# Objects look different sizes in the right and left eyes

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Coren and Porac (1976) reported that objects looked larger in the right eye of right-eye dominant subjects and in the left eye of left-eye dominant subjects. This paper attempts to repeat that finding. Two circles of same or different size were presented haploscopically in a binocular three-field tachistoscope, to right or left visual half-field and to the upper or lower visual field, one to the right eye and one to the left. A total of 43 subjects reported which of the two circles was the larger, each subject carrying out 120 trials of the experiment. Overall subjects reported that the stimulus to the left eye was significantly larger than that presented to the right eye. There was no association with eye dominance, and therefore the Coren and Porac finding could not be repeated. There was however a very significant association with handedness, left-handed subjects tending to report that the stimulus in the right eye looked larger, and right-handed subjects reporting that the stimulus in the left eye looked larger.

Cerebral hemispheric specialisation is a very well studied phenomenon (Hellige, 1993). The majority of people are right-handed and the majority of people also have language processing in their left hemisphere. However about 10% of the population are left-handed and a similar proportion is right hemisphere dominant for language. Although handedness and language lateralisation are correlated it must be emphasised that the majority of left-handers have language in the *left* hemisphere (McManus & Bryden, 1992).

As well as being right-handed, a majority of the population are also right-footed, right-eared, and right-eyed (although as with handedness and language lateralisation, there are only relatively weak correlations between these different lateralisations). The particular interest of this paper is in eyedness, which is assessed in the sense of *sighting dominance* (Porac & Coren, 1976). Although there have been many studies of the incidence of right and left eyedness (see

Bourassa, McManus, & Bryden, 1996, for a meta-analysis), there are relatively few studies that have looked at the possible mechanisms underlying eyedness and eye preference. An important exception is the various studies of Porac and Coren (e.g., 1978, 1982, 1986a, 1986b), who have suggested that object perception is different in the two eyes, and Coren and Porac (1976) in particular suggested that objects look larger when they are viewed with the dominant rather than the non-dominant eye. It is that suggestion which will be looked at in detail in this paper.

Coren and Porac (1976) used an extremely simple experimental paradigm. Each subject looked at two white circular targets in a haploscope (which presents entirely separate images to each eye). One target was presented to the right eye and the other to the left eye, both targets being 105 mm in diameter and presented at a distance of 400 mm. Each subject made only a single judgement, being asked to judge which of the two disks appeared ''larger'' to them. Of 25 subjects who were right-eyed, 17 (68%) said that the image in the right eye looked larger, and of 20 subjects who were left-eyed, 13 (65%) said that the image in the left eye looked larger. The difference was statistically significant ($\chi^2 = 4.90$, 1 df, $p < .05$). No other data were collected in the study, and the description above summarises the analysis in its entirety.

Although handedness, footedness, earedness, and eyedness seem to be correlated one with another, there is a particular theoretical problem in making sense of the relationship between eyedness and either handedness or cerebral lateralisation. Although the eyes, like the hands, feet, and ears, are paired organs, the projection of their nerves to the brain is complicated by the existence of the optic chiasm. In what is a well-known anatomical organisation, the nasal half of each eye projects to the contralateral cerebral hemisphere and the temporal half of each eye projects to the ipsilateral cerebral hemisphere. This anatomical arrangement is exploited in tachistoscopic divided visual field studies, so that images presented to the left of fixation are presented to the right cerebral hemisphere and those to the right to the left cerebral hemisphere. Such considerations raise an immediate problem for interpreting the study of Coren and Porac, since the targets were presented centrally. More generally, the problem must be raised as to what it means to have a dominant *eye*, when each eye consists of two halves projecting to different hemispheres. The present study uses a tachistoscopic half-field technique in order to assess whether the perceived size of objects is different in the two different eyes as such, or in the visual fields projecting to the two different hemispheres. Because we wished to be able to present two stimuli to the same visual field, one of necessity was presented above the other. However, that also allowed us the opportunity to compare size perception in the upper and lower visual fields, which is of interest, particularly given that they have been linked to the dorsal and ventral visual pathways (Drain & Reuter-Lorenz, 1996).

The technique of Coren and Porac also presents problems in that although the results were statistically significant at the group level, having only a single measurement for each subject makes it impossible to assess the statistical significance of the effect within each subject. In particular it means that it is not possible to ask whether there are some subjects for whom the effect is reversed (i.e., objects appear larger in the non-dominant eye). There is also the problem that with only a single presentation of the display (in which the object in the right and left eye is in fact identical), demand characteristics may make response difficult for subjects, and it also becomes impossible for the experimenter to assess the reliability of the results. The present study therefore uses a formal psychophysical procedure in which the stimuli presented to the two eyes are not always the same size; such a technique also allows the magnitude of any difference between the two eyes to be assessed.

If there are differences between subjects in the magnitude or the direction of the difference between the two eyes, then it would be useful to be able to assess its relationship with a range of other measures of lateralisation, in particular handedness. The use of a handedness questionnaire therefore allows a more systematic assessment of handedness, and in particular the differentiation of effects due to writing hand and throwing hand, which are often discordant (McManus, Porac, Bryden, & Boucher, 1999). Eye dominance is also said to be related to head tilt (Previc, 1994), and therefore that was also assessed in the present study.

