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The Efficiency of Different Cue Types for Reducing Spatial-frequency Uncertainty

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Detection experiments reveal that performance is decreased when the signal's spatial frequency varies unpredictably across trials compared with conditions where it is held constant. However, this effect can more or less be compensated by presenting cues shortly before each trial. To investigate the efficiency of different sensory and symbolic cue types a signal-detection experiment with spatial-frequency uncertainty was carried out. The inter-stimulus interval between cue and signal as well as for the sensory cue types, the spatial overlap between cue and signal, was varied. The results reveal appreciable efficiency differences. While some cues were only of little help, others reduced uncertainty almost entirely. However, the efficiency of cues which were identical to the signals was severely restricted by forward-masking effects when they were presented at the same position as the signal.

Spatial-frequency uncertainty Cuing Sinusoidal gratings Signal detection

INTRODUCTION

When subjects have to detect or respond to stimuli whose attributes vary from trial to trial, then their detection performance or speed in responding is reduced compared with a situation where the attributes remain constant. With respect to *visual* perception, such *uncertainty effects* have been observed for attributes such as phase (Burgess & Ghandeharian, 1984a), location (Burgess & Ghandeharian, 1984b; Davis, Kramer & Graham, 1983; Posner, Snyder & Davidson, 1980; Swensson & Judy, 1981), direction of movement (Ball & Sekuler, 1981), spatial frequency (Davis *et al.*, 1983; Graham, Robson & Nachmias, 1978), and related to the latter, size (Cave & Kosslyn, 1989; Larsen & Bundesen, 1978).

On the other hand, providing the subjects with specific cues shortly before each trial can compensate for the reduction in performance caused by uncertainty, where the amount of compensation depends on the employed cue type (Müller & Humphreys, 1991). The fact that different cue types are differentially efficient in improving performance under uncertainty is not only interesting in itself, but renders cuing an essential procedure for exploring selective-attention processes (cf. Kinchla, 1992).

Unfortunately, while cuing has been applied extensively in connection with research on spatial uncertainty (for an overview see Kinchla, 1992), to the knowledge of the author, up until now, there has been no systematic research on cuing effects with respect to spatial-frequency uncertainty, although it might provide valuable information about selective attention for spatial frequency or about processes relevant for the selection of spatial scale (cf. Cave & Kosslyn, 1989; Watt, 1990). Therefore, the present paper aims to explore the efficiency of different cue types for improving signal-detection performance under spatial-frequency uncertainty.

It is reasonable to assume that some of the concepts developed mainly in connection with spatial cuing and attention are also useful for examining cuing with respect to other attributes. One example is the distinction between symbolic and sensory cues (Johnston & Dark, 1986). While symbolic cues convey indirect information about a stimulus attribute which can be utilized to concentrate on that attribute only by means of top-down processes, sensory cues provide direct information by triggering bottom-up processes. For instance, arrows presented at the fixation point can serve as symbolic cues to uniquely indicate the position (if the distance between fixation and target is fixed) of a subsequent visual target. Sensory cues, on the other hand, such as luminance increments at the target position, indicate the location of the subsequent target directly. Usually, sensory cues are more efficient than symbolic cues (Jonides, 1981; Müller & Humphreys, 1991).

Posner (1980) distinguishes an endogenous from an exogenous orienting mechanism which seem to correspond to the two cue classes. While the former is a voluntary orientation in response to a symbolic indication,

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the latter is a reflexive response to salient stimuli such as sensory cues. It has been proposed that the exogenous mechanism is automatic and the endogenous is controlled (Jonides, 1981).

Symbolic and sensory cues can also be distinguished by their time-course. For instance, Müller and Findlay (1988) varied the stimulus-onset asynchrony (SOA) and demonstrated that facilitation built up more slowly with symbolic cues. Ball and Sekuler (1981) also employed symbolic cues and found that maximal facilitation for the detection of motion direction was not reached before an interstimulus interval (ISI) of 450–700 msec.

One important question with respect to uncertainty and cuing is whether sensory or decision processes are affected (cf. Sperling & Dosher, 1986). Usually, at least two functional stages of processing between stimulus and response are assumed (Shaw, 1984), a coding stage in which the stimulus is transformed into an internal representation, and a decision stage where the representation is used to determine the response.

It has been argued that for detection of luminance increments only the decision stage is affected by location uncertainty and cues (Shaw, 1984; Müller & Findlay, 1987). However, there is ample evidence that cues also affect the coding stage by improving sensitivity (Bashinski & Bacharach, 1980; Downing, 1988; Hawkins, Hillyard, Luck, Mouloua, Downing & Woodward, 1990; Müller & Humphreys, 1991).

