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# Magnocellular involvement in flanked-letter identification relates to the allocation of attention

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## Abstract

To verify the hypothesis that the magnocellular system is important to flanked-letter identification [Neuropsychologia 40 (2002) 1881] because it subserves attention allocation, we conducted three letter-naming experiments in which we manipulated magnocellular involvement (colour vs. luminance contrast) and prior information regarding target-letter location. Location information was provided through constant presentation at the same location (Experiment 1) or through auditory precueing (Experiments 2 and 3). In control conditions, either no (Experiments 1 and 3) or invalid (Experiment 2) location information was given. In line with the hypothesis, magnocellular input helped flanked-letter identification only when no prior location information was given.

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## 1. Introduction

Visual attention facilitates perception, for instance by enhancing the target signal (e.g., Carrasco, Penpeci-Talgar, & Eckstein, 2000), inhibiting distracter signals (e.g., Theeuwes, Kramer, & Atchley, 2001), or accelerating the rate of information processing (e.g., Carrasco & McElree, 2001). In order to attend to a particular stimulus, there must be some mechanism that is concerned with the allocation of attention. An important brain area identified in such a mechanism is the parietal cortex (Maunsell, 1992; Milner & Goodale, 1995; Mishkin, Ungerleider, & Macko, 1983; Ungerleider & Haxby, 1994), a brain region within the dorsal stream. Because the majority of the visual input into the dorsal stream and, hence, into the parietal cortex derives from the magnocellular system (Milner & Goodale, 1995), one of the two main retino-striate pathways, it seems likely that the allocation of attention is mediated by magnocellular input preferably.

Psychophysical evidence for the dominant role of the magnocellular system in the allocation of attention, in the specific situation of an automatic (transient) attention shift due to rapid stimulus onset, was provided by Steinman, Steinman, and Lehmkuhle (1997). These authors made use of the so-called line-motion illusion. In this illusion, a visual cue is presented followed shortly by a line with one of its end points near the cue. The line then appears to build up or “move away” from the cue, even though it is presented all at once. The explanation of the illusion is based on the already mentioned phenomenon that attention accelerates information processing. The cue captures attention and the processing of the line will be facilitated especially in the region closest to the cue (Hikosaka, Miyauchi, & Shimojo, 1993). Steinman and colleagues used two cues instead of one (one near either end point of the line), while one of the cues stimulated the magnocellular and the other the parvocellular system specifically. The authors observed that the magnocellular cue overrode the parvocellular cue, producing illusory line movement from the magnocellular cue in the direction of the parvocellular cue, even if the latter was presented earlier than the former by as much as 50 ms. Thus, at least for sudden stimulus onsets, in line with anatomical predictions, attention

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seems to be attracted predominantly on the basis of magnocellular input.

A well-known theory of developmental dyslexia holds that the reading problems in the disorder are partly due to some abnormality in the magnocellular pathway (e.g., Breitmeyer, 1993; Demb, Boynton, Best, & Heeger, 1998; Eden et al., 1996; Hari, Renvall, & Tanskanen, 2001; Iles, Walsh, & Richardson, 2000; Livingstone, Rosen, Drislane, & Galaburda, 1991; Ridder, Borsting, & Banton, 2001; Slaghuis & Lovegrove, 1985; Sperling, Lu, Manis, & Seidenberg, 2003; Stein & Walsh, 1997; Steinman, Steinman, & Garzia, 1998; Vidyasagar & Pammer, 1999; but see, e.g., Amitay, Ben-Yehudah, Banai, & Ahissar, 2002; Farrag, Khedr, & Abel-Naser, 2002; Ramus et al., 2003; Skottun, 2000; Williams, Stuart, Castles, & McAnally, 2003). In line with the foregoing, it has been suggested that the magnocellular deficit in developmental dyslexia results in problems with the allocation of attention, which in turn would lead to the reading problems (e.g., Hari et al., 2001; Stein & Walsh, 1997; Steinman et al., 1998; Vidyasagar & Pammer, 1999). However, despite the attractiveness of these suggestions, direct evidence for the role of the magnocellular system in the allocation of attention during reading, or at least in a setting directly relevant to the reading process, is scarce.

Such evidence, however, may have been provided by a previous study of ours (Omtzigt, Hendriks, & Kolk, 2002). In this study, letters were presented briefly in one of three possible locations ( $-1^\circ$ ,  $0^\circ$ , or  $+1^\circ$  from fixation), either singly or flanked by one  $x$  to the left and right (e.g.,  $xax$ ). The task was to name the target letter. Magnocellular function was investigated by the use of different contrasts between characters and background: (isoluminant) colour contrast and weak (isochromatic) luminance contrast. Colour contrast is known to trigger parvocellular activity better than magnocellular activity, whereas for low levels of luminance contrast, the reverse is true (Livingstone & Hubel, 1988). Therefore, colour vs. luminance contrast can be used as a manipulation of magnocellular activity. (For more details of the contrast manipulation, the reader is referred to Omtzigt et al., 2002.) A significant interaction of contrast with stimulus was found on the reaction-time and/or the error-score data, where the single letters were identified just as adequately under colour as under luminance contrast whereas for the flanked letters colour contrast yielded a disadvantage relative to luminance contrast. The colour-contrast disadvantage for flanked-letter identification was ascribed to the relative paucity of magnocellular activity generated by the colour contrast. In other words: the magnocellular system appears to provide visual information that is important to the identification of flanked letters. We interpreted this finding as indicating that magnocellular activity subserves the process of attention allocation to the flanked target letter.

In the present study, we intended to find direct evidence for the idea that the magnocellular system is important for identifying flanked letters specifically because it enables attentional selection of these letters. If indeed the magnocellular system provides the primary visual input for this attentional selection, one would predict that if subjects are informed of the location of the target letter prior to stimulus presentation, magnocellular input would lose its special importance to flanked-letter identification since attention could already have been allocated before stimulus presentation. Thus, under those circumstances, the interaction of contrast with stimulus should disappear. This prediction was tested in all three experiments of the present paper. In the first experiment, prior information regarding target-letter location was given by presenting blocks of stimuli with the target letter always appearing in the same (central) position. In the other two experiments, the location of the target letter was indicated by an auditory cue (white noise) presented 300 ms prior to letter-stimulus presentation. In all three experiments, control conditions were included in which the location information was either absent (Experiments 1 and 3) or incorrect (Experiment 2).

## 2. Experiment 1

### 2.1. Method

#### 2.1.1. Participants

Twenty-four normally reading students nearly all from the University of Nijmegen took part in this experiment. There were 3 males and 21 females, whose ages ranged from 19 to 25, with a median of 23. They were paid or given course credit for their participation. All reported that they had normal or corrected-to-normal vision, including normal colour vision.

#### 2.1.2. Materials

Stimuli were generated by an Apple Power Macintosh 7200/90 and presented on an Apple Multiple Scan 15 in. display (M2978) with aluminised P22 medium-short persistence phosphor. The CIE co-ordinates of the phosphors were as follows: for red,  $x = 0.610$ ,  $y = 0.342$ ; for green,  $x = 0.298$ ,  $y = 0.588$ ; for blue,  $x = 0.151$ ,  $y = 0.064$ . The refresh rate of the screen was 66.7 Hz. Screen resolution was  $640 \times 480$  pixels, and the computer was running in 256-colour mode. Luminance and contrast of the monitor were set to their maximum values.