## METHOD

### Procedure and stimuli

Stimuli were presented separately to the two eyes using a binocular, three-field tachistoscope (Hampton Electronic Developments, Middlesex) in which control of stimuli to the two eyes was entirely separate. On each trial a subject saw two black circles on a white background (see Figure 1). One black circle was presented to the right eye and the other to the left eye. The circles were presented in one of four positions, 45, 135, 225, and 315 degrees around the fixation point. The circles were each at a distance of 21 mm from the fixation point, which was 2 mm in diameter, and the viewing distance was 500 mm, so that the circles were 2.4 degrees of visual angle from the fovea. On each trial the diameters of the two circles were either 11.25 and 10.75 mm, 11.125 and 10.875 mm, or were both 11 mm in diameter (1.288° and 1.232°, 1.275° and 1.246°, and both 1.260° respectively). The larger circle was therefore 2.27% or 4.54% greater in diameter than the smaller circle. Pilot testing had found that subjects regarded the 11.25 and 10.75 mm pairs as relatively easy to distinguish, and the 11.125 and 10.875 mm pairs as more difficult. Stimuli were printed using a 600 dots per inch inkjet printer on standard tachistoscope cards.

On each trial one circle was presented to the right eye and the other to the left eye, although subjects were not informed of that and none spontaneously noticed that it was the case. The two circles were also presented in all four possible positions relative to the fixation point, in a pseudo-random, balanced order. Overall 120 trials were presented to each subject, which represented all possible combinations of viewing eye (R vs L), stimulus layout (six combinations of two from four positions), and size (five sets, since 11.25–10.75 was different from 10.75–11.25, etc.), replicated twice. It should be noted that although on each trial one stimulus always went to the right eye and the other to the left, the presentation to visual half-fields was more complicated. In some trials, shown as *a*, *b*, *c*, and *d* in Figure 1, one stimulus was in the left visual half-field and the other in the right with both either above or below the fixation point (45 and 315 degrees, or 135 and 225 degrees), and in others (*i*, *j*, *k*, and *l* in Figure 1) the stimuli were in different half-fields but with one above and the other below the fixation point (''diagonal'' e.g., 45 and 225, or 135 and 315 degrees). In some
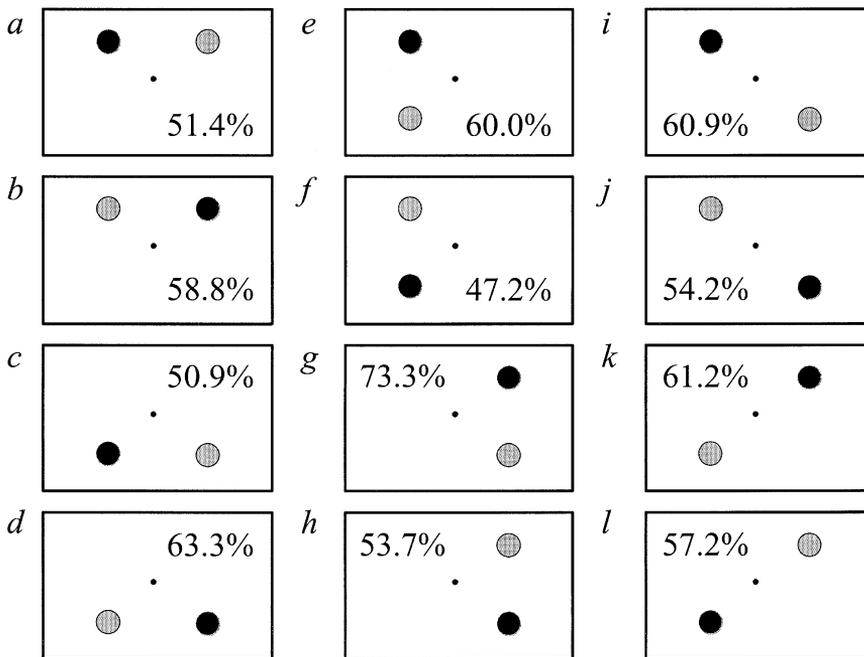


**Figure 1.** Schematic representation of the 12 stimulus combinations used in the experiment. On each stimulus there was a fixation point and two solid black circles (not always of the same size). In the schematic one of the black circles has been shaded grey to indicate that it is presented to the right eye, whereas the other (black) circle is presented to the left eye. The percentage in each figure is the percentage of cases in which the stimulus shown to the left eye was reported as being larger (see text for further details).

trials both stimuli were in the same visual field (but still in different eyes), e.g., 45 and 135 degrees, or 225 and 315 degrees (*e*, *f*, *g*, and *h* in Figure 1).

The subjects's task was to say which circle was the larger. Subjects initiated a trial by fixating on the binocular fixation point in the centre of the field and then pressing a foot switch, when the stimuli were immediately presented, followed by a random dot masking field which was the same in each eye and lasted for 1000 ms. Presentation times were set individually for each subject on the basis of a pilot task, and were typically between 80 and 140 ms. Subjects responded by means of a four-button key pad in which the four keys were arranged in the same layout as the four possible positions of the circles on the screen. Stimuli on the left were responded to with the left hand and those on the right with the right hand. Although reaction times were recorded, they will not be reported here, where the principle interest is in which stimulus was reported as the larger.

Subjects were informed that the experiment was about visual perception. After the tachistoscopic experiment was completed, sighting eye dominance was assessed by asking subjects to look down four 300 mm tubes, 40 mm in diameter and with a 2 mm aperture, held horizontally in retort stands, and to report what they could see on a translucent screen at the far end. The eye used for sighting was noted by the experimenter. Handedness and other aspects of lateralisation were then assessed by means of a questionnaire. Finally subjects were photographed against a grid of horizontal and vertical black lines on a white background, so that head tilt could be assessed. Subjects were mostly undergraduates who were recruited within University College London. Formal optometric assessment was not carried out, but all subjects were asked to wear any normal corrective lenses during the experiment.

## RESULTS

A total of 43 subjects took part in the experiment, 20 male and 23 female. Of the subjects 10 (23%) were left-handed, a slightly higher incidence than in the general population, a result that was achieved by JT asking subjects to participate whom she had discreetly noticed to be left-handed, the intention being to obtain a mixture of subjects in which left-eye dominant individuals were adequately represented.