A possible hypothesis is that symbolic cues affect mainly the decision stage, whereas sensory cues affect additionally the encoding stage by preactivating or priming the sensory pathway (cf. Müller & Humphreys, 1991). Analogous conclusions were also drawn from auditory signal-detection experiments with frequency uncertainty (Schlauch & Hafter, 1991; Hübner, 1993a; Hübner & Hafter, 1995).

To examine whether the observed cuing effects for the different stimuli attributes hold similarly for spatial-frequency, an experiment with sinusoidal gratings as signals was carried out. However, in a pilot study with spatial-frequency uncertainty unexpected results were obtained while employing a *temporal* two-interval forced-choice (2IFC) method as in Davis *et al.* (1983). So-called "iconic cues", i.e. cues identical to the signal but presented well above threshold, were of little help, which was unexpected in the light of the results from using corresponding cues in psychoacoustics (cf. Hübner & Hafter, 1995).

Since the cues were presented at the same location as the signals, it was reasonable to assume that some kind of forward masking might have occurred. To test this hypothesis, a *spatial* 2IFC-method was employed with cues presented either at the position where the noise or the signal-plus-noise would follow.

Overall, five different cue types were presented which are described in detail in the Method section.

EXPERIMENT 1

Method

Apparatus. The stimuli were presented on a 19″ color monitor (RGB) (Miro, Type GDM—1965) with a resolution of 1280 × 1024 pixels. The monitor was connected to a graphics-board (Miro-Tiger) with 256 gray levels and a refresh rate of 75 Hz (noninterlaced), resident in an IBM-compatible personal computer (PC). The PC also served for controlling stimuli presentation and response registration.

The space average luminance for each gray level was measured (via photometer L 1000 from LMT LICHTMESSTECHNIK, Berlin) and the data used to create a gamma look-up table to relate the required luminances with the corresponding gray levels.

Stimuli. Signals were static vertical sinusoidal gratings with a constant phase of zero. They were added to one-dimensional (vertical) static white noise. The stimuli (256 × 256 pixels) subtended approx. 2.66 deg horizontally and vertically and were viewed binocularly from a distance of 144 cm with a chin rest and natural pupils. The positions of the noise and signal-plus-noise fields (intervals) were adjacent.

Pseudo-random numbers (Box–Müller method) were used to construct white noise in a band of 0–48 c/deg. Since the number of gray levels was limited, the values were truncated at ± 3.2 SD. The 256 gray levels were distributed over a luminance range of 0.314–82 cd/m^2 which gives a *luminance-modulation* range in Michelson-contrast of 0.99. The standard deviation of the noise was 8.16 cd/m^2. On each trial, individual noise samples were drawn for each of the stimulus fields.

Five different spatial frequencies were presented: 0.75, 1.88, 3.38, 6.39, and 14.29 c/deg. Signal contrast was set to 1 dB above threshold, i.e. to 1 SL (sensation level). Different from the contrast-sensitivity function (CSF) obtained with sinusoidal gratings without external noise, the sensitivity here was monotonically decreasing with spatial frequency. This difference seems to be analogous to that observed in psychoacoustics (cf. Fletcher & Munson, 1933; Green, Mckey & Licklider, 1959). Interestingly, a monotonic CSF can also be obtained with gratings of a fixed number of cycles (Banks, Geisler & Bennett, 1987).

The used contrasts thus ranged from 0.0378 to 0.0635 for the 0.75 c/deg gratings, from 0.0642 to 0.0904 for the 1.88 c/deg gratings, from 0.0743 to 0.1003 for the 3.38 c/deg gratings, from 0.0919 to 0.1300 for the 6.39 c/deg gratings, and from 0.1212 to 0.2052 for the 14.29 c/deg gratings. Space average luminance for the signals was 41 cd/m^2. The homogeneous background, on which the stimuli were presented, had the same space average luminance as the signals.

Cues. Five different cue types were employed: iconic, rotated,* counter-phase, analog, and number cues. The iconic (i) cues were identical to the signals but presented without noise and with a contrast of 0.6. Rotated cues (r) were 90 deg rotated iconic cues, and phase cues

*I thank Professor Norma Graham, New York, for her suggestion to use horizontal gratings as cues.

(*p*) were similar to the iconic cues but with counter phase.

The analog (*a*) cues consisted of two patterns of small vertical lines which had a length of 1 deg and a width of one pixel. One pattern was presented directly above and the other below the stimuli. The number and distance of the lines in each pattern corresponded to that of the signals' luminance minima but not their position, since the patterns were centered horizontally on the display.

Number cues (*z*) were numbers presented at the center of the screen. They subtended approx. 0.6×0.4 deg.

Procedure. To investigate the effect of spatial overlap between cues and signals, a *spatial* 2IFC-method was employed. Signal-plus-noise and noise were presented simultaneously on the screen. Either the signal-plus-noise occurred left and the noise right of the fixation point (i.e. center of the screen), or vice versa. There was no spatial separation between the two stimulus fields.