In each condition and for each participant, the same subset of 20 letters of the Dutch alphabet (which is identical to the English alphabet) was presented. In half of the conditions (see Section 2.1.3) each letter was presented once and in the other half of the conditions

three times in total. Participants were not informed about which letters had been selected.

All letters were presented in a bold disproportional serif font of 31 points. Given the distance of the participants to the monitor (80 cm), this amounted to approximately  $0.4^\circ$  of visual angle per letter. In the flanked-letter conditions, a five-letter string appeared centred at the point of fixation, with the target letter appearing in second, third (middle), or fourth position. The other locations were occupied by x's, each centred about  $0.5^\circ$  from the neighbouring letters. In the single-letter conditions, one single letter was presented in one of the same three locations where the flanked target letters could appear.

The background (RGB values: 0.199, 0.199, and 0, respectively) was yellow and had a luminance of  $13.0 \text{ cd/m}^2$ , as measured with a Spectra Pritchard 1980A-CD photometer using a photopic filter. In the luminance-contrast conditions, targets and distracters (RGB values: 0.211, 0.211, and 0, respectively) differed from the background only with respect to their luminance, which was  $13.7 \text{ cd/m}^2$ . This resulted in a Michelson contrast of 2.6%. In the colour-contrast conditions, targets and distracters had a green appearance (the RGB values were usually within the range of (0.074, 0.227, 0) to (0.078, 0.242, 0)) and their luminance was set by means of heterochromatic flicker photometry (minimal flicker) such that virtually no luminance contrast remained between characters and background.

The flicker-photometry procedure was carried out with a centrally presented disk occupying approximately  $2.5^\circ$  of visual angle against a dark background. The disk flickered continuously alternating the colour contrast's fore- and background colour at a rate of 11.1 Hz. The luminance level of the foreground was adjusted manually by the experimenter until a level was found for which the participant judged the flicker to be minimal, after which it was recorded for use in the letter-naming experiment.

### 2.1.3. Design

There were four within-subject manipulations: presentation (random vs. blocked), contrast between letters and background (colour vs. luminance), stimulus (flanked letters vs. single letters), and location of the target letter (second, third, and fourth position, that is,  $-0.5^\circ$ ,  $0^\circ$ , and  $+0.5^\circ$ , respectively, from fixation). For blocked presentation, all target letters within a block appeared in the same central (third) position. For random presentation, the location of the target letters varied randomly from trial to trial, with the restrictions that all three locations were used equally often in each block and the same location was not used for more than three trials in a row. The presentation variable was manipulated in two separate tasks (of 8 blocks each), of which the order was counterbalanced across participants.

Contrast and stimulus remained constant during blocks and were counterbalanced both across and within participants. For random presentation, all 20 different letters were presented once in each of the 12 ( $2 \times 2 \times 3$ ) conditions; for blocked presentation, all 20 different letters were presented three times in each of the 4 ( $2 \times 2 \times 1$ ) conditions. There were 30 letter presentations in each block, and consecutive letters were always different. Each subject received a different letter-identity order as well as a different order of stimulus location (for random presentation).

### 2.1.4. Procedure

The participants sat about 80 cm from the computer screen in a dark room. After five minutes of dark adaptation, the luminance level of the foreground (letter) colour was determined that matched the luminance of the background (individual heterochromatic flicker photometry). Prior to the actual experiment, one block of practice trials was given to the participants.

Before stimulus presentation, a central fixation mark appeared for 210 ms, which consisted of two vertical dashes one above the other just outside the area where a central letter stimulus would be presented. It was the same yellow colour as the background but had a somewhat higher level of luminance. The fixation stimulus disappeared 300 ms before the presentation of the letter stimulus. Letter-stimulus duration was 105 ms. Participants were instructed to name the target letter as quickly as possible and to make a guess in case they could not determine which letter had been presented. The inter-trial interval started automatically after a response had been made (or 7500 ms after letter-presentation initiation if no response had been detected) and lasted 1500 ms. During this interval, the screen remained yellow. Timing of stimuli and responses was carried out with the aid of a button box that monitored on a millisecond basis both the participant's voice and the monitor's V-SYNC, allowing response-latency measurement to be accurate to the millisecond and stimulus appearance and removal to coincide with screen refreshes, resulting in timely stimulus presentations.

The whole session took about 45 min. This is inclusive of short breaks, which were present between all stimulus blocks.

### 2.1.5. Data-analysis

Responses with improper voice-key activation or a reaction time (RT) of less than 300 ms were removed. Then, for each of the conditions of every participant, the mean RT was determined. All responses that were more than 2 standard deviations slower or faster than their corresponding mean RT value were considered to be outliers and therefore discarded. (In total, 9.9% of the data were discarded.) For the thus trimmed data-set, the mean RT values were calculated anew and percentages

of errors were determined. The new mean RT values and the percentages of errors were used in the statistical analyses to be reported in the following section.

## 2.2. Results and discussion

The section is split up into two parts. First, it will be investigated whether (in the random-presentation mode) the identification of the flanked letters in the current flanked-letter stimuli consisting of five characters would evidence a special reliance on magnocellular activity relative to single letters, just as had the flanked target letters consisting of three characters in our previous study (Omtzigt et al., 2002). Second and contingent on the outcome of the first analysis, it will be investigated whether the role of the magnocellular system in flanked-letter identification, if indeed present for the current flanked-letter stimuli, was related to the allocation of attention.

A  $2 \times 2 \times 3$  (Contrast  $\times$  Stimulus  $\times$  Location) repeated-measures multivariate analysis of variance was conducted on the random-presentation data. This was done both for RTs and for error percentages. In either analysis, the main effects of Stimulus and Location were highly significant [for Stimulus:  $F(1, 23) = 88.79$ ,  $p < 0.001$ , one-tailed, for RTs, and  $F(1, 23) = 49.67$ ,  $p < 0.001$ , one-tailed, for error scores; for Location:  $F(2, 22) = 21.89$ ,  $p < 0.001$ , for RTs, and  $F(2, 22) = 6.45$ ,  $p < 0.01$ , for error scores], with flanked target letters being more difficult to identify than single target letters and non-central target letters being more difficult to identify than central target letters [ $F(1, 23) = 40.92$ ,  $p < 0.001$ , one-tailed, for RTs, and  $F(1, 23) = 12.72$ ,  $p < 0.001$ , one-tailed, for error scores]. The interaction of these two factors was significant as well [ $F(2, 22) = 20.25$ ,  $p < 0.001$ , for RTs, and  $F(2, 22) = 4.03$ ,  $p < 0.05$ , for error scores], with flanked target letters being more difficult to identify than single target letters for the non-central locations in particular [ $F(1, 23) = 41.93$ ,  $p < 0.001$ , one-tailed, for RTs, and  $F(1, 23) = 7.96$ ,  $p < 0.01$ , one-tailed, for error scores]. The interaction of Contrast  $\times$  Stimulus, which had the largest relevance to present purposes, just failed to reach significance in the RT analysis [ $F(1, 23) = 2.54$ ,  $p = 0.06$ , one-tailed] and was significant in the error analysis [ $F(1, 23) = 10.35$ ,  $p < 0.01$ , one-tailed]. This interaction is shown in Fig. 1, where it can be observed that colour contrast was slightly better than luminance contrast for the identification of the single letters but that the order was reversed when the letters were flanked. Since colour contrast generates relatively little magno activity, this