### Eye-dominance

Sighting dominance was assessed in two separate ways, by questionnaire and by a behavioural test of use of the eyes when looking monocularly into four tubes. Table 1 shows that there was a fairly good agreement between the two measures, Kendall's tau-b $= -.467$ ($p < .001$). However, there are some disagreements, and for the main analyses right and left dominance are defined in terms of those using the right eye on $>2$ or $\leq 2$ occasions respectively. Of the subjects 24 (56%) were therefore right-eyed, and 19 (44%) were left-eyed.

TABLE 1
Eye dominance and sighting dominance

| | *Number of times right eye used to look down tube* | | | | |
|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 |
| Always right | 3 | — | — | 1 | **9** |
| Usually right | — | — | — | **1** | 6 |
| Either | 2 | 3 | **2** | — | 6 |
| Usually left | 2 | **1** | — | — | 1 |
| Always left | **6** | — | — | — | — |

The association of eye dominance as assessed by an item on the laterality questionnaire (rows) and sighting dominance assessed by the eye used to look down four tubes.

## Overall analysis of tachistoscopic task

On each trial a subject saw two circles, one presented to the right eye and the other to the left eye, and had to judge which was the larger. A simple analysis of the entire data set, aggregating across the 5160 judgements made by all subjects, gives the results shown in the first part of Table 2. Without the need to do any formal statistical analysis, which will be left until the individual analysis of subjects, it is clear that when stimuli are actually identical in the right and left eyes, that subjects are about twice as likely (odds ratio) to report the left eye stimulus as being larger. In addition the data when the stimuli actually do differ in size indicate that there is a classical psychophysical function. The point of subjective equality occurs when the right eye stimulus is about 11.08 mm and the left eye stimulus about 10.92 mm. Phenomenologically, the left eye stimulus therefore appears to be about 1.5% larger in diameter or about 2.25% larger in area.

*Eye dominance.*   A primary purpose of the present study was to try and repeat the result of Coren and Porac. Table 2 therefore also includes an analysis broken down by the eye dominance of the subjects. The key results, again presented at this stage without any formal statistical analysis, is that when the stimuli are in fact equal in size, the one in the left eye is reported as being larger on 61% of occasions by left-eye dominant subjects, and by 59.2% of right-eye dominant subjects. There is no evidence that left-eye dominant subjects show the reverse pattern to that of right-eye dominant subjects.

*Visual half fields.*   A key question of theoretical interest concerns whether differences are between eyes or between visual half-fields. The simplest case for analysing this consists of those pairs of stimuli in which both are at the top (45 and 315 degrees) or both are at the bottom (135 and 225 degrees). One stimulus

TABLE 2
Perceived size in relation to eye dominance

| Stimuli | | All subjects (1032 judgements per row) | | Right-eye dominant (576 judgements per row) | | Left-eye dominant (408 judgements per row) | |
|---|---|---|---|---|---|---|---|
| Left eye | Right eye | Right eye judged to be larger | Left eye judged to be larger | Right eye judged to be larger | Left eye judged to be larger | Right eye judged to be larger | Left eye judged to be larger |
| 10.75 mm | 11.25 mm | 63.8% | 36.2% | 66.0% | 34.0% | 59.1% | 40.9% |
| 10.875 mm | 11.125 mm | 53.0% | 47.0% | 53.8% | 46.2% | 48.5% | 51.5% |
| 11 mm | 11 mm | 41.3% | 58.7% | 40.8% | 59.2% | 39.0% | 61.0% |
| 11.125 mm | 10.875 mm | 31.1% | 68.9% | 32.8% | 67.2% | 25.5% | 74.5% |
| 11.25 mm | 10.75 mm | 22.5% | 77.5% | 23.3% | 76.7% | 19.9% | 80.1% |

Percentage of occasions on which the stimulus presented to the right eye or the left eye was judged to be the larger. The first two columns of percentages show the results for all subjects, and the last four columns of percentages show the results separately for right and left eye dominant subjects. The total number of trials in each row is 1032 for all subjects, 576 for right-eye dominant subjects and 408 for left-eye dominant subjects.

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is in the left visual field and the other in the right visual field, and because of the experimental set-up, visual field and eye are completely crossed. Thus, for instance, the stimulus in the right visual field can either be seen by the right eye or the left eye. Table 3 shows the results for the two conditions. It can be seen that stimuli to the left eye are seen as larger and that there is no effect of hemi-field. Taking all the stimuli together, the left eye stimulus is judged larger on 55.1% of occasions when it is in the left visual field, 59.4% of occasions when it is in the right visual field, and 58.6% of occasions when the stimuli are in the same visual field. We therefore conclude that the effect is truly a difference between eyes rather than a difference between half-fields (and by implication, between hemispheres).

   *Top–bottom differences and nasal–temporal differences.*  As well as showing the layout of the stimuli, Figure 1 also shows the percentage of occasions overall in which the left eye stimulus was judged to be larger for all 12 different stimulus types. It is apparent from a comparison of stimulus *e* with *f* or *g* with *h*, as well as *i* with *j* and *k* with *l*, that there is a clear tendency for stimuli in the upper field to be judged larger than those in the lower field. Overall the left eye stimulus was judged larger on 63.8% of 1720 occasions when it was the uppermost stimulus, compared with 53.1% of occasions when it was the lower stimulus and 56.1% of occasions when the stimuli were at the same level. A theoretically interesting question concerns whether there is a larger difference when the stimuli are both presented in the nasal half-fields, as in stimuli *a*, *c*, *i*, and *l*, or both in the temporal fields, as in stimuli *b*, *d*, *j*, and *k*. Overall the left eye stimulus was judged larger on 55.1% of occasions when both stimuli were in nasal half-fields compared with 59.4% of occasions when both were in temporal half-fields.