The task of the subjects was to indicate which stimulus field contained the signal by pressing one of two buttons. There was no time limit for response. A trial started with a fixation mark which consisted of two short horizontally centered vertical lines (with a length of about 1 deg), one presented above and the other below the stimulus fields. The subjects were instructed to fix the midpoint between the two lines. Because the line patterns of the analog cues would have interfered with the lines of the fixation mark, a centered cross was presented for 200 msec as a fixation mark. A tone started simultaneously with the fixation mark and was presented for 200 msec to mark the beginning of the trial.

After a random time interval with a uniformly distributed duration between 400 and 800 msec, a cue was presented for 106 msec (in conditions with cues). A randomly chosen ISI of 200, 400, 600, 800, or 1000 msec separated the cues and the stimuli which were presented for 106 msec. The fixation lines remained up to the end of stimulus presentation. If the response was incorrect, an acoustic feedback was given. 2000 msec after the subjects' response the next trial started.

A transformed 1-up-2-down 2IFC-procedure (Levitt, 1970) was used to measure the thresholds of the individual spatial frequencies. By averaging the last six out of ten reversal points, estimates, which correspond to 70.7% correct responses, were obtained. For each spatial frequency three such adaptive tracks were randomly interleaved and the median of the estimates was taken as threshold.

Then the signal levels for the experiments were set to 1 dB above threshold, i.e. to 1 SL.

First, the control condition (*c*) with fixed spatial frequencies was carried out. It consisted of five blocks, one for each spatial frequency. Each block consisted of 100 trials (20 for each ISI). Altogether, there were 500 trials in this condition, 100 trials for each ISI, and 100 trials for each spatial frequency.

After finishing the *c*-condition, during which the subjects could get familiar with the different spatial frequencies, five blocks at 100 trials with mixed spatial frequencies (*m*-condition) were run. Thus, also in this condition we had altogether 500 trials, 100 trials for each ISI, and 100 trials for each spatial frequency.

Subsequently, the cue conditions were realized. For the iconic, rotated, and counter-phase cue conditions the cues were presented randomly but equally often either at the signal (*s*) or the noise (*n*) position. For each ISI and condition the cues were presented on 150 trials at the signal and on 150 trials at the noise position. Altogether, there were 1500 [(150 + 150) times five ISIs] trials for each condition divided into fifteen 100 trial blocks. Since all spatial frequencies occurred equally often there were also 150 trials for each spatial frequency and position.

For the number as well as for the analog cues ten 100 trial blocks were carried out (altogether we had 1000 trials in each of these conditions, 200 trials for each ISI, and 200 trials for each spatial frequency).

The blocks for the different cue types were randomly intermixed in each session, which consisted of four to five blocks.

Since we had two control conditions and since three of the five cue types could occur in two locations, there were altogether ten experimental conditions.

Subjects. The author and three paid persons served as subjects (aged 21–38 yr; two male, two female). All subjects had normal or corrected-to-normal vision.

Results

The results obtained under the different conditions and averaged for the four subjects are depicted in Fig. 1. By comparing the data of the *m*-condition and the *c*-condition it can be seen that the spatial-frequency uncertainty effect varies across the ISIs from about 10 to 15%. Obviously, the ISI variation did not have much effect on detection performance. A 10×5 (conditions $\times$ ISIs) repeated measures analysis of variance (ANOVA) reveals only a significant main effect for the conditions factor [$F(9,27) = 8.227$, $P < 0.001$]. Neither the ISI factor nor the interaction is significant.

t-tests for paired observations were used for multiple comparisons, where the α-error rate was adjusted according to the Bonferroni inequality for allowing all possible pair comparisons while not exceeding a total error rate (α_T) of 0.05, i.e. α was set to 0.00125.

It turned out that the analog cues reduced the spatial-frequency uncertainty effect only slightly (*a*-condition compared with *m*-condition) but significantly [$t(19) = 4.06$, $P < 0.001$]. The efficiency of the number cues was similar to that of the analog cues. They also improved detection performance significantly [*z*-condition vs *m*-condition: $t(19) = 4.31$, $P < 0.001$].

