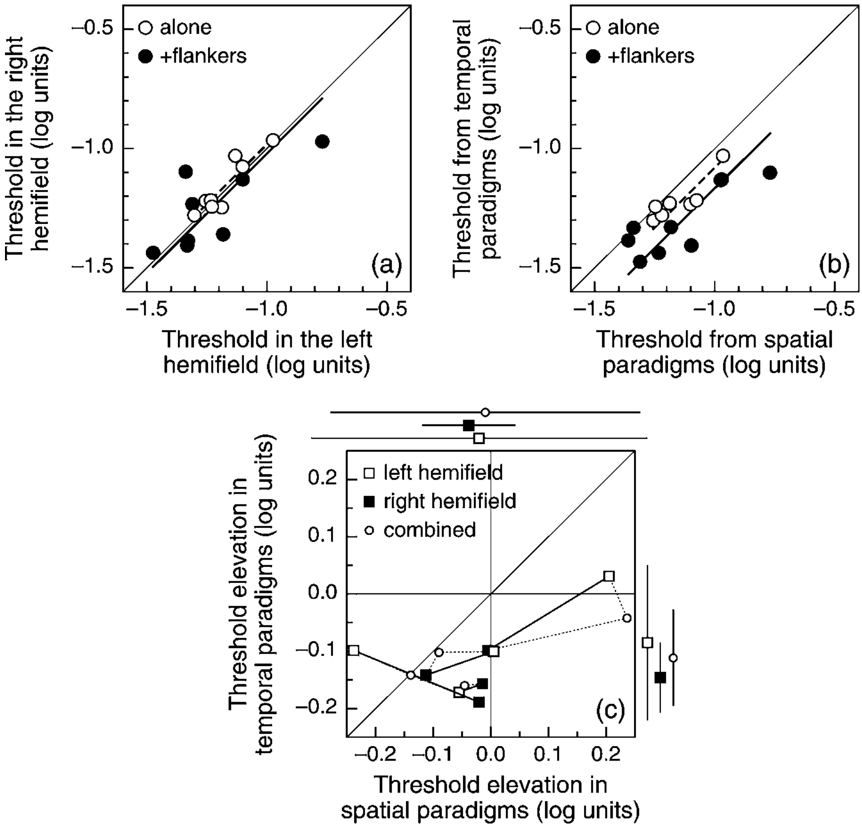


Figure 3. Summary results of Experiment 1. (a) Relationship between thresholds at one versus the other spatial location. Each open (alternatively, solid) circle pertains to a given subject and a given paradigm in the target alone (alternatively, target plus flanker) condition; solid and dashed line segments along the span of solid and open circles indicate the average distance of each subset of data from the diagonal identity line. Thresholds are not exactly identical at both locations, but no systematic trend can be observed and the differences are not statistically significant. (b) Relationship between thresholds determined with spatial versus temporal paradigms. Each open (alternatively, solid) circle pertains to a given subject and a given spatial location in the target alone (alternatively, target plus flanker) condition; solid and dashed line segments along the span of solid and open circles indicate the average distance of each subset of data from the diagonal identity line. Temporal paradigms tend to produce lower thresholds than spatial paradigms, more so in stimulus configurations involving flankers (solid circles and solid line) than in stimulus configurations not involving flankers (open circles and dashed line). The differences are significantly different from zero for either condition, and the two conditions also differ significantly. (c) Relationship between threshold elevation indices from spatial and temporal paradigms in the left hemifield (open squares), right hemifield (solid squares), and for data pooled across hemifields (open circles connected with dotted lines to the applicable data points from each hemifield). Most points are located in the third quadrant and below the diagonal identity line, indicating that the presence of flankers has facilitatory effects on detection and that temporal paradigms generally yield more facilitation than spatial paradigms. The symbols and error bars outside the frame at the top (alternatively, right) indicate means and 95% confidence intervals for the corresponding conditions in the spatial (alternatively, temporal) paradigms.

paradigms. In addition, the set of solid circles (for target plus flanker conditions) is farther apart from the diagonal than the set of open circles (for target alone conditions). This characteristic is clearly apparent by inspection of the dashed and solid line segments along the clusters of data points (and also in the raw data in Fig. 2). Each segment depicts the average difference between temporal-paradigm and spatial-paradigm thresholds for the corresponding subset of data, which amounts to −0.080 log units in the target alone conditions (open circles and dashed line) and −0.167 log units in the target plus flanker conditions (solid circles and solid line). Both values are significantly different from zero ($t_7 = -3.999$ and −3.958, respectively; $p < 0.01$). At the same time, the average difference in the target alone condition is also significantly different from the average difference in the target plus flanker condition ($t_7 = -2.386$; $p < 0.05$).

In other words, although thresholds obtained with a temporal paradigm are generally lower than those obtained with a spatial paradigm, the magnitude of the reduction varies with stimulus complexity and is larger in the presence of flankers. This differential effect of 2AFC paradigm on detection thresholds in the target plus flanker condition is likely to affect conclusions regarding facilitation or impairment of target detection in the presence of flankers, as discussed next.

3.3. Effect of the presence of flankers

Figure 3c shows how the results described thus far regarding separate thresholds combine to yield a relative measure of threshold elevation in the presence of flankers, where threshold elevation is defined as the difference between the log detection threshold for the target in the presence of flankers and the log detection threshold for the target alone. If threshold elevation is positive, the presence of flankers impairs (masks) detection; if negative, the presence of flankers facilitates detection. The horizontal and vertical dimensions in Fig. 3c respectively represent threshold elevation in spatial and temporal paradigms. The horizontal coordinate of a solid (alternatively, open) square is the algebraic difference between the abscissae of solid and dashed vertical lines in the top right (alternatively, top left) panels of Fig. 2, and the vertical coordinate is the corresponding difference in the bottom right (alternatively, bottom left) panel. Most data points lie in the third quadrant (negative threshold elevation in both paradigms), indicating that the target is generally more easily detected in the presence of flankers than when alone; at the same time, most data points also lie below the diagonal identity line, indicating that there is more evidence of facilitation (or less evidence of impairment) with temporal paradigms than with spatial paradigms.