## Significance within subjects

Thus far the analysis has been primarily exploratory, and no formal statistics have been carried out, principally because results have been aggregated across subjects. However the large number of trials carried out by each subject means that analysis can also be carried out at the level of each subject, and significance tests carried out to see if the effect is significant within individuals, and hence whether there are significant individual differences. A straightforward descriptive measure of effect size within each subject is the *simple percentage* of occasions (out of 120) on which the subject reported that the stimulus presented to the left eye was larger. It is also possible separately to estimate the point of subjective equality for each subject by means of a logistic regression. The dependent variable was left eye judgement (1 = left eye seen as larger, 0 = right eye seen as larger), which was regressed on the actual difference in size of the stimuli (left eye stimulus 0.5, 0.25, 0, $-0.25$ and $-0.5$ mm larger). The overall

## TABLE 3
## Perceived size in relation to visual field

| Stimuli | | Left eye looking at left visual field / Right eye looking at right visual field | | Left eye looking at right visual field / Right eye looking at left visual field | |
| --- | --- | --- | --- | --- | --- |
| Left eye | Right eye | Right eye (RVF) judged to be larger | Left eye (LVF) judged to be larger | Right eye (LVF) judged to be larger | Left eye (RVF) judged to be larger |
| 10.75 mm | 11.25 mm | 73.8% | 26.2% | 58.7% | 41.3% |
| 10.875 mm | 11.125 mm | 59.9% | 40.1% | 48.3% | 51.7% |
| 11 mm | 11 mm | 44.8% | 55.2% | 40.1% | 59.9% |
| 11.125 mm | 10.875 mm | 39.5% | 60.5% | 26.2% | 73.8% |
| 11.25 mm | 10.75 mm | 26.2% | 73.8% | 21.5% | 78.5% |

Percentage of occasions on which the stimulus presented to the right eye or the left eye was judged to be the larger, for stimulus pairs in which both stimuli are at the same level, analysed according to whether the left eye is looking at the left visual field or the right visual field. The total number of trials in each row in 172 in each condition.

significance of a difference between right and left eyes can be assessed from the standard error of the fixed constant (*the intercept*) in such an analysis. The simple percentage and the intercept are almost entirely equivalent ($r = .979$). The slope and the intercept from the logistic regression also allow calculation of the *point of subjective equality*, the difference in size for which stimuli presented to the two eyes appear equal. The point of subjective equality correlates well with the simple percentage ($r = .907$). Figure 2 shows the relationship. It should be noted that the maximal difference in the stimuli presented was 4.5%, and therefore estimation of the point of subjective equality outside that range involves extrapolation rather than interpolation. Although for simplicity the remainder of this paper will use the simple percentage as the dependent variable of interest, the point of subjective equality has the important advantage that it
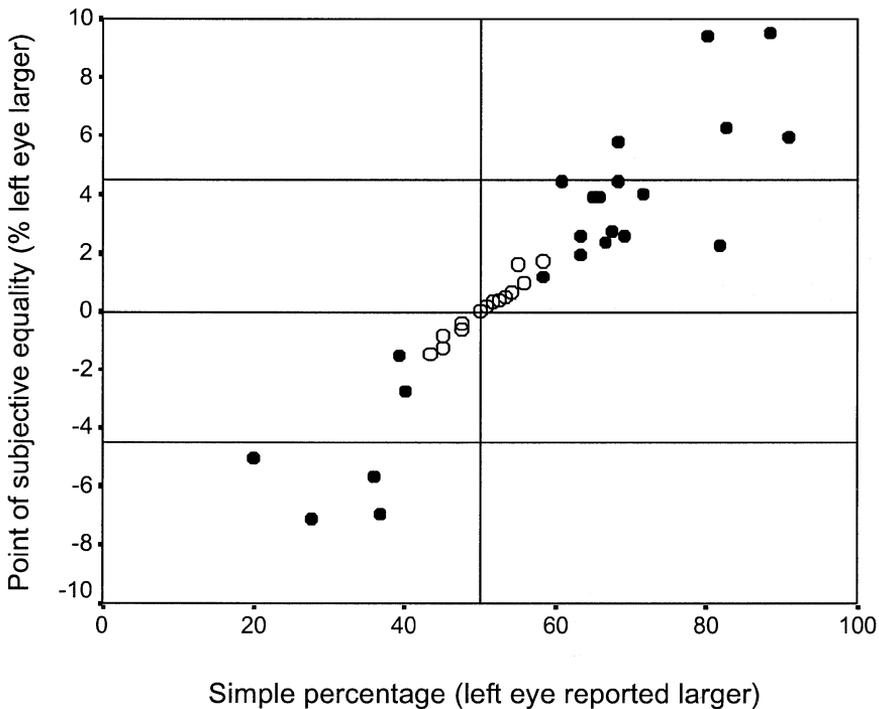


**Figure 2.** Scattergram for the 43 subjects of the simple percentage of judgements in which the stimulus in the left eye looked larger (abscissa) against the point of subjective equality, positive values indicating the percentage by which the image in the left eye looks larger. It should be noted that one subject, who reported the left eye stimulus as larger on only 8.3% of occasions, and for whom the estimated effect was −19.9%, has been omitted from the figure. Solid circles indicate subjects for whom the effect is significantly different for the two eyes ($p < .05$). The horizontal lines at ±4.5% indicate the limits of stimulus size presented in the experiment, so that values outside those limits are calculated by extrapolation.

estimates the psychophysical function and allows a direct estimate of the relative phenomenal size of the image in the two eyes. Figure 3 shows the percentage of left eye responses for each subject, in rank order, along with a confidence interval of ±1.4 standard errors (this value was chosen because any two subjects whose error bars do not overlap are significantly different at the 5% level, Goldstein et al., 1998). It is important that there are large differences between subjects, both between those reporting the right or the left eye stimulus as systematically larger, and those reporting the left eye stimulus as moderately or very much larger.