By considering the iconic-cue data it can be seen that the presentation of cues at the signal position (*is*-condition) produced a severe negative effect compared with presentation at the noise-position (*in*-condition) [$t(19) = 5.29$, $P < 0.001$]. However, the negative effect seems to decrease with increasing ISI. The ANOVA had not enough power to detect the trend obvious in the

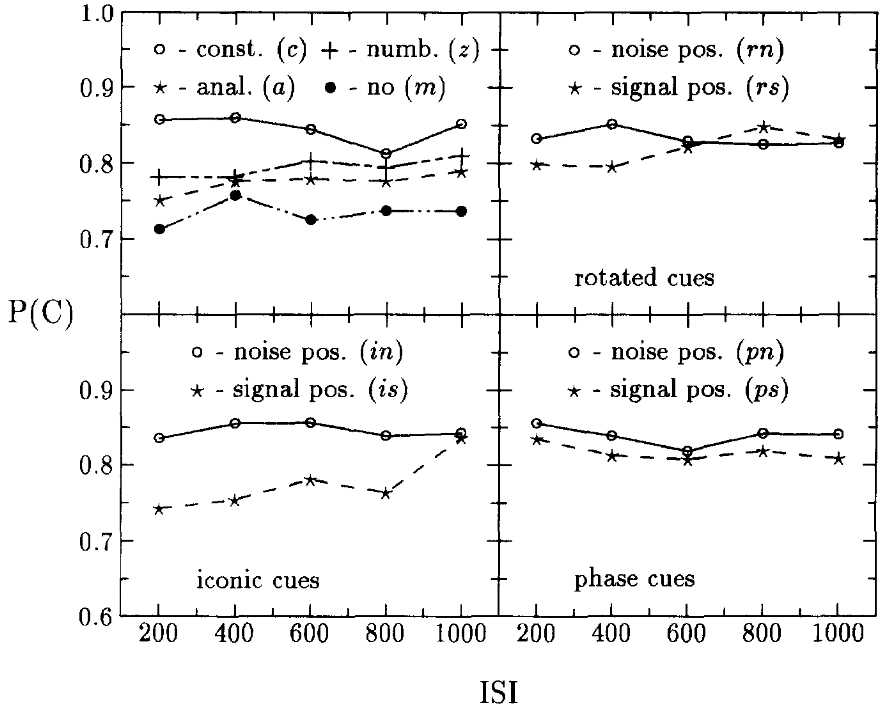

FIGURE 1. This figure depicts the percentage of correct detection of sinusoidal gratings for different interstimulus intervals (ISIs) and experimental conditions. In the upper-left panel the data for the two control conditions without cues, one with spatial-frequency uncertainty (m) and the other without (c), are given, as well as those for the condition with the number (z) and analog (a) cues. In the lower-left panel the data for the iconic-cue conditions (i) are given. The two curves correspond to the conditions where the cues were either presented at the subsequent noise (in) or signal-plus-noise (is) position. The upper- and lower-right panels show the data for the rotated- (r) and phase-cue (p) condition, respectively. The results are averaged across spatial frequencies and subjects.

is-condition data. However, linear regression reveals it to be significant [$F(1,18) = 5.42$, $P < 0.05$].

The efficiency of the rotated and counter-phase cues was not significantly affected by their position. Although the mean data seem to indicate a systematic difference at least for the counter-phase cues, a t-test provided no confirmation [$t(19) = 1.86$, $P > 0.07$].

Moreover, both cue types were not significantly different from the iconic cues presented at the noise position (in) and from the blocked condition (c). On the contrary, number and analog cues were significantly less effective than the iconic cues [z-conditions vs in-condition: $t(19) = 5.68$, $P < 0.001$; a-condition vs in-condition: $t(19) = 7.32$, $P < 0.001$]. They were also less effective than the phase cues [z-conditions vs pn-condition: $t(19) = 4.39$, $P < 0.001$; a-conditions vs pn-condition: $t(19) = 6.76$, $P < 0.001$].

In comparison with the rotated cues, the analog cues were less effective [a-conditions vs rn-condition: $t(19) = 4.81$, $P < 0.001$], whereas the difference to the number cues failed to reach our strong significance criterion [z-condition vs rn-condition: $t(19) = 2.66$, $P < 0.02$].

If the data for the counter-phase and rotated cues are averaged across positions and then all data are also averaged across the ISIs one gets the result shown in Fig. 2, which allows easy comparison of the different conditions. As can be seen, the rotated cues were only slightly less effective than the phase cues. That their difference to the number cues nevertheless did not reach our significance criterion, contrary to the phase cues, is mainly due to the larger variance of the rotated-cue data compared with that of the phase-cue data.

An interesting question is whether the different spatial frequencies were equally affected within each condition. The results for individual spatial frequencies,

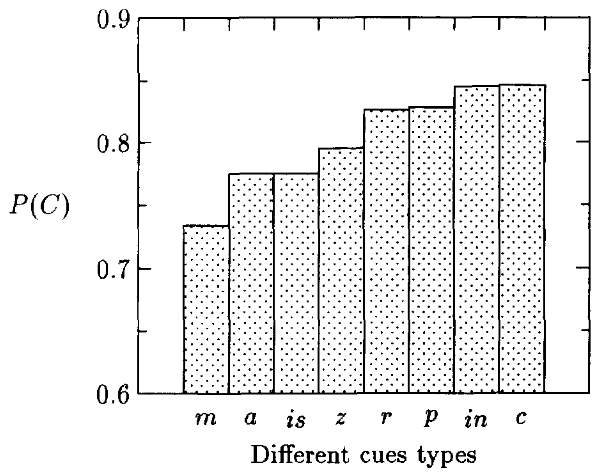

FIGURE 2. Percentage of correct detection for the condition of no cue (m), analog cue (a), number cue (z), phase cue (p), rotated cue (r), iconic cue at the noise position (in), iconic cue at the signal-plus-noise position (is), and of the blocked condition (c). The data are averaged across spatial frequencies, subjects and ISIs. The data for the rotated (r) and for the phase (p) cues were also averaged across positions.