Over the top and on the right outside the frame of Fig. 3c, open and solid squares and error bars through them respectively indicate the means and 95% confidence intervals for threshold elevation from the spatial and temporal paradigms at each spatial location. Perhaps due to considerable individual differences, the spatial paradigm does not render statistically significant threshold elevation at any location: All applicable confidence intervals depicted at the top of Fig. 3c cross zero threshold elevation. Conversely, the temporal paradigm yields statistically significant facilitation on the right hemifield but not on the left (see the applicable confidence intervals on the right of Fig. 3c).

3.4. Data pooled across spatial locations

One reason to analyze separately the data from each of the two locations involved in the spatial paradigm is that each location might rightly yield a different threshold owing to visual inhomogeneity or to the spatial inhomogeneity of the display monitor. This type of analysis has not generally been carried out in the past (an exception is Tailby *et al*., 2001). For instance, Williams and Hess (1998), Zenger-Landolt and Koch (2001), and Giorgi *et al.* (2004) used spatial paradigms but they did not separate trials at each location. In these conditions, their measures reflected a mixture of the potentially different psychometric functions that hold at each of the intervening locations, thus hiding differences across locations that may, in turn, cancel each other out at the pooled level. It is thus worth looking at how the results for data pooled across spatial locations differ from the results at each location that were shown in Fig. 2. Although Fig. 3a suggested that thresholds at the two spatial locations are analogous, note that the threshold obtained by pooling the data across locations is not the average of the thresholds separately obtained at each location, the reason being that pooling the raw data requires fitting the psychometric function anew and, thus, renders a different set of estimated parameters.

Summary relative threshold elevation results from the pooled data are plotted with open circles in Fig. 3c, one symbol per subject. Each circle is in turn connected to the two data points indicating separate results at each individual spatial location for the corresponding subject. Generally, the data point for the pooled responses does not lie midway between the two data points from the segregated response sets, revealing that pooling data that do not belong together may yield reasonable-looking results that are devoid of meaning. In any case, the combined data also corroborate that temporal paradigms yield more facilitation than spatial paradigms: All circles in Fig. 3c lie below the diagonal. At the same time, threshold elevation is significantly different from zero in the temporal paradigm (see the applicable confidence interval on the right of Fig. 3c) but not in the spatial paradigm (see the applicable confidence interval at the top of Fig. 3c).

3.5. Discussion

This experiment has shown that spatial paradigms tend to yield higher thresholds than temporal paradigms, more so when the stimulus configuration includes additional elements (flankers). The particular form of this differential effect further makes it look as if the presence of flankers facilitated target detection more under temporal than under spatial paradigms, and this result (shown in Fig. 3c) agrees with results reported by Giorgi *et al.* (2004).

One reason that spatial 2AFC renders higher thresholds (i.e. lower sensitivity) may lie in the spatial uncertainty associated with this paradigm: Subjects must split resources across space in order to monitor simultaneously two disparate presentation locations. Indeed, several studies have shown that increasing spatial uncertainty as to the presentation location of a target usually raises threshold (Burgess and Ghandeharian, 1984; Cameron *et al.*, 2002; Carrasco *et al.*, 2000; Cohn and Lasley, 1974). In addition to the inevitable spatial uncertainty associated with this paradigm, the stimulus arrangement in our Experiment 1 represents the farthest distance at which two locations can be set each of which is 4 deg into the periphery. Because two spatial locations that are closer together may be easier to monitor simultaneously, one might surmise that reducing the distance between the two locations for the target would bring the results of spatial and temporal paradigms into closer agreement. To prevent contamination from variations in sensitivity with visual inhomogeneity (Peli *et al.*, 1991; Pointer and Hess, 1989, 1990) or from variations in lateral interactions with eccentricity (Giorgi *et al.*, 2004), reducing the distance between the two locations should alter neither the 4-deg eccentricity of each individual location with respect to fixation nor the relative location of the flankers with respect to the target. The stimulus configuration depicted in Fig. 1b served this purpose, and the results of the corresponding experiment are reported next.

4. RESULTS OF EXPERIMENT 2

Recall from Section 2.2 that, for the spatial paradigm depicted in our Fig. 1b, obtaining the threshold at each location using the appropriate orientation required separate sessions. Figure 4 shows summary results of Experiment 2 in the same format as that of Fig. 3. Next we describe these results along the lines of Section 3 above, but we omit the stage in which data are pooled across locations because in this experiment the target is not the same at both locations.

4.1. Differences between left and right in the upper hemifield

Figure 4a reveals that, despite the fact that the stimulus has a different orientation at each location — but perhaps because these two orientations are ±45 deg from vertical — the threshold at both locations is similar. The average differences between locations are 0.013 and 0.100 log units in the target alone condition (open circles and dashed segment in Fig. 4a) and in the target plus flanker condition (solid circles and solid segment in Fig. 4a), respectively. Neither difference is statistically significant at the 0.05 level, nor is the difference between them.