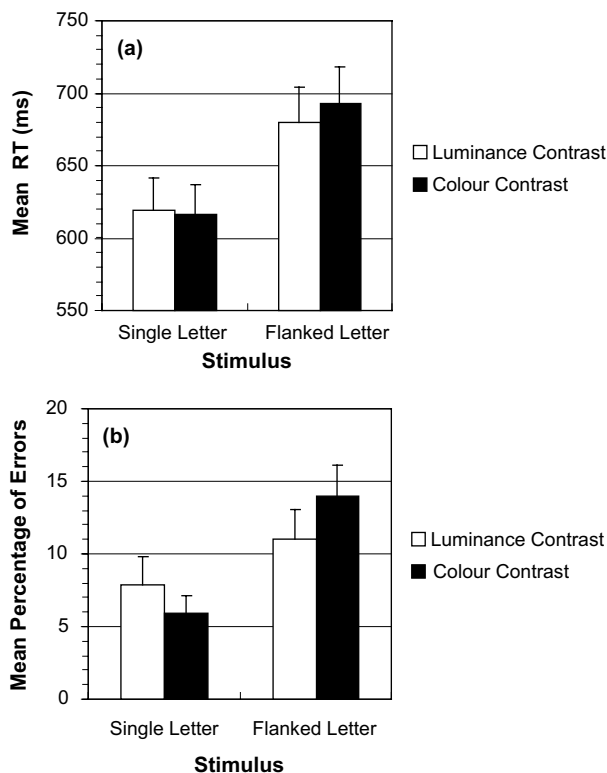


Fig. 1. Mean naming performance with standard error as a function of contrast and stimulus for random presentation (averaged across location) in Experiment 1 for: (a) reaction time (RT) and (b) percentage of errors.

suggests that the magnocellular system was important for the naming of the flanked letters.

Because the current flanked target letters evidenced magnocellular involvement in their identification, the second question regarding the relation with the allocation of attention becomes relevant. As already mentioned in the Introduction, if the interaction of Contrast  $\times$  Stimulus represents magnocellular involvement in the allocation of attention, the interaction should disappear when participants know the location of the target letter in advance, because attention could already have been allocated prior to stimulus presentation. A  $2 \times 2 \times 2$  (Presentation  $\times$  Contrast  $\times$  Stimulus) repeated-measures multivariate analysis of variance was conducted on the central-location data, both for RTs and for error percentages. In the RT analysis, significant were the main effects of Presentation [ $F(1, 23) = 16.38$ ,  $p < 0.001$ , one-tailed; blocked presentation led to faster naming latencies] and Stimulus [ $F(1, 23) = 34.01$ ,  $p < 0.001$ , one-tailed; flanked letters were responded to more slowly than single letters], as well as their interaction [ $F(1, 23) = 7.87$ ,  $p < 0.01$ , one-tailed]. The identification of flanked letters profited more from location knowledge than did the identification of single letters. These findings are in agreement with the purpose of the presentation manipulation as a manipulation of attention, since prior

<sup>1</sup> Throughout the paper, for the effects that involve only two-level factors, the two-tailed  $p$  values are given, unless indicated otherwise (that is, when a specific direction had been hypothesised).

knowledge could be expected to lead to the employment of attention more quickly, which could be particularly useful to the identification of the flanked target letters. In the error analysis, there was also a significant main effect of Stimulus [ $F(1, 23) = 4.39, p < 0.05$ , one-tailed; flanked letters were more difficult to identify than single letters], and, more interestingly, although not significant at the 0.05 level, the second-order interaction of Presentation  $\times$  Contrast  $\times$  Stimulus did reach significance at the 0.10 level [ $F(1, 23) = 1.79, p < 0.10$ , one-tailed]: separate  $2 \times 2$  (Contrast  $\times$  Stimulus) repeated-measures multivariate analyses of variance conducted on the error scores for random and blocked presentation revealed that the interaction of Contrast  $\times$  Stimulus was clearly not significant for blocked presentation [ $F(1, 23) = 0.18$ , ns], but—in line with the error-score analysis mentioned earlier that included all of the three stimulus locations—approached significance for random presentation [ $F(1, 23) = 2.62, p = 0.06$ , one-tailed]. As can be observed in Fig. 2, colour contrast was relatively inefficient for the naming of the flanked letters only when target location was unknown, which is in agreement with the notion that the magnocellular system plays a role in the allocation of attention to flanked letters.

To obtain stronger evidence for the role of the magnocellular system in the allocation of attention to flanked letters, we changed the attention manipulation in a number of ways. Given that the central fixation

stimulus might have functioned as a cue, attracting attention to the central position in all experimental conditions including the random-location conditions, which may have reduced the strength of the attention manipulation, we had the target letters appear in non-central locations also in the prior-knowledge conditions. Further, blocked presentation is less an effective method of having subjects allocate their attention prior to stimulus presentation than is random presentation with a precue on each trial (Posner, Snyder, & Davidson, 1980). Therefore, for Experiment 2 we followed a (standard) paradigm with stimuli presented randomly to the left and right of the fixation point, preceded by a cue that did or did not direct attention to the same location as where the target stimulus would appear. In 80% of the trials, the cue was valid (i.e., the target letter appeared in the cued location) whereas in the remaining 20%, the cue was invalid (i.e., the target letter appeared in the uncued location). We reasoned that in the valid-cue conditions the participants did not need to rely on magnocellular activity to direct their attention, so that a zero interaction of contrast with stimulus could be expected. In the invalid-cue conditions, however, the participants would have to relocate their attention after stimulus appearance, which we hypothesised would rely on magnocellular activity just as for the situation when no cue would have been available, so that again an interaction of contrast with stimulus could be expected.