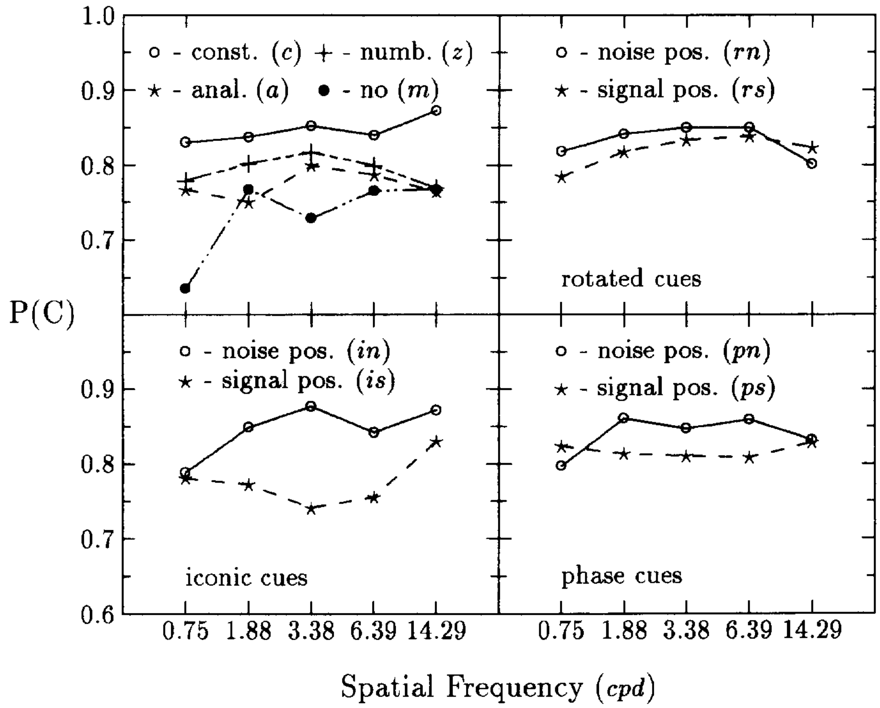

FIGURE 3. This figure depicts the percentage of correct detection of sinusoidal gratings for the different experimental conditions and as a function of their spatial frequency. In the upper-left panel the data for the two control conditions without cues, one with spatial-frequency uncertainty (m) and the other without (c), are given, as well as those for the condition with the number (z) and analog (a) cues. In the lower-left panel the data for the iconic-cue conditions (i) are given. The two curves correspond to the conditions where the cues were either presented at the subsequent noise (in) or signal-plus-noise (is) position. The upper- and lower-right panels show the data for the rotated- (r) and phase-cue (p) condition, respectively. The data are averaged across ISIs and subjects.

but averaged across ISIs and subjects, are depicted in Fig. 3.

Besides the dramatic drop in performance at 0.75 c/deg in the m-condition, the i-conditions again show an interesting pattern. A 2 × 5 (positions × spatial frequencies) ANOVA revealed that additionally to the significant position effect [$F(1,3) = 15.64$, $P < 0.05$] there is also a significant interaction [$F(4,12) = 3.88$, $P < 0.05$].

EXPERIMENT 2

It might be asked whether the obtained cuing effects are specific to spatial frequency. One could argue that presenting, for instance, a grating with an orthogonal orientation shortly before the stimuli might improve detection performance independently of its spatial frequency. Although it is highly unlikely that this explanation is true, the data obtained from Experiment 1 cannot rule it out, since in all trials valid cues were presented.

Therefore, a second experiment was performed in which also invalid cues were presented in some trials. If the cuing effect is indeed unspecific, then one would expect the same performance for the valid and invalid cues. However, if the cues are specific, then one would expect in addition to a benefit for the valid-cue trials a cost for the invalid-cue trials (cf. Bashinski & Bacharach, 1980).

Since the rotated cues were highly efficient independently of their position they were used in Experiment 2.