For 20 subjects (47%) the left eye stimulus was significantly larger, in 7 cases (16%) the right eye stimulus was seen as significantly larger, and in the remaining 16 (37%) cases, there was no significant difference. The non-significant cases pose an interesting question. Are these subjects genuinely seeing the stimuli as being the same size, or are they perhaps unable to judge the stimuli properly, in which case they could be responding at random, and thereby
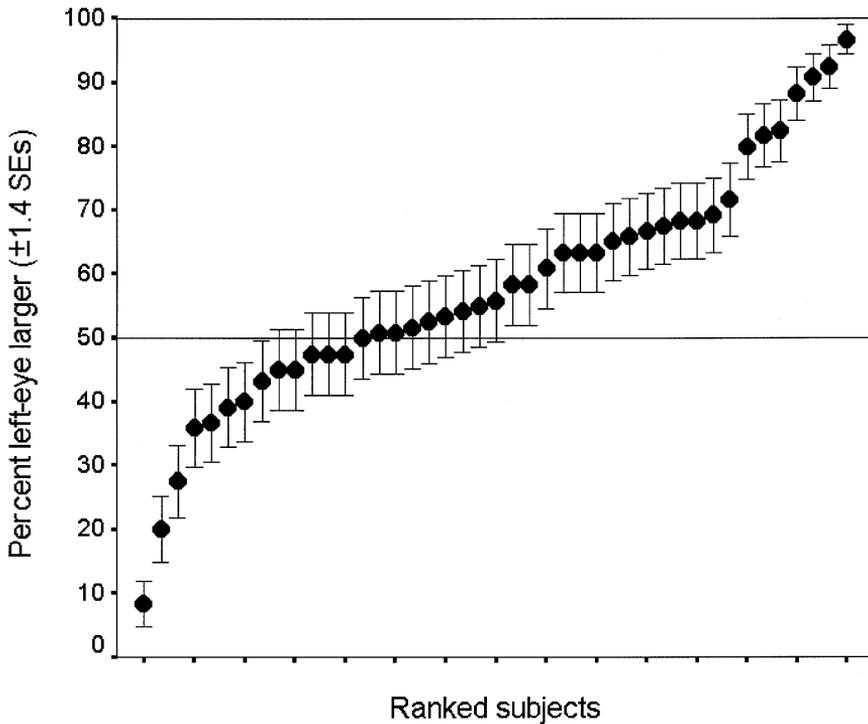


**Figure 3.**   The percentage of left-eye larger responses for subjects, ranked in order of effect size, and showing a confidence interval based on 1.4 times the standard error of the mean. Subjects whose confidence intervals do not overlap are significantly different from one another at the 5% level.

giving the impression of judging left and right eye stimuli as being of the same size? The two possibilities can be compared by looking at psychophysical functions, since if the non-significant group cannot make judgements properly they should be less good at judging stimuli in which there are large differences. Table 4 suggests that the group with no significant difference between the eyes are equally as good as other subjects at differentiating between circles in which there is a difference in size present, a result confirmed by one-way ANOVA of the slopes (sensitivities) comparing those for whom there was a significant eye effect (right eye larger: mean = 0.436, $SD$ = 0.279, $N$ = 7; left eye larger: mean = 0.636, $SD$ = 0.408, $N$ = 20) with those for whom there was no significant eye effect (mean = 0.563, $SD$ = 0.149, $N$ = 16); $F(2, 40) = 1.077$, $p = .350$). The conclusion therefore has to be that the group with a non-significant eye effect is performing the task equally as well as the group with significant differences, but that size perception in the two eyes is indeed genuinely equivalent.

## Correlates of individual differences

The analysis so far has shown that there are statistically significant differences in size perception between the two eyes in a majority of subjects (27/43 = 63%). The remainder of the analysis will ask whether these differences between subjects correlate with other background factors, in particular to do with lateralisation. The dependent variable in each case will be the simple percentage of judgements in which the left eye image was said to be larger.

*Eye-dominance.*   There was no significant correlation between the simple percentage and eye dominance as scored on the five-part questionnaire (1 = always right, 5 = always left; Spearman's rho = .111, NS, $N$ = 43) or the number of right-eye choices for sighting down the tubes (Spearman's rho = −.105, NS).

*Handedness.*   A conventional laterality index [100*(R−L)/(R+L)] was calculated for all 11 items on the handedness questionnaire. A measure of degree of lateralisation was calculated as the absolute value of the laterality index, and direction of lateralisation was scored as 1 (right-handed) if the laterality index was > 0 and 0 otherwise. All of the subjects who wrote with their right hand had a laterality index greater than zero and those who wrote with their left hand had a laterality index less than zero. The simple percentage showed a significant correlation with the laterality index (Spearman's rho = .392, $p$ = .01), with the effect mainly being due to direction of lateralisation (Spearman's rho = .395, $p$ = .01), and with no significant effect due to degree of lateralisation (Spearman's rho = .170, $p$ = .281) (Figure 4). In view of the interest in the association of eye dominance with writing hand and throwing hand, the subjects were looked at in detail in terms of their writing and throwing hands. All of the subjects right-handed for writing also threw with their right hand. However two