4.2. Differences between spatial and temporal paradigms

Figure 4b shows that temporal paradigms also yield lower thresholds than spatial paradigms under the conditions of this experiment and that the difference is again

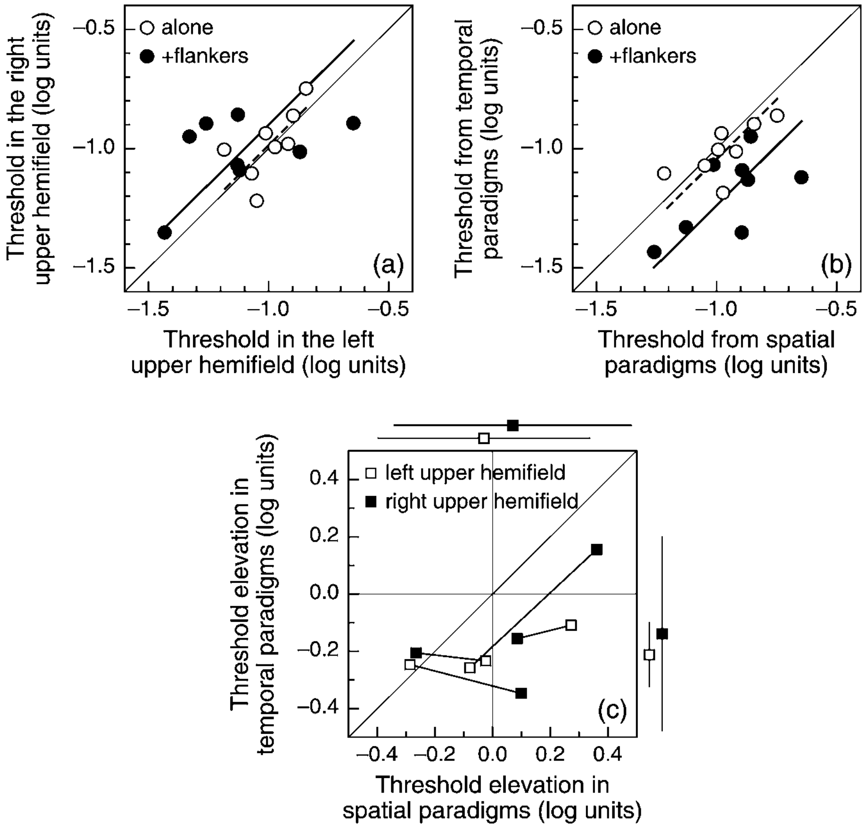


Figure 4. Summary results of Experiment 2. (a) Relationship between thresholds at one versus the other spatial location. Each open (alternatively, solid) circle pertains to a given subject and a given paradigm in the target alone (alternatively, target plus flanker) condition; solid and dashed line segments along the span of solid and open circles indicate the average distance of each subset of data from the diagonal identity line. Thresholds are not exactly identical at both locations, but no systematic trend can be observed and the differences are not statistically significant. (b) Relationship between thresholds determined with spatial versus temporal paradigms. Each open (alternatively, solid) circle pertains to a given subject and a given spatial location in the target alone (alternatively, target plus flanker) condition; solid and dashed line segments along the span of solid and open circles indicate the average distance of each subset of data from the diagonal identity line. Temporal paradigms tend to produce lower thresholds than spatial paradigms, more so in stimulus configurations involving flankers (solid circles and solid line) than in stimulus configurations not involving flankers (open circles and dashed line). The difference is significantly different from zero only in the target plus flanker condition, and the two conditions also differ significantly. (c) Relationship between threshold elevation measures from spatial and temporal paradigms in the left upper hemifield (open squares) and the right upper hemifield (solid squares). Most points are located below the diagonal identity line, indicating that temporal paradigms generally yield more facilitation than spatial paradigms. The symbols and error bars outside the frame at the top (alternatively, right) indicate means and 95% confidence intervals for the corresponding conditions in the spatial (alternatively, temporal) paradigms.

larger in the presence of flankers (solid circles and solid segment in Fig. 4b) than when the target is presented alone (open circles and dashed segment in Fig. 4b). The average difference in the former condition is −0.239, which is statistically significant ($t_7 = -4.370$; $p < 0.01$); the average difference when the target is alone is −0.043, which is non-significant at the 0.05 level. The difference between them is also significant ($t_7 = -3.113$; $p < 0.02$).

4.3. Effect of the presence of flankers

Figure 4c shows the amount of facilitation or impairment exerted by the flankers for each subject at each spatial location as measured with spatial or temporal paradigms. Most data points lie below the diagonal, indicating again that temporal paradigms yield less threshold elevation than spatial paradigms. For the stimulus configuration involved in this experiment, the presence of flankers in temporal paradigms generally produces strong facilitation (negative values on the ordinate), whereas their presence in spatial paradigms can produce facilitation (negative values on the abscissa) or impairment (positive values on the abscissa).

Average values and 95% confidence intervals plotted outside the frame of Fig. 4c indicate that spatial paradigms render an average threshold elevation that is not significantly different from zero at either visual field location (symbols and lines at the top of the panel), whereas temporal paradigms result in negative average threshold elevation that is significantly different from zero only in the left upper hemifield (symbols and lines on the right of the panel).

4.4. Discussion

By comparison with Experiment 1, bringing the two locations closer in space seems to eliminate the difference that was observed across paradigms in the target alone condition (a difference that was significant in Fig. 3b but is not significant in Fig. 4b) whereas the difference in the target plus flanker condition remains (a difference that was significant in both Figs 3b and 4b). At the same time, the overall picture of greater facilitation in temporal than in spatial paradigms also remains.

Despite the fact that the distance between target locations has been reduced by a factor of $\sqrt{2}$ with respect to that used in Experiment 1, one may wonder whether this pattern of results will occur regardless of the particular location in the visual field. The next experiment explores this by rigidly rotating the entire stimulus setup 90 deg clockwise around the fovea to yield the stimulus configuration shown in Fig. 1c, so that target and flanker locations all fall in the right hemifield.