Method

The method was similar to that employed in the first experiment. However, the blocks consisted of 80 trials in 20 of which invalid cues were presented. For each of the five different signals there were four invalid cues, each with one of the remaining spatial frequencies which are not identical to that of the signal. After a training block, there were five test blocks comprising 400 valid-cue and 100 invalid-cue trials. The ISI was fixed to 400 msec. No feedback was given so as to not confuse the subjects at invalid-cue trials by providing inconsistent information. However, all subjects were told that there would be a certain number of invalid cues.

Three males (aged between 21 and 38 yr) served as subjects, two of whom had also participated in the first experiment. For these two subjects the thresholds of Experiment 1 were used. For the new subject thresholds were measured using the same procedure as in the first experiment.

Results

The results are depicted in Fig. 4. An appreciable difference between the valid- and invalid-cue condition can be seen. For comparison, no-cue data are also considered. For the two subjects who had also participated in Experiment 1, the 400 msec ISI data of the

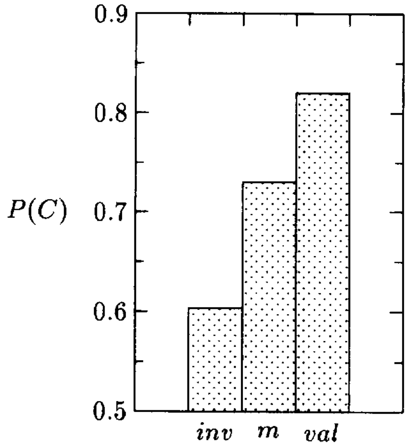

FIGURE 4. Percentage of correct detection of sinusoidal gratings with valid (*val*) and invalid (*inv*) rotated cues and with no cues (*m*). The results are averaged across spatial frequencies and subjects.

m-condition were used. Corresponding data for the new subject were collected separately. The result is represented by the central bar in Fig. 4. The difference between the invalid-cue and the no-cue condition is significant [$t(2) = 3.61$, $P < 0.05$], as is the difference between the no-cue and the valid-cue condition [$t(2) = 3.90$, $P < 0.05$].

DISCUSSION

The results clearly show that different cue types are differentially efficient in improving detection performance under spatial-frequency uncertainty. In this respect they are in line with those obtained for spatial uncertainty (Müller & Humphreys, 1991), as well as for frequency uncertainty in psychoacoustics (Hübner & Hafter, 1995). However, in contrast to effects known from psychoacoustics, iconic cues may also produce masking over a relatively long time when presented at the signal position, which severely restricts their positive effects. That masking effects continue over such extended time intervals is surprising. Usually, there are no forward-masking effects for ISIs longer than 200 msec (see Breitmeyer, 1984).

As one reviewer pointed out, an objection to the masking interpretation could be that asymmetrical cuing may have caused a response bias against that field where the cue was presented. Although such a bias cannot definitely be ruled out by the data, it is highly unlikely that it alone is responsible for the observed negative effects. For instance, why should a bias only occur for the iconic cues and not for the other asymmetrical cues?

Additionally, it is unreasonable to assume that a response bias produced the interaction between spatial-frequency and position for the iconic cues. Interestingly, the position effect is maximal for spatial frequencies for which the visual system shows its highest contrast sensitivity (as measured with sinusoidal gratings without added external noise; e.g. DeValois & DeValois, 1988).

Since no significant position effects showed up with counter-phase and rotated cues, the masking observed here for the iconic cues was probably caused by negative retinal afterimages which, under certain circumstances, can last for several seconds (cf. Brown, 1965).

While the masking thus occurred at an initial stage of visual processing, the facilitation produced by the iconic cues obviously took place at a later stage, where the representation of spatial frequency is abstracted at least from retinal coordinates. The efficiency of the phase and rotated cues suggests that they operate successfully at an even higher stage where the representation of spatial frequency is also abstracted from stimulus orientation and phase. Such an interpretation is in line with results showing that at higher stages in the visual pathway stimulus orientation and spatial frequency are coded independently (Burbeck & Regan, 1983; Bradley & Skottun, 1984; Heeley, Buchanan-Smith & Heywood, 1993; Magnussen, Greenlee, Aspund & Dyrnes, 1990) and that the resulting representations are independent of retinal coordinates (Burbeck, 1987).

How did the sensory cues operate on these stages? Did they improve signal coding by preactivating the corresponding spatial-frequency channel? In this case one would have expected the channel activation to increase gradually after the presentation of a sensory cue and then to decay to its former level. Consequently, the efficiency of the cues should have varied correspondingly. Indeed, such a variation has been observed, for instance, with sensory spatial cues (Müller & Humphreys, 1991). Here, however, neither an increase, except that caused by the decreasing masking effect, nor a decrease in efficiency was found with the sensory spatial-frequency cues. One could argue that a possible increase and decrease of channel activation might have occurred within the shortest ISI. However, under this assumption there should be no difference between sensory and symbolic cues, as is the case with spatial cuing. There, symbolic and sensory cue effects do not differ at long SOAs (Müller & Humphreys, 1991).