TABLE 4
Perceived size in relation to overall size judgement

| Stimuli | | Subjects in whom left eye Stimulus significantly larger | | Subjects for whom no significant difference between the eyes | | Subjects in whom right eye Stimulus significantly larger | |
|---|---|---|---|---|---|---|---|
| Left eye | Right eye | Right eye judged to be larger | Left eye judged to be larger | Right eye judged to be larger | Left eye judged to be larger | Right eye judged to be larger | Left eye judged to be larger |
| 10.75 mm | 11.25 mm | 47.7% | 52.3% | 75.0% | 25.0% | 83.9% | 16.1% |
| 10.875 mm | 11.125 mm | 35.6% | 64.4% | 63.3% | 36.7% | 79.2% | 20.8% |
| 11 mm | 11 mm | 24.6% | 75.4% | 48.2% | 51.8% | 73.2% | 26.8% |
| 11.125 mm | 10.875 mm | 17.1% | 82.9% | 35.4% | 64.6% | 61.3% | 38.7% |
| 11.25 mm | 10.75 mm | 9.0% | 91.0% | 25.5% | 74.5% | 54.2% | 45.8% |

Percentage of occasions on which the stimulus presented to the right eye or the left eye was judged to be the larger, for stimulus pairs in which both stimuli are at the same level, analysed according to whether the left eye is looking at the left visual field or the right visual field. The total number of trials in each row is 168 for the right-eye larger group, 480 for the left-eye larger group, and 384 for the group in which eye effects were not significant.

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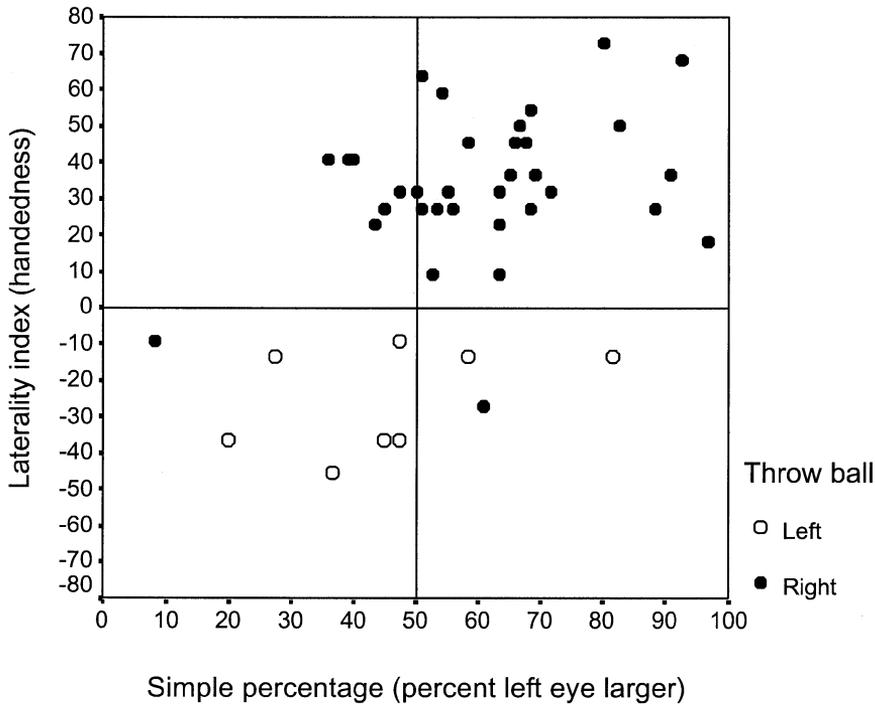
**Figure 4.** The simple percentage of cases in which the left eye stimulus was judged to be larger than the right eye stimulus in relation to the laterality index calculated from the 11 handedness questionnaire items. A score of zero perfectly differentiates between those writing with their right hand (>0) and those writing with their left hand (<0). Hand used to throw a ball is indicated using solid symbols (right hand) and open symbols (left hand).

of the subjects left-handed for writing threw with their right hands. A multiple regression of the simple percentage on writing and throwing hand, with effects calculated after taking into account the other variable, showed that the simple percentage was significantly related to writing hand ($t = 2.177$, $p = .035$), but not to throwing hand ($t = .799$, $p = .429$) (see Figure 4) in each case the regression taking the other variable into account.

*Footedness.* There was no significant correlation between footedness, measured using a single questionnaire item, and the simple percentage of left eye responses (Spearman's rho $= .125$, $p = .423$).

*Demographic measures.* There was no significant relationship between the simple percentage and the sex of subjects (Spearman's rho $= .130$, $p = .407$), or the age of subjects (Spearman's rho $= .075$, $p = .631$), although the range of ages was very limited (19–32).

*Head tilt*.    In 29 (67%) subjects the left eye was higher, and in the remaining 14 subjects the right eye was higher. There was no correlation between head tilt and the simple percentage of cases in which the left eye stimulus was reported as larger (Spearman's rho = .056, *p* = .721).

## DISCUSSION

This paper set out with the intention of examining the claim made in the study of Coren and Porac (1976), that objects seen by the dominant eye look larger than those seen with the non-dominant eye. A citation search has found fewer than half a dozen citations of the 1976 paper, mostly by Coren and Porac themselves, and with no study collecting further data on the topic. The original Coren and Porac study had the problem that the significance of results could not be assessed within subjects, since only a single data point was collected for each subject. The present study remedies that defect and it is clear, overall, that a majority, about two thirds, of subjects do see objects in the right and left eye as having significantly different sizes. However, overall it is objects seen with the *left* eye that are reported as being larger. Coren and Porac claimed that subjects with right-eye dominance saw objects as larger in the right eye and subjects with left-eye dominance saw objects in the left eye as larger. Since right-eye sighting dominance is far more common in the population than left-eye dominance (Bourassa et al., 1996), this would predict that aggregated across a typical random sample such as ours, in which there are more right-eyed than left-eyed subjects, objects would on average seem larger when seen with the right eye. In fact our study, in which a majority of subjects were right-handed, found the opposite effect, that on average objects were seen as larger with the left eye. More problematic for the Coren and Porac claim is that we could find no correlation between measured or reported eye dominance and the eye that saw objects as larger. We have therefore to conclude that there is no support for the Coren and Porac suggestion. As far as we are aware, we are the first people to try and test it in the almost quarter of a century since its original publication in a very high-profile journal.