5. RESULTS OF EXPERIMENT 3

Recall from Section 2.2 that two separate spatial paradigms were required to obtain thresholds at each spatial location with the appropriate target orientation. Figure 5 shows summary results of Experiment 3 in the same format as that of Fig. 4. We also omit pooling data across locations in this experiment. Yet, because one of the locations and the corresponding local stimulus configuration here is identical to one of those in Experiment 2, in Section 5.4 below we will compare the results obtained at this particular location in each experiment.

5.1. Differences between upper and lower parts of the right hemifield

Figure 5a reveals that thresholds at these locations are similar even though the stimulus used at each location is tilted 45 deg in a different direction from vertical. The average differences in threshold for the target alone (open circles and dashed segment in Fig. 5a) and in the presence of flankers (solid circles and solid segment in Fig. 5a) are now 0.012 and 0.080 log units. Neither difference is statistically significant at the 0.05 level, nor is the difference between them.

5.2. Differences between spatial and temporal paradigms

Figure 5b shows that temporal paradigms continue to yield lower thresholds than spatial paradigms under the conditions of this experiment and that the pattern reproduces the results observed in Experiment 2. The difference is larger in the presence of flankers (solid circles and solid segment in Fig. 5b) than when the target is presented alone (open circles and dashed segment in Fig. 5b). The average difference in the former condition is −0.351, which is statistically significant ($t_7 = -3.344$; $p < 0.02$); the average difference when the target is alone is −0.049, which is non-significant at the 0.05 level; the effect of paradigm is also significantly different in the target alone and the target plus flanker conditions ($t_7 = -2.915$; $p < 0.03$).

5.3. Effect of the presence of flankers

Figure 5c shows the index of threshold elevation for each subject at each spatial location as measured with spatial or temporal paradigms. All data points lie below the diagonal, indicating again that temporal paradigms yield less threshold elevation than spatial paradigms. In this experiment, the presence of flankers in spatial paradigms generally produces strong impairment (positive values on the abscissa), whereas their presence in temporal paradigms is either facilitatory (negative values on the ordinate) or neutral (values around zero on the ordinate).

Average values and 95% confidence intervals plotted outside the frame of Fig. 5c indicate that spatial paradigms render positive average threshold elevation that is nevertheless not significantly different from zero at either visual field location (symbols and lines at the top of the panel), whereas temporal paradigms result in negative average threshold elevation that is significantly different from zero only in the lower right hemifield (symbols and lines on the right of the panel).

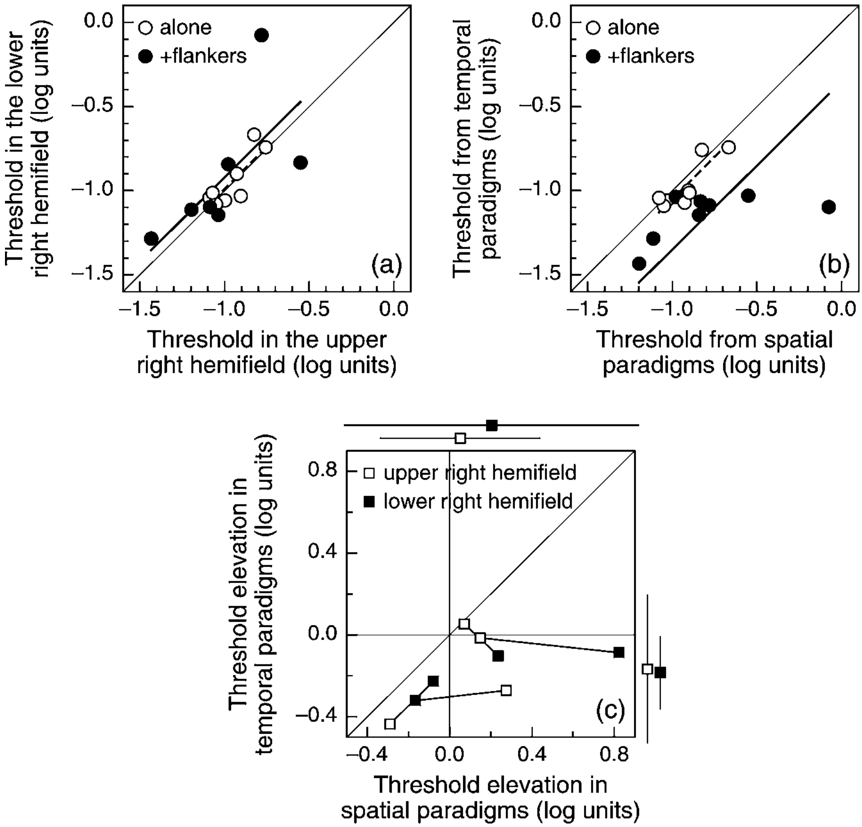


Figure 5. Summary results of Experiment 3. (a) Relationship between thresholds at one versus the other spatial location. Each open (alternatively, solid) circle pertains to a given subject and a given paradigm in the target alone (alternatively, target plus flanker) condition; solid and dashed line segments along the span of solid and open circles indicate the average distance of each subset of data from the diagonal identity line. Thresholds are not exactly identical at both locations, but no systematic trend can be observed and the differences are not statistically significant. (b) Relationship between thresholds determined with spatial versus temporal paradigms. Each open (alternatively, solid) circle pertains to a given subject and a given spatial location in the target alone (alternatively, target plus flanker) condition; solid and dashed line segments along the span of solid and open circles indicate the average distance of each subset of data from the diagonal identity line. Temporal paradigms tend to produce lower thresholds than spatial paradigms, more so in stimulus configurations involving flankers (solid circles and solid line) than in stimulus configurations not involving flankers (open circles and dashed line). The difference is significantly different from zero only in the target plus flanker condition, and the two conditions also differ significantly. (c) Relationship between threshold elevation indices from spatial and temporal paradigms in the upper right hemifield (open squares) and the lower right hemifield (solid squares). All points are located below the diagonal identity line, indicating that temporal paradigms generally yield more facilitation than spatial paradigms. The symbols and error bars outside the frame at the top (alternatively, right) indicate means and 95% confidence intervals for the corresponding conditions in the spatial (alternatively, temporal) paradigms.