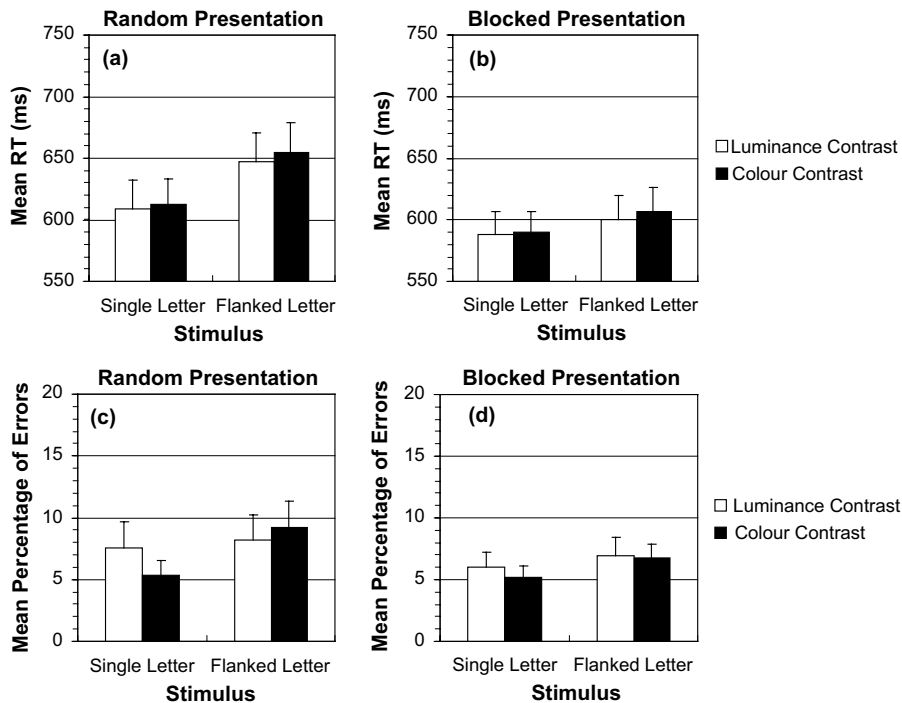


Fig. 2. Mean naming performance with standard error as a function of contrast and stimulus for the central location in Experiment 1 for: (a) reaction time (RT) and random presentation; (b) reaction time (RT) and blocked presentation; (c) percentage of errors and random presentation and (d) percentage of errors and blocked presentation.

We used auditory rather than visual cues in order to avoid possible visual interference of the cue with the letter stimulus, which might be detrimental especially for the low levels of contrast that we used. Note that by the use of non-central locations and the use of precues, it now became essential to monitor eye movements. Since in the five-letter flanked stimuli the target letters were centred only  $0.5^\circ$  from the fixation point, which could make it difficult to determine whether participants had correctly maintained fixation, we returned to the original three-letter flanked stimuli of our previous paper (Omtzigt et al., 2002), where the target letters were presented  $1^\circ$  from fixation.

Because we did not know which cue lead time, or Stimulus Onset Asynchrony (SOA), would be needed to have attention deployed in time, we carried out a pilot experiment with five different SOAs of about 100, 200, 300, 400, and 500 ms. It appeared that the cue was able to speed up naming latencies for the valid- relative to the invalid-cue conditions already from the earliest SOA onwards. However, the desired cueing effect on the *interaction of Contrast*  $\times$  *Stimulus* did not seem to occur with an SOA of less than 300 ms. Because it was likely that with SOAs of more than 200 ms eye movements would occur, even if we instructed our subjects to refrain from making them, we chose the possibly smallest suitable SOA of 300 ms for use in Experiment 2. To take care that our data would not be contaminated by the occurrence of eye movements, eye position was monitored, so that trials in which an eye movement had occurred could be excluded from subsequent analyses.

### 3. Experiment 2

#### 3.1. Method

##### 3.1.1. Participants

Twenty-four normally reading subjects (23 students and one postdoc, all from the University of Nijmegen) took part in this experiment, one of whom had also participated in Experiment 1. There were 6 males and 18 females, whose ages ranged from 18 to 30, with a median of 22. They were paid or given course credit for their participation. All reported that they had normal or corrected-to-normal vision including normal colour vision, as well as normal hearing.

##### 3.1.2. Materials

Compared to Experiment 1, there were a number of differences. First, due to the fact that there were validly and invalidly cued trials, which were presented in unequal proportions (80% and 20%, respectively), the letter set was reduced to 12 letters, with each of the letters presented four times in each of the valid-cue conditions and only once in each of the invalid-cue conditions.

Second, the font was changed to a 31-point bold proportional Arial font, which was identical to the one used in our previous paper (Omtzigt et al., 2002). Third, also the stimuli from our previous paper were used: the flanked target letters were flanked by one x to the left and right, and they were presented  $1^\circ$  to the left or right of fixation. (Different from our previous paper, the fixation location itself was not used for letter presentations.) The single letters, of course, also appeared at  $-1^\circ$  or  $+1^\circ$  from fixation. Fourth, a different computer monitor was used, which, despite having identical specifications, gave a slightly different appearance of colours and luminances. The RGB values of the background were unaltered, but the luminance of the background now was  $12.3 \text{ cd/m}^2$ . In the luminance-contrast conditions, the RGB values of the characters were changed <sup>2</sup> slightly to 0.215, 0.215, and 0, respectively, giving a luminance of  $13.2 \text{ cd/m}^2$ , which resulted in a Michelson contrast of 3.5%. In the colour-contrast conditions, the RGB values of the characters were usually within the range of (0.094, 0.230, 0) to (0.102, 0.246, 0), depending on the individual's isoluminance point.

##### 3.1.3. Design

There were four within-subject manipulations: cue validity (valid vs. invalid), contrast between letters and background (colour vs. luminance), stimulus type (flanked vs. single letter), and location of target-letter presentation ( $-1^\circ$  vs.  $+1^\circ$  from fixation). Location varied randomly from trial to trial, with the restrictions that either location was used equally often in each block and the same location was not used for more than six trials in a row. Cue validity also varied randomly from trial to trial, with the restriction that each block contained the same 4:1 ratio between validly and invalidly cued trials. Contrast and stimulus remained constant during blocks and were counterbalanced both across and within participants. There were 16 blocks in total, and there were four different block orders across participants. Each block contained 30 trials. Consecutive letter identities were always different, and each subject received different orders of letter identity, stimulus location, and cue.

##### 3.1.4. Procedure

In general, see Experiment 1. However, due to the introduction of auditory cues, the sequence of events within each trial was more complex; see Fig. 3. Each trial started with a 210-ms presentation of a fixation-

<sup>2</sup> Adjustment of the character settings was necessary in order to obtain single-letter-identification performance at about the same level for both contrasts, just as was the case in Experiment 1 and in Omtzigt et al. (2002). The specific adjustment followed from pilot experiments in which several contrast settings had been used.