Our study is similar to the original study in that images are presented haploscopically, and in some cases the subjects compared stimuli of identical physical size. Differences between the studies were that Coren and Porac used free-viewing whereas our stimuli were presented tachistoscopically, and our study did not potentially mislead subjects by asking them to judge which of two actually identical stimuli was ''larger'', since there were many cases in which one stimulus was clearly larger than the other. Our stimuli were black on white, whereas those of Coren and Porac were white on black, although it is difficult to believe that that would dramatically alter the results which were found. Perhaps the most important difference between the experiments is that Coren and Porac's stimuli were very much larger than ours, subtending a visual angle of 14.9°,

whereas our stimuli averaged 1.26°, and were presented at 2.4° from the fovea. Whether we can call our study a ''replication'' in the strict sense, is open to some philosophical debate (and a referee stated that, ''calling this study a 'replication' is clearly nonsensical''). We believe it is effectively a replication in all important matters, and the original finding is not upheld. If our study is not a replication, then the onus has now to be on those who believe in the original finding to show a clear difference in outcome between the original method in all its details and our approach with its variations.

Although we can reject Coren and Porac's suggestion of a link with eye dominance, there seems no doubt from our results that there is nevertheless a clear phenomenon to be explained—objects do not look the same size when viewed with the right and the left eye, although there are substantial indivi-dual differences in *which* eye sees objects as larger. However, the overall effect is small, with the median absolute difference being about 2.25% of linear extent. Such differences are close to or below the Weber fraction for linear extent—see Laming (1986 Table 5.1) for a summary of Weber frac-tions—which probably explains what would otherwise be a difficult problem, that if one looks at the world first with only one eye open and then with the other eye open, there does not appear to be any obvious difference in the apparent size of the objects.

A possibility that must be considered seriously is that our results represent some form of artefact. The experimental design excludes many possibilities, but one that must be considered is a difference in refraction between the two eyes. If the two eyes have different refraction and they are uncorrected, then the same object will produce a smaller image on the retina of the eye with the greater refractive power. Although we did not make any specific attempts to control the refraction of our subjects, those who needed glasses or contact lenses wore them during the experiment. Perhaps the strongest argument against refraction being the explanation for our results is that although there is no doubt that refraction does differ between the two eyes in many subjects, there is no evidence of any systematic directional bias to one side, half the population having a stronger right eye and the other half having a stronger left eye, particularly in individuals who are properly corrected (Velasco e Cruz & Bicas, 1988). In our data there is a clear population-level asymmetry, objects looking larger in the left eye in most subjects, which could only be explained if refraction were systematically greater in the right eye, for which there is no evidence in other studies. Likewise, the clear correlation in our study between seeing an object as larger in the left eye and being right-handed, in particular writing with the right hand, is also extre-mely difficult to explain if the phenomenon is secondary to differences in refraction. Overall then, it seems unlikely that errors of refraction are respon-sible for the effect we have found. It would be desirable to confirm that in a better-controlled study, perhaps using artificial pin-hole pupils, etc., but it is unlikely that the basic phenomenon would disappear. Likewise, it would also be

desirable to indicate the findings using some more controlled form of psycho-physical procedure assessing thresholds using an adaptive procedure.

An alternative artefact is that there could be a small difference between the left and right eye channels in the tachistoscope. If this were of the order of 1–2% then it might explain the overall shift to the left of the distribution in Figure 3. Our binocular tachistoscope does not use crossed polaroids, and therefore it is not possible easily to reverse the channels of the tachistoscope. The only possibilities would involve inverting either the subject or the equipment, neither of which is very practical. It should be emphasised that even if the overall population bias were the result of an artefact in the two channels of the tachistoscope, and there were no systematic population-level difference between the two eyes, there would still be a phenomenon at the level of the individual that requires explanation, since subjects are significantly different from one another, some showing right eye effects and others left eye effects, and no systematic bias in the equipment can explain away such a difference. One possibility is that the two channels of the tachistoscope are not exactly equivalent. This was assessed directly by using a high-resolution (3.2 mega-pixel) digital camera mounted on a tripod to photograph the same stimulus, a piece of graph paper, through both channels of the tachistoscope. Comparison of the two images showed that the image in the left-hand channel was 0.32% larger in linear extent than that in the right-hand channel. That difference is only about one fifth of the average 1.5% difference in perceived difference in size between the two channels. We can therefore conclude that the differences found do not result from inadvertent asymmetries in the channels of our tachistoscope.

Although it might seem an eccentric idea that objects may look a different size in the two eyes, there is no reason in principle why that could not be the case. Ross (1997) has pointed out that there is no obvious relationship between the physical magnitude of a stimulus and its perceived magnitude. Ross has also reviewed a number of possible biases in the perceived magnitude of objects and notes, in particular (see 1997, p. 196) that early studies found that objects appeared larger in the upper than the lower part of the visual field, a finding also found in more recent studies (Bradshaw, Nettelton, Nathan, & Wilson, 1985; Drain & Reuter-Lorenz, 1996; McCourt & Olafson, 2003; Van Vugt, Fransen, Creten, & Paquier, 2000) and which our data also replicate. In 1834, Weber (see Ross & Murray, 1996) suggested that weights seemed heavier when pressed on to the left rather than the right hand, and speculated that this might be a result of a different density of receptors. The eyes show a complex distribution of photopic receptors, varying in terms of left and right visual half fields, upper and lower parts of the retina, and central versus peripheral receptors, all of which may modulate size perception. It is therefore not inconceivable that there could be receptor differences between the two eyes, and, for instance, differences have been found between the eyes and optic nerves on the two sides in their normal anatomy (Narang, 1977; Wang, 1927) and in their pathology (King, 1931).