5.4. Comparison with similar stimulus configurations in Experiment 2

The stimulus configuration in the upper location in this experiment is identical in all respects (i.e. target and flanker orientations and positions) to the right location in Experiment 2 (see Figs 1b and 1c). Therefore, thresholds obtained at this particular location with temporal paradigms should be identical (within random error) in both experiments because the different runs involved are all mere repeats. Conversely, there is no strong reason to expect thresholds obtained with spatial paradigms to be similar in both experiments because in these paradigms the need to split resources between competing spatial locations may affect performance differently depending on just what pair of locations has to be monitored, and these differed across Experiments 2 and 3.

Figure 6 displays thresholds from Experiment 3 against thresholds from experiment 2 at the common location and separately for temporal and spatial paradigms. In the temporal paradigm (Fig. 6a), all data points lie tight around the identity line and differences between experiments are non-significant at the 0.05 level, both in the target alone condition and in the target plus flanker condition. In the spatial paradigm (Fig. 6b), data from the target alone condition are also tightly packed around the diagonal, but data from the condition involving flankers display a broader dispersion, although the differences between experiments are non-significant at the 0.05 level.

In summary, data from temporal paradigms and otherwise identical conditions in Experiments 2 and 3 have the aspect of mere replicates. The same is technically true for data from spatial paradigms and analogous conditions in Experiments 2 and 3, although in this case one important difference remains between the two experiments

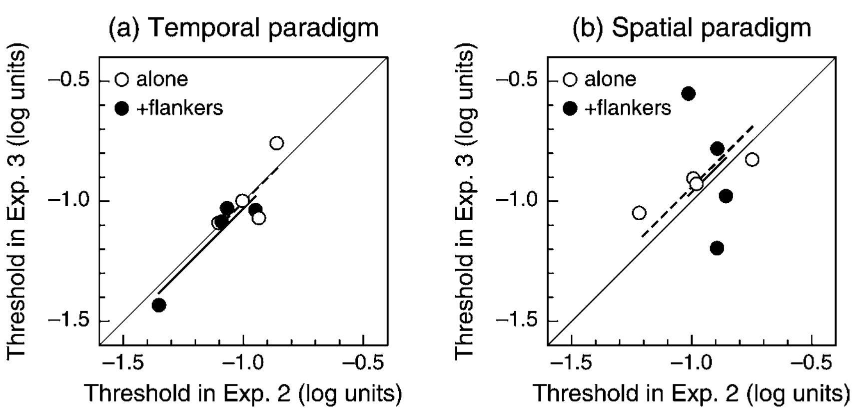


Figure 6. Relationship between thresholds for co-oriented targets and flankers at the same spatial location (on the upper right quadrant in the sketches in Figs 1b and 1c) across Experiments 2 and 3. Open and solid circles respectively represent thresholds in the target alone and target plus flanker conditions. Dashed and solid line segments indicate the average distance of each subset of data from the diagonal identity line. (a) Results obtained with temporal paradigms. (b) Results obtained with spatial paradigms.

in what regards the alternative spatial location (see Figs 1b and 1c). This difference seems to produce a larger spread of data in the target plus flanker condition (solid symbols in Fig. 6b) than in the target alone condition (open symbols in Fig. 6b). But we must refrain from trying to test for significant differences in variability with so small a sample.

5.5. Discussion

Experiment 3 yields results that are thoroughly analogous to those observed in Experiment 2, so whether one or two cerebral hemispheres are involved does not seem to alter the basic phenomenon that temporal paradigms yield lower thresholds than spatial paradigms. Threshold differences between paradigms continue to be larger in the case of target plus flanker configurations, which further makes it look as if there is more facilitation in the case of temporal paradigms.

6. GENERAL DISCUSSION

The major finding in this paper is that temporal 2AFC paradigms generally produce lower thresholds than spatial 2AFC paradigms. These threshold differences further vary with the type of stimulus and its position in the visual field or, in other words, thresholds from spatial and temporal 2AFC paradigms do not differ by a fixed and invariant amount. The smallest differences occur when the stimulus configuration is simple (target alone condition) and, among them, the largest (however small) and only significant difference was 0.08 log units in the spatial arrangement of Experiment 1, which implies the largest possible distance between two locations each of which is 4 deg into the periphery. Conversely, differences are much larger and statistically significant when the stimulus configuration is complex (target plus flanker condition): The differences amount to 0.17, 0.24, and 0.35 log units respectively for Experiments 1 to 3. The form of this dependence of threshold on 2AFC paradigm and stimulus complexity creates a picture of larger facilitation when peripheral lateral interactions are measured with temporal paradigms. This differential effect explains conflicting results in the literature on the presence or absence of peripheral facilitation (Giorgi *et al.*, 2004; Polat and Sagi, 1994a; Williams and Hess, 1998; Zenger-Landolt and Koch, 2001).

We have documented individual differences in that some subjects consistently show facilitation whereas others show impairment (see Figs 3c, 4c, and 5c). The latter appears less prevalent, explaining why average indices of lateral interactions generally show either facilitation or no effect. Individual differences can also be appreciated in previous papers where individual data have been reported (e.g. Giorgi *et al.*, 2004; Polat and Sagi, 1993; Woods *et al.*, 2002) but they have generally been overlooked. The functional significance of individual differences is yet to be determined.