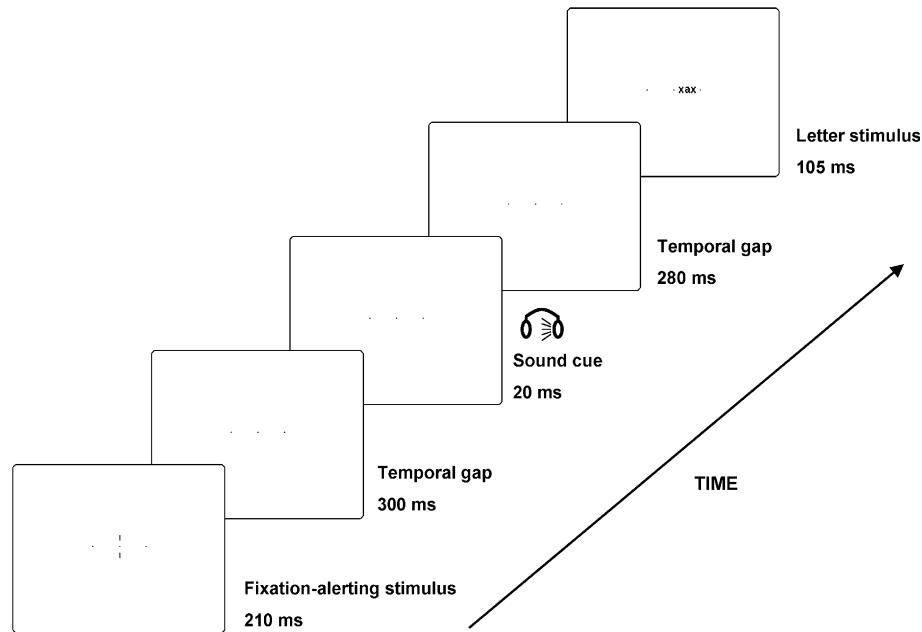


Fig. 3. Temporal sequence of events for the cueing procedure of Experiments 2 and 3. The diagram shows the situation of a valid cue and a flanked target letter  $1^\circ$  to the right of fixation.

alerting stimulus, identical to the fixation stimulus of Experiment 1, which urged the participants to focus their attention onto the centre of the screen. In the centre, there was a second fixation stimulus (a small black dot) that was visible throughout the experiment (see also Section 3.1.5). Then, a time period of 300 ms followed, during which the participants had to keep their eyes at the dot in the centre. After this, a 20-ms sound cue (white noise) was presented in either the left or the right speaker of the headphones. The participants were instructed to maintain central fixation and to shift their attention to the location where, according to the cue, the letter stimulus was most likely to appear. Then, 280 ms after the cue had disappeared, the letter stimulus was presented for 105 ms. The participants were instructed to name the target letter as fast as they could (or to make a guess in case they could not determine which letter had been presented), for which they had, measured from the moment of stimulus onset, 1500 ms. After the 1500-ms response interval, the inter-trial interval started, which lasted 495 ms.

The whole session took about 55 min.

### 3.1.5. Eye-movement analysis

The participants' eyes were monitored by means of a SKALAR Medical IRIS infra-red-light eye-movement-measurement system connected to the button-box that was used during the letter-naming experiment and to a Pentium PC. Eye position was sampled on a 200-Hz basis. Calibration of the measurements was performed directly before and after each stimulus block by having the participants fixate three small black dots plotted

onto the computer screen at  $0^\circ$ ,  $-2^\circ$ , and  $+2^\circ$  (which were present throughout the experiment). Eye position during letter-stimulus presentation was then related to the average of the two calibrations surrounding the experimental block and to central eye position during the trial itself, which was assumed to have been attained 100 ms after the offset of the fixation-alerting stimulus. Eye position during letter-stimulus presentation was averaged across the 105-ms time period of letter presentation. Right-eye measurements were used for all trials, unless these were consistently flawed, in which case the measurements for the left eye were used for all trials.

### 3.1.6. Data-analysis

Responses with improper voice-key activation or an RT less than 300 ms were removed, as were all trials in which eye and/or head movements had occurred that were  $0.5^\circ$  or larger. Thus, 54.8% of the trials remained, leaving 6.6 trials in each of the invalid-cue and 26.4 in each of the valid-cue conditions per subject on the average. Because of the small number of observations in the invalid-cue conditions, we followed a different method of outlier exclusion than in Experiment 1. There were two related arguments why we did this. First, the minimum number of data points mathematically required to have the possibility of finding observations that are more than two standard deviations from the mean is six (see Appendix A for a more general theorem together with a proof). Second, if there are few observations in some of the conditions while there are many more in others, an artificial RT difference is introduced

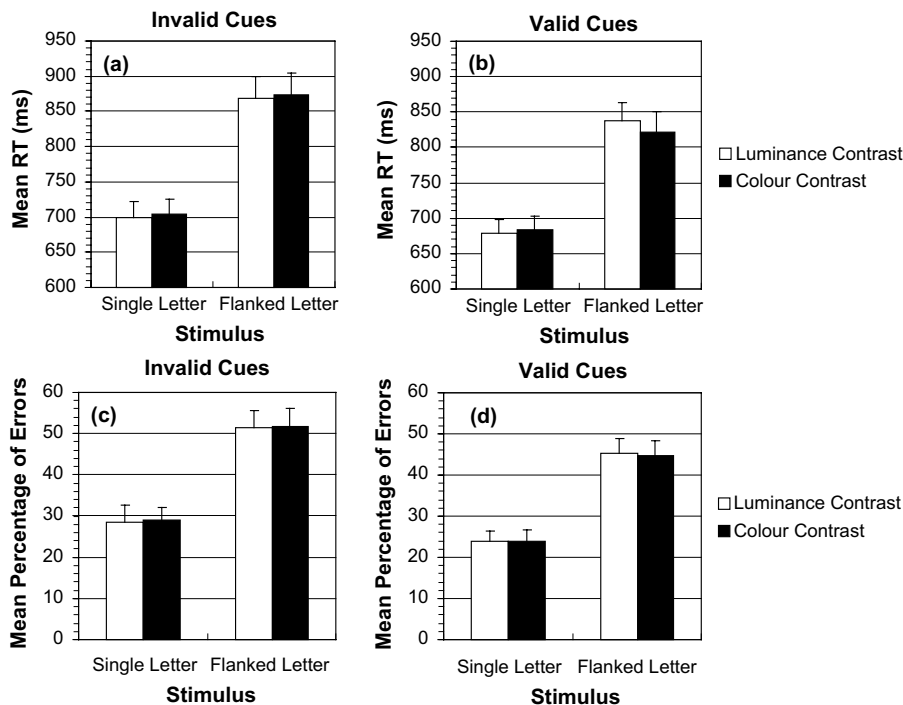


Fig. 4. Mean naming performance with standard error as a function of contrast and stimulus (averaged across location) in Experiment 2 for: (a) reaction time (RT) and invalid cues; (b) reaction time (RT) and valid cues; (c) percentage of errors and invalid cues and (d) percentage of errors and valid cues.

between the conditions<sup>3</sup> (Miller, 1991; Ponsoda & Alcázar, 1996). Therefore, we used a different outlier-exclusion method in which instead of the mean and the standard deviation the median and the median of the absolute deviations from the median (MAD), respectively, are used. The rule is as follows: exclude all observations with an RT that is more than  $3 \times 1.483 \times \text{MAD}$  from the median. This method was shown by Ponsoda and Alcázar (1996) to remedy the problem of an artificial RT difference. The use of this rule resulted in 5.3% data exclusion (relative to the data set that remained after the first data exclusions).

The rest of the data-analysis procedure followed that of Experiment 1.