These differences to the results from spatial cuing make our data difficult to interpret. A *post hoc* explanation of the data would be to assume that preactivation built up faster than the shortest employed ISI and remained at that level for at least 1 sec. However, an alternative and more plausible account of the data is given by the concept of late selection, where selection denotes the process of stimulus sampling into visual short-term memory (VSTM). The selection is called late, when it operates on the output of a parallel stage of stimulus processing (for a general discussion of early versus late selection see Lavie & Tsal, 1994). That cues might affect late selection rather than very early processing has also been discussed by Müller and Humphreys (1991).

The fact that the sensory spatial-frequency cues were highly effective over a relatively long period of time can then be related to the nearly perfect retention of VSTM for spatial-frequency information of sinusoidal gratings over time periods up to several seconds (Magnussen *et al.*, 1990; Magnussen, Greenlee, Aspund & Dyrnes, 1991). The stored precise spatial-frequency information might have served for optimally selecting the appropriate channel outputs.

The relatively poor efficiency of the symbolic (number and analog) cues is in line with other results previously mentioned but contrasts with those of Davis *et al.* (1983), who presented clicks as cues, the number of which indicated the spatial frequency of the signals. With these symbolic cues, detection performance for sinusoidal gratings was similar to that without spatial-frequency uncertainty. It is unclear why their cues were so successful. The main difference between their experiment and the experiments reported here, is that they partly used less spatial frequencies and did not add noise to the signals.

That the efficiency of the symbolic cues did not improve over the employed ISIs is at variance with results obtained for spatial cuing (Müller & Findley, 1988; Müller & Rabbit, 1989) or motion detection (Ball & Sekuler, 1981). Their steady effect is difficult to explain by the channel-preactivation assumption. One would have to assert that their maximum effect occurred within the shortest ISI, which, however, is rather unreasonable in this case. A simpler account of the data is to suppose that the symbolic spatial-frequency cues merely affected the decision criteria.

However, also for the symbolic cues it could be speculated that they affected stimulus sampling. Their reduced efficiency compared with the sensory cues could be due to the fact that in this case the subjects had to rely on spatial-frequency information retrieved from visual long-term memory, which is less perfect. Consequently, they sampled less optimal channel outputs or too many outputs, which increased the internal noise. In both cases, a poor performance would be expected (cf. Graham, 1989; Hübner, 1993a, b).

Given such an account it no longer makes sense to postulate a strong dichotomy between the effects of sensory and symbolic cues. Rather, as our data suggest, there seems to be a continuum of cue efficiency. Efficiency is determined by the information provided by the cues for sampling the channel outputs more or less optimally. However, even if one agrees with the hypothesis that cues affect stimulus sampling, it is possible that they additionally affect the decision criteria, particularly if more than one channel output has been sampled.

REFERENCES

Ball, H. S. & Sekuler, R. (1981). Cues reduce direction uncertainty and enhance motion detection. *Perception & Psychophysics, 30*, 119–128.

Banks, M. S., Geisler, W. S. & Bennett, P. J. (1987). The physical limits of grating visibility. *Vision Research, 27*, 1915–1924.

Bashinski, H. S. & Bacharach, V. R. (1980). Enhancement of perceptual sensitivity as the result of selectively attending to spatial location. *Perception & Psychophysics, 28*, 241–248.

Bradley, R. & Skottun, B. C. (1984). The effect of large orientation and spatial frequency differences on spatial discriminations. *Vision Research, 24*, 1889–1896.

Breitmeyer, B. G. (1984). *Visual masking*. New York: Oxford University Press.

Brown, J. L. (1965). Afterimages. In Graham, C. H. (Ed.), *Vision and visual perception* (pp. 497–503). New York: Wiley.

Burbeck, C. A. (1987). Locus of spatial-frequency discrimination. *Journal of the Optical Society of America, A 4*, 1807–1813.

Burbeck, C. A. & Regan, D. (1983). Independence of orientation and size in spatial discrimination. *Journal of the Optical Society of America, 73*, 1691–1694.

Burgess, A. & Ghandeharian, H. (1984a). Visual signal detection I. Ability to use phase information. *Journal of the Optical Society of America, A 1*, 900–905.

Burgess, A. & Ghandeharian, H. (1984b). Visual signal detection. II. Signal-location identification. *Journal of the Optical Society of America, A 1*, 906–910.

Cave, K. R. & Kosslyn, S. M. (1989). Varieties of size-specific visual selection. *Journal of Experimental Psychology: General, 118*, 148–164.

Davis, E. T., Kramer, P. & Graham, N. (1983). Uncertainty about spatial frequency, spatial position, or contrast of visual patterns. *Perception & Psychophysics, 33*, 20–28.