We have also documented differences across retinal locations when tested with temporal paradigms, differences that were not found when we used spatial paradigms despite taking the precaution of obtaining independent threshold measures at each spatial location in the latter paradigm (see Figs 3c, 4c, and 5c). It could be that temporal paradigms are more sensitive to detect this type of effect, but the effect itself could also be an artifact of temporal paradigms or of the interaction of temporal paradigms with individual differences.

Our finding of differences between thresholds obtained with spatial and temporal 2AFC paradigms demands an investigation into the reasons for these different outcomes. We have already mentioned that spatial and temporal paradigms may involve different attention and memory loads. But it may also be that other peculiarities of these paradigms account for their different outcomes, as discussed next.

Suppose the detection threshold for some target is to be measured at some visual field location. An experimenter may choose to set up a spatial 2AFC paradigm that will bring into play an alternative location in the visual field and, then, the detection threshold at this location will be affected by the noise distribution at that alternative location (which might be different). But the experimenter may as well set up a temporal 2AFC paradigm so that the noise distribution that affects threshold measurements comes from the same location where the threshold is measured. However, in this latter case, mere presentation of the target on the second interval in a trial may alter the effect of the target (or the blank, for that matter) presented on the first interval in the next trial (as a result, for example, of adaptation or temporal masking) if the inter-trial interval is insufficient. Therefore, unwanted effects of different types arise in either spatial or temporal 2AFC, and it is not clear which one is the lesser evil.

Whatever the reasons for the different effects of spatial and temporal paradigms are, our finding reveals that stimulus detection is not a simple passive process whose outcome is determined solely by the amount of energy falling on the retina. Rather, it seems to require the allocation of resources that are limited and cannot be deployed simultaneously at separate spatial locations as effectively as they can be used on a fixed spatial location over time. What these resources are is unclear but our series of experiments indicates that the outcome of their operation varies with the particular spatial locations and stimuli that are involved. Until the underlying processes are elucidated, visual psychophysicists should be aware that the choice of a spatial or a temporal 2AFC paradigm is not without consequences. We have also shown here that lateral interactions in peripheral vision appear to be stronger when tested with a temporal paradigm, but it is unclear whether or not this is the appropriate paradigm to study this phenomenon.

Acknowledgements

Supported in part by grants EY05957 and EY12890 from the National Institutes of Health. MAGP was also supported by grant BSO2001-1685 from Ministerio de Ciencia y Tecnología.

REFERENCES

Alcalá-Quintana, R. and García-Pérez, M. A. (2004a). The role of parametric assumptions in adaptive Bayesian estimation, *Psychological Methods* **9**, 250–271.

Alcalá-Quintana, R. and García-Pérez, M. A. (2004b). Response bias in forced-choice paradigms, and how to compensate for it (manuscript in preparation).

Ben-Yehudah, G., Sackett, E., Malchi-Ginzberg, L. and Ahissar, M. (2001). Impaired temporal contrast sensitivity in dyslexics is specific to retain-and-compare paradigms, *Brain* **124**, 1381–1395.

Burgess, A. E. and Ghandeharian, H. (1984). Visual signal detection. II. Signal-location identification, *J. Opt. Soc. Amer. A* **1**, 906–910.

Cameron, E. L., Tai, J. C. and Carrasco, M. (2002). Covert attention affects the psychometric function of contrast sensitivity, *Vision Research* **42**, 949–967.

Carrasco, M., Penpeci-Talgar, C. and Eckstein, M. (2000). Spatial covert attention increases contrast sensitivity across the CSF: Support for signal enhancement, *Vision Research* **40**, 1203–1215.

Cohn, T. E. and Lasley, D. J. (1974). Detectability of a luminance increment: Effect of spatial uncertainty, *J. Opt. Soc. Amer.* **64**, 1715–1719.

Corkin, S. (1974). Serial-ordering deficits in inferior readers, *Neuropsychologia* **12**, 347–354.

Eden, G. F., Stein, J. F., Wood, H. M. and Wood, F. B. (1995). Temporal and spatial processing in reading disabled and normal children, *Cortex* **31**, 451–468.

García-Pérez, M. A. (1998). Forced-choice staircases with fixed step sizes: Asymptotic and small-sample properties, *Vision Research* **38**, 1861–1881.

García-Pérez, M. A. and Alcalá-Quintana, R. (2004). Sampling plans for fitting the psychometric function (manuscript under review).

García-Pérez, M. A. and Peli, E. (2001). Luminance artifacts of cathode-ray tube displays for vision research, *Spatial Vision* **14**, 201–215.

Giorgi, R., Soong, G. P., Woods, R. L. and Peli, E. (2004). Facilitation of contrast detection in near-peripheral vision, *Vision Research* **44**, 3193–3202.

Kaernbach, C. (1991). Simple adaptive testing with a weighted up-down method, *Perception and Psychophysics* **49**, 227–229.

Klein, S. A. (2001). Measuring, estimating, and understanding the psychometric function: A commentary, *Perception and Psychophysics* **63**, 1421–1455.

Leek, M. R. (2001). Adaptive procedures in psychophysical research, *Perception and Psychophysics* **63**, 1279–1292.

May, J. G., Williams, M. C. and Dunlap, W. P. (1988). Temporal order judgements in good and poor readers, *Neuropsychologia* **26**, 917–924.

Metha, A. B., Vingrys, A. J. and Badcock, D. R. (1993). Calibration of a color monitor for visual psychophysics, *Behavior Research Methods, Instruments, and Computers* **25**, 371–383.

Numerical Algorithms Group (1999). *NAG Fortran Library Manual, Mark 19*. Oxford.

Peli, E. and García-Pérez, M. A. (1997). Contrast sensitivity in dyslexia: Deficit or artifact? *Optometry and Vision Science* **74**, 986–988.