<sup>3</sup> This is because reaction-time distributions are usually positively skewed, so that RTs to the right of the mean have a larger probability of being removed from the data set than do RTs to the left, resulting in a restricted-mean-RT value that will generally be smaller than the true-mean-RT value. Important, for small numbers of observations, no (when there are less than six observations) or only the most extreme outliers are excluded, resulting in no or only a modest degree of bias in the mean RT. Thus, conditions with few and conditions with many observations will differ in the amount of bias that the outlier-exclusion rule generates, leading to an artificial RT difference between the conditions. (For the most extremely skewed reaction-time distributions studied by Miller (1991) and Ponsoda and Alcázar (1996), the artificial difference was as large as 50 ms.)

### 3.2. Results and discussion

Both on the RT and on the error-score data, a  $2 \times 2 \times 2 \times 2$  (Cue  $\times$  Contrast  $\times$  Stimulus  $\times$  Location) repeated-measures multivariate analysis of variance was conducted. For both dependent variables, the main effects of Cue [ $F(1, 23) = 19.06$ ,  $p < 0.001$ , one-tailed, for RTs;  $F(1, 23) = 9.13$ ,  $p < 0.01$ , one-tailed, for error scores], Stimulus [ $F(1, 23) = 129.74$ ,  $p < 0.001$ , one-tailed, for RTs;  $F(1, 23) = 88.27$ ,  $p < 0.001$ , one-tailed, for error scores], and Location [ $F(1, 23) = 13.68$ ,  $p < 0.01$ , for RTs;  $F(1, 23) = 8.79$ ,  $p < 0.01$ , for error scores] were significant, showing that performance was better for valid than for invalid cues, for single than for flanked target letters, and for presentations to the right than to the left, respectively. Of all the other effects, only the interaction of Contrast  $\times$  Location was significant [ $F(1, 23) = 6.75$ ,  $p < 0.05$ , for error scores]: the right-visual-field advantage on the error scores was found for colour-contrast presentations [ $F(1, 23) = 16.88$ ,  $p < 0.001$ ], but not for luminance-contrast presentations [ $F(1, 23) = 0.78$ , ns]. Neither the interaction of Contrast  $\times$  Stimulus nor the interaction of Cue  $\times$  Contrast  $\times$  Stimulus was significant (see Fig. 4).

Thus, although the cueing manipulation had clearly functioned, we did not find different interactions of Contrast  $\times$  Stimulus for the validly cued and the invalidly cued trials. Indeed, the interaction of Con-



trast×Stimulus was not significant at all. For the validly cued trials, the absence of a significant interaction of Contrast×Stimulus was precisely as had been predicted, and suggests that the magnocellular system is involved in the allocation of attention. For the invalidly cued trials, however, the absence of a significant interaction of Contrast×Stimulus was unexpected. However, it can be explained if it was the case that after a voluntary shift of attention to the cued location the participants were not able to make use of the early and transient bottom-up magnocellular activity from the other location in relocating their attention. Indeed, inhibition is commonly reported in relation to invalid cues. Thus, the present results could be thought of as consistent with the hypothesised role of the magnocellular system in attention allocation during flanked-letter identification. However, to obtain more clear-cut evidence, we performed a third experiment with valid vs. *neutral* cues, a manipulation for which different interactions of Contrast×Stimulus should definitely be expected.

## 4. Experiment 3

### 4.1. Method

#### 4.1.1. Participants

Sixteen normally reading students from the University of Nijmegen took part in this experiment, three of whom had also participated in Experiment 2, of whom one also in Experiment 1. There were 3 males and 13 females, whose ages ranged from 18 to 28, with a median of 21.5. They were paid or given course credit for their participation. All reported that they had normal or corrected-to-normal vision including normal colour vision, as well as normal hearing.

#### 4.1.2. Materials

See Experiment 2. There was one difference: because of equal numbers of measurements in the valid- and neutral-cue conditions, the letter set was expanded to 25 different members, with some of the letters presented twice in each condition, giving 30 presentations in each of the conditions in total.

#### 4.1.3. Design

There were four within-subject manipulations: cue validity (valid vs. neutral), contrast between letters and background (colour vs. luminance), stimulus type (flanked vs. single letter), and location of target-letter presentation ( $-1^\circ$  vs.  $+1^\circ$  from fixation). The cue-validity variable was manipulated in two separate tasks (of 8 blocks each), of which the order was counterbalanced across participants. Location varied randomly from trial to trial, with the restrictions that either loca-

tion was used equally often in each block and the same location was not used for more than six trials in a row. Contrast and stimulus remained constant during blocks and were counterbalanced both across and within participants. There were eight different task/block orders across participants. Each block contained 30 trials. Consecutive letters were always different, and each subject received a different letter-identity order and a different order of stimulus location.

#### 4.1.4. Procedure

See Experiment 2. However, there were separate tasks with valid and neutral cues. In the neutral-cue conditions, the sound cue was presented in both speakers of the headphones simultaneously, which the participants were instructed to ignore. Each of the two tasks started with a practice block.

#### 4.1.5. Eye-movement analysis

See Experiment 2.

#### 4.1.6. Data-analysis

Because the number of observations was, also after exclusion of all trials that were contaminated by eye/head movements, RTs less than 300 ms, or faulty voice-key registration, similar across the valid and the neutral-cue conditions (12.6 vs. 13.6 observations per condition per subject on the average, respectively), we used the outlier-exclusion method of Experiment 1, yielding 4.9% of outliers (relative to the data set that remained after the first data exclusions).

## 4.2. Results and discussion

Both on the RT and on the error-score data, a  $2 \times 2 \times 2 \times 2$  (Cue×Contrast×Stimulus×Location) repeated-measures multivariate analysis of variance was conducted. In all but one respect, the same results as in Experiment 2 were obtained. The main effects of Cue [ $F(1, 15) = 4.18$ ,  $p < 0.05$ , one-tailed, for RTs], Stimulus [ $F(1, 15) = 125.61$ ,  $p < 0.001$ , one-tailed, for RTs;  $F(1, 15) = 101.02$ ,  $p < 0.001$ , one-tailed, for error scores], and Location [ $F(1, 15) = 8.44$ ,  $p < 0.05$ , for RTs] were significant, as was the interaction of Contrast×Location [ $F(1, 15) = 7.21$ ,  $p < 0.05$ , for RTs] (direction of the effects the same as in Experiment 2). Different from Experiment 2, however, the second-order interaction of Cue×Contrast×Stimulus now was significant [ $F(1, 15) = 3.61$ ,  $p < 0.05$ , one-tailed, for RTs]: When the cueing was valid, the interaction of Contrast×Stimulus was absent [ $F(1, 15) < 1$ , ns], but when it was neutral, the interaction of Contrast×Stimulus was present [ $F(1, 15) = 4.84$ ,  $p < 0.05$ , one-tailed] (see Fig. 5).