DeValois, R. L. & DeValois, K. K. (1988). *Spatial vision*. Oxford: Oxford University Press.

Downing, C. G. (1988). Expectancy and visual spatial attention: Effects of perceptual quality. *Journal of Experimental Psychology: Human Perception and Performance, 14*, 188–202.

Fletcher, H. & Munson, W. A. (1933). Loudness, its definition, measurement, and calculation. *Journal of the Acoustical Society of America, 5*, 82–108.

Graham, N. (1989). *Visual pattern analyzers*. New York: Oxford University Press.

Graham, N., Robson, J. G. & Nachmias, J. (1978). Grating summation in fovea and periphery. *Vision Research, 18*, 815–825.

Green, D. M., Mckey, M. J. & Licklider, J. C. R. (1959). Detection of a pulsed sinusoid in noise as a function of frequency. *Journal of the Acoustical Society of America, 31*, 1446–1452.

Hawkins, H. L., Hillyard, S. A., Luck, S. J., Mouloua, M., Downing, C. G. & Woodward, D. P. (1990). Visual attention modulates signal detection. *Journal of Experimental Psychology: Human Perception and Performance, 16*, 802–811.

Heeley, D. W., Buchanan-Smith, H. M. & Heywood, S. (1993). Orientation acuity for sine-wave gratings with random variation of spatial frequency. *Vision Research, 33*, 2509–2513.

Hübner, R. (1993a). On possible models of attention in signal detection. *Journal of Mathematical Psychology, 37*, 266–281.

Hübner, R. (1993b). Different ways of modeling spatial-frequency uncertainty in visual signal detection. *Biological Cybernetics, 69*, 457–462.

Hübner, R. & Hafter, E. R. (1995). Mechanisms of cuing in auditory signal detection. *Perception & Psychophysics, 57*, 197–202.

Johnston, W. A. & Dark, V. J. (1986). Selective attention. *Annual Review of Psychology, 37*, 43–75.

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye. In Long, J. & Baddeley, A. (Eds), *Attention and performance IX*. Hillsdale, N.J.: Erlbaum.

Kinchla, R. A. (1992). Attention. *Annual Review of Psychology, 43*, 711–742.

Larsen, A. & Bundesen C. (1978). Size scaling in visual pattern recognition. *Journal of Experimental Psychology: Human Perception and Performance, 4*, 1–20.

Lavie, N. & Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Perception & Psychophysics, 56*, 183–197.

Levitt, H. (1970). Transformed up-down methods in psychoacoustics. *Journal of the Acoustical Society of America, 49*, 467–476.

Magnussen, S., Greenlee, M. W., Asplund, R. & Dyrnes, S. (1991). Stimulus-specific mechanisms of visual short-term memory. *Vision Research, 31*, 1213–1219.

Magnussen, S., Greenlee, M. W., Asplund, R. & Dyrnes, S. (1990).

Perfect visual short-term memory for periodic patterns. *European Journal of Cognitive Psychology*, *2*, 345–362.

Müller, H. J. & Findlay, J. M. (1987). Sensitivity and criterion effects in the spatial cuing of visual attention. *Perception & Psychophysics*, *42*, 383–399.

Müller, H. J. & Findlay, J. M. (1988). The effect of visual attention on peripheral discrimination thresholds in single and multiple element displays. *Acta Psychologica*, *69*, 129–155.

Müller, H. J. & Humphreys, G. W. (1991). Luminance-increment detection: Capacity limited or no? *Journal of Experimental Psychology: Human Perception and Performance*, *17*, 107–124.

Müller, H. J. & Rabbit, P. M. A. (1989). Reflexive and voluntary orientation of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology: Human Perception and Performance*, *15*, 315–330.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*, 3–25.

Posner, M. I., Snyder, C. R. R. & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General*, *109*, 160–174.

Schlauch, R. S. & Hafter, E. R. (1991). Listening bandwidths and frequency uncertainty in pure-tone signal detection. *Journal of the Acoustical Society of America*, *90*, 1332–1339.

Shaw, M. L. (1984). Division of attention among spatial location: A fundamental difference between detection of letters and detection of luminance increments. In Bouma, H. & Bouwhuis, D. G. (Eds), *Attention and performance X*. Hillsdale, N.J.: Erlbaum.

Sperling, G. & Dosher, B. A. (1986). Strategy and optimization in human information processing. In Boff, K., Kaufman, L. & Thomas J. (Eds), *Handbook of perception and performance*. Hillsdale, N.J.: Erlbaum.

Swensson, R. G. & Judy, P. F. (1981). Detection of noisy visual targets: Models for the effect of spatial uncertainty and signal-to-noise ratio. *Perception & Psychophysics*, *29*, 521–534.

Watt, R. J. (1990). *Visual processing: Computational, psychophysical and cognitive research*. Hillsdale, N.J.: Erlbaum.

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