Peli, E., Yang, J. and Goldstein, R. B. (1991). Image invariance with changes in size: The role of peripheral contrast thresholds, *J. Opt. Soc. Amer. A* **8**, 1762–1774.

Pointer, J. S. and Hess, R. F. (1989). The contrast sensitivity gradient across the human visual field: With emphasis on the low spatial frequency range, *Vision Research* **29**, 1133–1151.

Pointer, J. S. and Hess, R. F. (1990). The contrast sensitivity gradient across the major oblique meridians of the human visual field, *Vision Research* **30**, 497–501.

Polat, U. and Sagi, D. (1993). Lateral interactions between spatial channels: Suppression and facilitation revealed by lateral masking experiments, *Vision Research* **33**, 993–999.

Polat, U. and Sagi, D. (1994a). Spatial interactions in human vision: From near to far via experience-dependent cascades of connections, *Proc. Natl Acad. Sci. USA* **91**, 1206–1209.

Polat, U. and Sagi, D. (1994b). The architecture of perceptual spatial interactions, *Vision Research* **34**, 73–78.

Solomon, J. A. and Morgan, M. J. (2003). Flanked targets: Easier to see, harder to identify, *Perception (Suppl.)* **32**.

Stuart, G. W., McAnally, K. I. and Castles, A. (2001). Can contrast sensitivity functions in dyslexia be explained by inattention rather than a magnocellular deficit? *Vision Research* **41**, 3205–3211.

Swift, D., Panish, S. and Hippensteel, B. (1997). The use of *VisionWorks*™ in visual psychophysics research, *Spatial Vision* **10**, 471–477.

Tailby, C., Cubells, O. and Metha, A. (2001). Enhanced sensitivity for peripherally-presented collinearly-aligned stimulus elements: Contour detection or spatial summation? *Clin. Exper. Optometry* **84**, 354–360.

Treutwein, B. (1995). Adaptive psychophysical procedures, *Vision Research* **35**, 2503–2522.

Wichmann, F. A. and Hill, N. J. (2001). The psychometric function: I. Fitting, sampling, and goodness of fit, *Perception and Psychophysics* **63**, 1293–1313.

Williams, C. B. and Hess, R. F. (1998). Relationship between facilitation at threshold and suprathreshold contour integration, *J. Opt. Soc. Amer. A* **15**, 2046–2051.

Woods, R. L., Nugent, A. K. and Peli, E. (2002). Lateral interactions: Size does matter, *Vision Research* **42**, 733–745.

Zenger-Landolt, B. and Koch, C. (2001). Flanker effects in peripheral contrast discrimination — Psychophysics and modeling, *Vision Research* **41**, 3663–3675.

APPENDIX A

Software limitations forced us to gather data in Experiments 2 and 3 under spatial 2AFC paradigms with configurations in which the target is cross-oriented with the flankers (see Section 2.2). As there was no analogous temporal-2AFC data in cross-oriented configurations, these spatial-2AFC data do not bear on the main goal of our paper. Nevertheless, we report these data here because a comparison of detection thresholds (or facilitation) in co-oriented versus cross-oriented conditions has occasionally been addressed. For instance, Tailby *et al.* (2001) used a spatial 4AFC paradigm with peripheral presentations, and they observed minimally higher thresholds (i.e. less sensitivity) with cross-oriented than with co-oriented targets. Because it was the target that changed orientation across conditions in that study, and also because detection thresholds for targets alone at each location had not been determined (and, hence, differential threshold elevation with co-oriented and cross-oriented targets could not be assessed), it is uncertain whether the higher thresholds with cross-oriented targets is a result of cross-orientation itself or it is merely a manifestation of different thresholds for different targets. Also, Zenger-Landolt and Koch (2001), who had not found facilitation in a spatial 2AFC paradigm similar

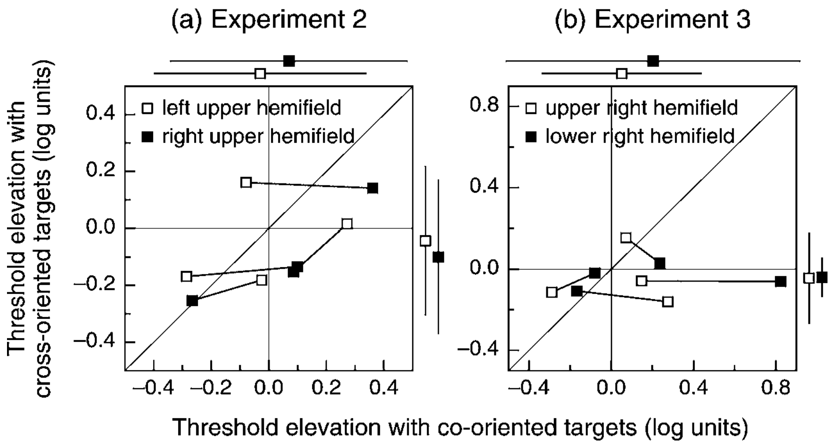


Figure A1. Threshold elevation with cross-oriented targets plotted against threshold elevation in identical conditions except that targets were co-oriented. All data come from spatial 2AFC paradigms in Experiments 2 (a) and 3 (b). The horizontal coordinates of all data points are exactly the same as those in Figs 4c (for Experiment 2) and 5c (for Experiment 3), and the scale of the plots has been made identical to that of the corresponding plots in Figs 4c and 5c to facilitate comparisons. Pictorial conventions as in Figs 4c and 5c.

to ours with co-oriented targets, reported facilitation when the flankers were cross-oriented (as opposed to our conditions in which it was the targets that were cross-oriented). Our experiments involving peripheral presentations and a spatial 2AFC paradigm yielded similar amounts of threshold elevation that were not significantly different from zero in either cross-oriented or co-oriented conditions (see the scatter of points around the diagonal identity line in the panels of Fig. A1, and the means and 95% confidence intervals drawn outside the panels). If anything, the only difference between cross-oriented and co-oriented conditions was that the former appeared to produce less variability in the data (note the smaller vertical spread of the data in the panels of Fig. A1 as compared to their horizontal spread).