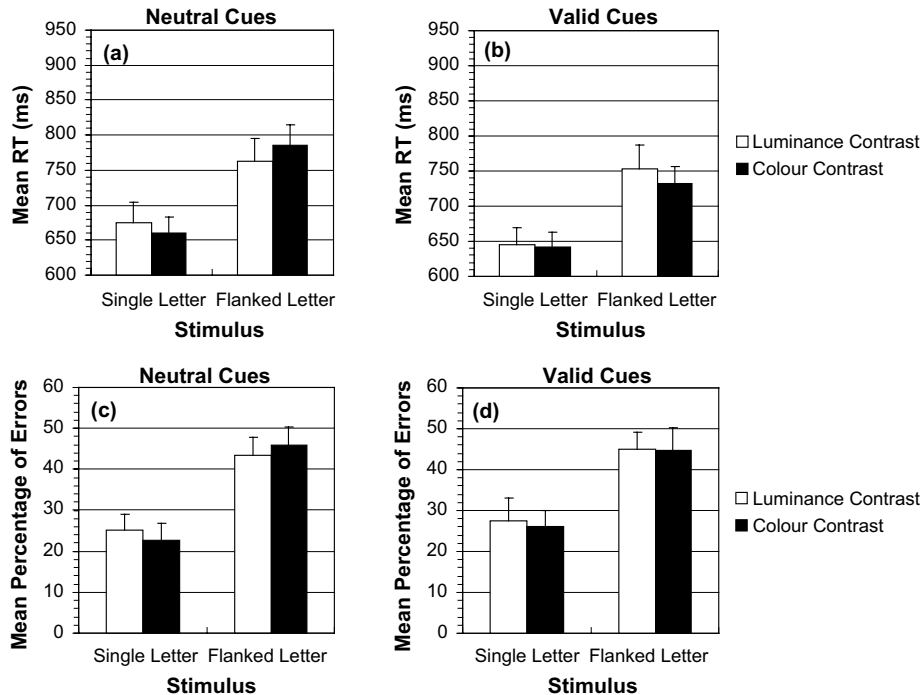


Fig. 5. Mean naming performance with standard error as a function of contrast and stimulus (averaged across location) in Experiment 3 for: (a) reaction time (RT) and neutral cues; (b) reaction time (RT) and valid cues; (c) percentage of errors and neutral cues and (d) percentage of errors and valid cues.

## 5. General discussion

In the present study, three letter-naming experiments were conducted with single and with flanked letters, and with colour and with luminance contrast between characters and background. The letter stimuli all appeared within the central area of vision. Of main interest was the interaction of contrast with stimulus, which, given the specific sensitivities of the magno- and the parvocellular system to luminance and colour contrast, respectively, could signify a role of the magnocellular system in flanked-letter identification (see also Omtzigt et al., 2002). When prior information as to the location of the target letter was provided (Experiments 1–3), there was no indication of an interaction of contrast with stimulus: colour and luminance contrast were equally suited for the naming of the single letters and also for the naming of the flanked letters. When prior location information was *not* provided (Experiments 1 and 3), however, an interaction of contrast with stimulus did appear,<sup>4</sup> with colour contrast being relatively inadequate for the naming of the flanked letters. This latter finding was also obtained, consistently across all three letter-naming experiments, in our previous study

(Omtzigt et al., 2002), in which also no prior location information was given. The present finding that the interaction of contrast with stimulus disappears if prior location information *is* given then strongly suggests that the role of the magnocellular system in identifying flanked letters is in the allocation of attention.

Previous studies using colour and luminance contrast already suggested that the magnocellular system is important to the reading process. Chase, Ashourzadeh, Kelly, Monfette, and Kinsey (2003) used colour and luminance contrast in combination with a red-colour filter. Such a filter has the effect of suppressing magnocellular but not parvocellular activity during reading. It was found that the filter suppressed the reading of luminance-contrast but not colour-contrast text, which provides evidence for a role of magnocellular-system activity during reading. O'Brien and Zimmerman (1997) showed that blurring isoluminant colour-contrast and luminance-contrast text, thereby removing the luminance artefacts from the colour contrast, led to the strongest impairment in reading performance for the colour contrast. Important, the colour-contrast disadvantage was seen for static whole-sentence presentation but not for rapid serial visual presentation (RSVP). Since eye movements are required for the former mode of presentation only, a possible interpretation of the data is that the magnocellular system is important for the execution of eye movements. This would be in accordance with the magnocellular system's role in the

<sup>4</sup> In Experiment 1, the interaction was significant for all three target-letter locations taken together, and just dropped below the 5% significance level ( $p = 0.06$ ) if only the—attentionally manipulated—central location was considered.

allocation of attention, since attention is shifted to the location where the eye movement will land prior to the actual eye movement (Deubel & Schneider, 1996; McPeck, Maljkovic, & Nakayama, 1999; Shepherd, Findlay, & Hockey, 1986). Studies comparing colour and luminance contrasts in a reading task that show that normal reading performance for colour contrast is possible (Knoblauch, Arditi, & Szlyk, 1991; Legge, Parish, Luebker, & Wurm, 1990; Travis, Bowles, Seton, & Peppe, 1990) seem to be in conflict with the idea that the magnocellular system is essential to a normally functioning reading process. However, it should be noted that normal colour-contrast reading performance was obtained in these studies for high levels of colour contrast, for which the magnocellular system is far from silent (Lee, 1996).

There are indications that developmental dyslexia is associated with a deficit in the magnocellular pathway (e.g., Breitmeyer, 1993; Demb et al., 1998; Eden et al., 1996; Hari et al., 2001; Iles et al., 2000; Livingstone et al., 1991; Ridder et al., 2001; Slaghuis & Lovegrove, 1985; Sperling et al., 2003; Stein & Walsh, 1997; Steinman et al., 1998; Vidyasagar & Pammer, 1999; but see, e.g., Amitay et al., 2002; Farrag et al., 2002; Ramus et al., 2003; Skottun, 2000; Williams et al., 2003). The present results suggest a mechanism how a magnocellular deficit could lead to reading difficulties. Shifts of attention to flanked letters occur virtually continuously during reading, both overtly and covertly. Covert shifts of attention, which were studied here, are not only a precursor to overt shifts of attention (saccades), they also have a function in word identification of their own. Supporting this latter contention, preview of the letters that are the subsequent target of a saccade lead to a reduced processing time of the fixated word (the so-called *parafoveal-preview benefit*; see Rayner, 1998, for a review). Thus, a dysfunction of the afferent magnocellular stream could potentially disrupt the smooth allocation of attention and, consequently, impair the reading process. It is important to note that dyslexic readers do indeed have difficulties with the naming of flanked letters (e.g., Bouma & Legein, 1977, 1980; Omtzigt, Hendriks, & Kolk, 2003). It would be interesting to investigate whether these flanking problems would diminish if prior target-location information is given.

Why is letter identification more difficult if there are other letters in the vicinity of the target letter? Different proposals have been made in the literature to account for this phenomenon: low-level spatial interactions (contour interaction) between target and distracters (e.g., Liu, 2001), change of the physical spatial-frequency band used in letter identification (e.g., Hess, Dakin, & Kapoor, 2000), and, most relevant to the present study, poor spatial selection of the target letter (e.g., Huckauf & Heller, 2002; Intriligator & Cavanagh,

2001). By investigating the spatial properties of the spatial-selection mechanism (e.g., coarse spatial representation, performance drop-off with eccentricity, lower-field advantage), Intriligator and Cavanagh (2001) argued that the most likely locus of spatial selection is the parietal cortex. Given the strong reliance of the parietal cortex on magnocellular input (e.g., Milner & Goodale, 1995), the present finding that the magnocellular system mediates the attentional selection of flanked letters is consistent with this suggestion.