APPENDIX B

A logistic psychometric function Ψ of log contrast x ($x \leqslant 0$) is given by

$$\Psi(x) = \gamma + \frac{1 - \lambda - \gamma}{1 + \exp[-b(x - T)]}, \tag{B.1}$$

where γ is the guessing rate and sets a lower asymptote, λ is the lapsing rate and sets an upper asymptote at $1 - \lambda$, T is a location parameter, and b is a slope parameter. Although γ is usually regarded as a constant valued at 0.5 for 2AFC tasks, when used with data from the spatial paradigm we had to free this parameter for reasons discussed in Section 2.3 and illustrated in Fig. B1. To eliminate excessive random variability in the left end of the curve, bins were discarded if they did not contain at least 20 responses. Maximum likelihood estimates $\hat{\lambda}$, $\hat{b}$, and $\hat{T}$ (and $\hat{\gamma}$ when

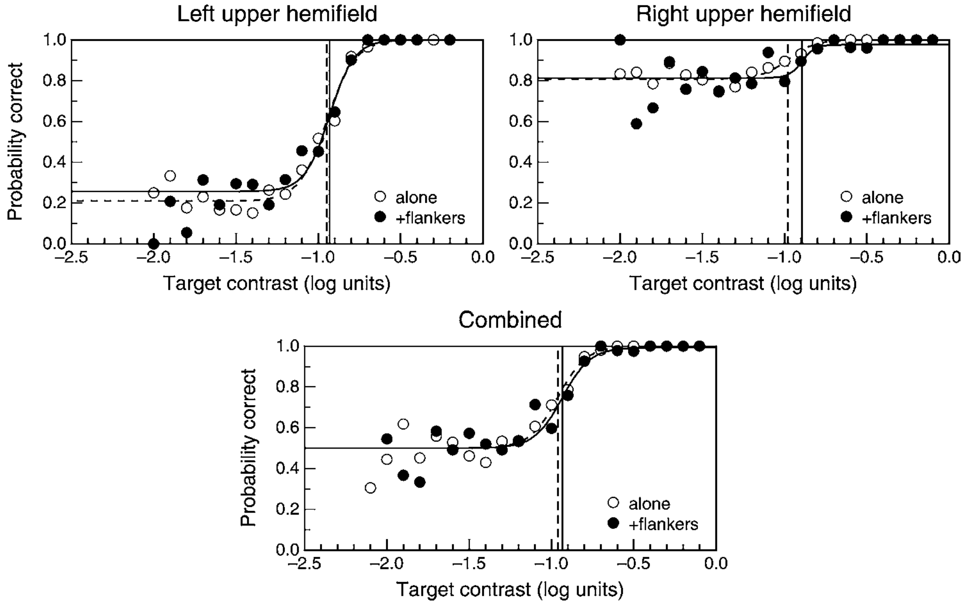


Figure B1. Illustration, with actual data, of how biased an experienced subject can be, and thus the value of regarding γ as a free parameter when fitting the psychometric function. Data and fitted functions reflect the performance of subject #4 in the spatial paradigm of Experiment 2 in which the target was co-oriented with the flankers in the right upper hemifield (that is, the condition depicted in Fig. 1b). The upper panels represent data segregated by presentation location; data shown in the top left panel were reported in Appendix A, but they were not involved in our comparison of spatial and temporal paradigms because the target was cross-oriented with the flankers; data in the top right panel were used in these comparisons. In both cases, γ was regarded a free parameter when fitting Ψ. The lower panel represents aggregated data from the two upper panels, but only to make clear that the overall guessing rate in the whole session is actually 50% (the fitted Ψ and threshold estimates in this latter case are meaningless).

appropriate) were obtained with NAG subroutine E04JYF (Numerical Algorithms Group, 1999), which allows constrained optimization. We implemented the natural constraints that $\hat{b} > 0$ and $\hat{T} < 0$ and, following the recommendations of Wichmann and Hill (2001) regarding the upper asymptote, we constrained $0 \leqslant \hat{\lambda} \leqslant 0.06$. When γ was treated as a free parameter, we also constrained $0.1 \leqslant \hat{\gamma} \leqslant 0.9$.

As discussed by García-Pérez (1998) and Alcalá-Quintana and García-Pérez (2004a), a convenient reparameterization of Ψ replaces the slope parameter b with a spread parameter σ that describes the effective support of Ψ, and also replaces the location parameter T with a threshold parameter θ that is directly interpretable as the point (in log units) at which the probability of a correct response is π for arbitrarily chosen $\pi \in (\gamma, 1 - \lambda)$. This reparameterization is better accomplished after λ, b, T, and γ have been estimated, and uses the transformations

$$\hat{\sigma} = \frac{2}{\hat{b}} \ln\left[\frac{1 - \hat{\lambda} - \hat{\gamma} - \delta}{\delta}\right], \tag{B.2}$$

where $\delta = (1 - \hat{\lambda} - \hat{\gamma})/100$ (see García-Pérez and Alcalá-Quintana, 2004) and

$$\hat{\theta} = \hat{T} + \frac{1}{\hat{b}} \ln\left[\frac{\pi - \hat{\gamma}}{1 - \hat{\lambda} - \pi}\right]. \tag{B.3}$$

We used $\pi = (1 - \hat{\lambda} + \hat{\gamma})/2$ so that threshold is defined as the midpoint between the lower and upper asymptotes. This choice for π renders $\hat{\theta} = \hat{T}$.