What is not clear from the present experiments is the precise attentional mechanism in which the magnocellular system has helped to direct attention to the target letter: voluntary shifting of attention or automatic attraction of attention due to pop-out. (Note that although in pop-out the location of the target probably becomes available pre-attentively, for precise identification of the target focal attention is necessary; Sagi & Julesz, 1985; Treisman & Gelade, 1980.) It is conceivable that for the five-letter-string stimulus in Experiment 1—with its constant string location, and varying target location within the string—pop-out played a relatively important role, whereas for the three-letter-string stimulus in Experiment 3—with its varying string location, and constant target location within the string—a relatively stronger reliance on voluntary attention shifting was present. Follow-up studies are required to differentiate between these two mechanisms of attention allocation.

An important issue in attention research has been whether the attentional-selection mechanism acts at early (e.g., Broadbent, 1958; Kahneman, 1973; Treisman, 1964) or late (e.g., Deutsch & Deutsch, 1963; Duncan, 1980; Posner, 1978) stages of information processing. During the last few years, it is becoming increasingly clear that selective attention can influence visual-information processing already at a very early stage. Recent studies have shown attentional modulation at the level of the primary visual cortex (e.g., Somers, Dale, Seiffert, & Tootell, 1999; Watanabe et al., 1998) and even at the level of the lateral geniculate nucleus (O'Connor, Fukui, Pinsk, & Kastner, 2002). As a possible mechanism, it has been suggested that feedback loops originating from the dorsal stream, and therefore driven by fast magnocellular input, act on the earlier stages of visual-information processing (e.g., Vidyasagar, 1999). The present psychophysical data showing that the magnocellular system is important to the allocation of attention are in line with this suggestion.

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**Appendix A**

**Theorem.** Let  $n \geq 2$  ( $n$  an integer) and  $k > 0$  ( $k$  a real number). There exists a set of  $n$  real-valued elements with a member that is more than  $k$  standard deviations from the mean if and only if  $k < \frac{n-1}{\sqrt{n}}$  or, equivalently,  $n > 1 + \frac{1}{2}k^2 + \frac{1}{2}k\sqrt{k^2 + 4}$ .<sup>5</sup>

**Proof.** Let  $n \geq 2$  ( $n$  an integer) and  $k > 0$  ( $k$  a real number). For any set of  $n$  real-valued elements,  $\{x_1, x_2, \dots, x_n\}$ , the mean  $m$  and the standard deviation ‘ $s$ ’ are given by

$$m = \frac{1}{n} \cdot \sum_{i=1}^n x_i \quad \text{and} \quad s = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^n (x_i - m)^2}.$$

Call a set in which all members are the same except one element *minimally distinct*. Denoting the common value of a minimally distinct set by  $a$  and the deviant (extreme) value by  $b$  (for  $n = 2$ , it is arbitrary which

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$$\begin{aligned} s_1 &= \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^n (x_i - m)^2} = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^n \{(x_i - m_{n-1}) + (m_{n-1} - m)\}^2} \\ &= \sqrt{\frac{1}{n-1} \cdot \left\{ \sum_{i=1}^n (x_i - m_{n-1})^2 + \sum_{i=1}^n 2 \cdot (x_i - m_{n-1}) \cdot (m_{n-1} - m) + \sum_{i=1}^n (m_{n-1} - m)^2 \right\}} \\ &\geq \sqrt{\frac{1}{n-1} \cdot \left\{ (x_n - m_{n-1})^2 + 2 \cdot (x_n - m_{n-1}) \cdot (m_{n-1} - m) + \sum_{i=1}^n (m_{n-1} - m)^2 \right\}} \\ &= \sqrt{\frac{1}{n-1} \cdot \left\{ \sum_{i=1}^n (y_i - m_{n-1})^2 + \sum_{i=1}^n 2 \cdot (y_i - m_{n-1}) \cdot (m_{n-1} - m) + \sum_{i=1}^n (m_{n-1} - m)^2 \right\}} = s_2. \end{aligned}$$


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value to call “common” or “deviant”), it can be deduced that the mean and the standard deviation of a minimally distinct set are  $m = \frac{(n-1)a+b}{n}$  and  $s = \frac{|a-b|}{\sqrt{n}}$ . Now,  $b$  is more than  $k$  standard deviations from the mean if and only if  $\frac{|b-m|}{s} = \frac{n-1}{\sqrt{n}} > k$ , which is equivalent to  $n > 1 + \frac{1}{2}k^2 + \frac{1}{2}k\sqrt{k^2 + 4}$ . Note that this condition is independent of  $a$

<sup>5</sup> The variant of the standard deviation has been chosen that has the sum of squares divided by  $(n - 1)$ . If the variant is chosen with division by  $n$  instead of  $(n - 1)$ , the condition becomes  $k < \sqrt{n - 1}$ , or, equivalently,  $n > 1 + k^2$ .

and  $b$ . Thus, if the condition is met, any minimally distinct set will provide an example of a set with a member that is more than  $k$  standard deviations from the mean. If the condition is not met, however, no minimally distinct set will do.

To complete the proof, it must be shown that if the condition is not met, also no other, not minimally distinct, set exists with a member that is more than  $k$  standard deviations from the mean. This can be done as follows. Let  $S_1 = \{x_1, x_2, \dots, x_n\}$  be any not minimally distinct set. If  $S_1$  has *all* of its members identical, it is obvious that it does not contain any element that is more than  $k$  standard deviations from the mean. If  $S_1$  does *not* have all of its members identical, let  $x_n$  be the element of  $S_1$  that is the largest distance from the mean (or one of those elements, if there are more). Consider a minimally distinct set  $S_2 = \{y_1, y_2, \dots, y_n\}$ , with  $y_n = x_n$  and  $y_1 = y_2 = \dots = y_{n-1} = m_{n-1}$  with  $m_{n-1} = \frac{1}{n-1} \cdot \sum_{i=1}^{n-1} x_i$ , that is, the mean of all elements of  $S_1$  except  $x_n$ . Note that the mean of all elements of  $S_2$  except  $y_n$  is also  $m_{n-1}$ , and that, hence, the means of  $S_1$  and  $S_2$  are equal. Thus,  $x_n$  and  $y_n$  are the same (absolute) distance from their respective means. The idea now is to show that the standard deviation of  $S_1$  cannot be smaller than the standard deviation of  $S_2$  (which is intuitively clear, because the variation of the elements in  $S_1$  is larger than in  $S_2$ ). Denote the common mean of  $S_1$  and  $S_2$  by  $m$  and the standard deviations of  $S_1$  and  $S_2$  by  $s_1$  and  $s_2$ , respectively. We then have

Thus,  $s_1 \geq s_2$ , so that  $\frac{|x_n-m|}{s_1} \leq \frac{|x_n-m|}{s_2} = \frac{|y_n-m|}{s_2} \leq k$ , which completes the proof.

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