An important result in our study is that because the stimuli were presented to right and left of the fixation point, it is possible to distinguish true eye effects from visual half-field differences. Although there have been many studies that have suggested differences between visual half-fields, and by implication cerebral hemispheres (Hellige, 1993, pp. 73–98), the effects reported in the present study (see Table 3) show clear evidence of a main effect of eye which is independent of any possible half-field differences. This raises many interesting questions about the possible locus of the effect, which seems unlikely to be related to traditional hemispheric differences, since each hemisphere is responsible for half the visual field of each eye. Nevertheless the individual differences we have found do suggest that hemispheric dominance may be involved in some way because of the association with handedness.

In previous studies of eye dominance we have confirmed the often found finding that eye dominance is related to handedness (Bourassa et al., 1996), and have found evidence that it is most strongly related to throwing hand rather than writing hand (McManus et al., 1999). Not only has the present study found no association between eye dominance and the eye effect, it has found evidence which suggests that the eye effect may be more strongly related to writing hand than to throwing hand. That provides additional support for the idea that eye dominance is nothing to do with the eye effect. Although the association of the eye effect with writing hand is statistically robust, and there is no evidence that the effect can be explained by any other correlates of handedness, such as writing hand positions, it is not at all clear in theoretical terms quite why or how handedness can be related to the eye effect.

Although the visual half-fields are generally thought to project to the contralateral half of the brain (e.g., right visual half-field or left hemi-retina to left hemisphere), that is only the case for geniculo-striate projections. McCourt, Garlinghouse, and Butler (2001) quote Posner and Rafal (1987, p. 199) that ''the collicular midbrain system is mainly crossed'', and projecting to the contra-lateral half of the brain. The result is that attentional signals to the right eye are driven by the left colliculus, and vice-versa. Posner and Rafal invoke the mechanism as an explanation of the effectiveness of right eye patching for the treatment of left-sided visual neglect after right-hemispheric strokes. A relationship of eye differences to neglect can also be found in normal subjects, McCourt et al. (2001) finding that pseudo-neglect is substantially greater in the left eye than the right. Other work suggests that retino-tectal projections are not quite as simple as Posner and Rafal suggest. There seems little doubt that in non-mammalian species the retina in each eye projects in its entirety to the contralateral tectum (the precursor of the mammalian superior colliculus) (Buser & Imbert, 1992, p. 323). However in fishes and reptiles the eyes are on the side of the head, the visual fields barely overlap, and it would make little sense to have a representation of each eye in each half of the tectum. The situation in mammals is more complex (Buser & Imbert, 1992), although there certainly

seem to be species, including the squirrel, the tree shrew, and the macaque monkey (Hubel, LeVay, & Wiesel, 1975; Lane, Allman, & Kaas, 1971) in which the projections are primarily crossed. Kaas, Harting, and Guillery (1974) have pointed out that Karl Lashley came to that same conclusion in the 1930s, and his work had been almost entirely ignored (Lashley, 1934). It does therefore seem possible that the phylogenetically ancient crossed projection from retina to tectum is still present, at least in part. However, it should be remembered that the mammalian colliculus also receives a large amount of its afferent projections from the ipsilateral cortex, and that the colliculi themselves also project to the ipsilateral cortex.

The possibility is therefore raised that pseudoneglect and the eye effect we have reported here are associated, and that the common mechanism for both is collicular. If that is the case then it might also be predicted that pseudoneglect would be reversed in a minority of subjects who write with their left hand. The meta-analysis of pseudoneglect by Jewell and McCourt (2000) found only two studies that had looked at the handedness of subjects. In one of these (Sampaio & Chokron, 1992) there was some evidence in the kinaesthetic scanning task of reversed pseudoneglect in left-handers. Clearly that study needs replication. It should also be emphasised that although handedness is generally regarded as a hemispheric phenomenon, that is not necessarily the case, and it is more than possible that it finds its origins as a turning tendency resulting from mid-brain or cerebellar processes (McManus & Cornish, 1997). A speculative mechanism for the current findings may be that they are driven by the superior colliculus, and that there is a general tendency within individuals for there to be a slightly higher level of dopamine or some other neurotransmitter on one side of the brain stem compared to the other. This would result in greater activity of that half, with the greater activity of colliculus making input to that eye seem larger, and the greater activity of the substantia nigra producing greater activity of the dominant hand.

Having raised the possibility that the projections from the retina to the colliculi are entirely crossed, it must be said that there are other studies that deny any such suggestion, in some cases (e.g., Perry & Cowey, 1984) suggesting that the collicular projections are entirely parallel to those of the projections to the cortex, splitting by half-field at the optic chiasm. A third possibility is also raised by the suggestion of Zackon, Casson, Stelmach, Faubert, and Racette (1997), explicitly in their Figure 1, that the collicular projections from the retina are entirely crossed but come only from the nasal half of the retina. The situation is therefore analogous to the nucleus of the optic tract, which receives input only from the nasal retina (and hence monocular optokinetic nystagmus is highly asymmetric). If this is correct, then such an anatomical arrangement allows one to make a very specific prediction. If the locus of the ''left-eye larger effect'' is the colliculi and projection is entirely from nasal hemi-retinae then the left–right difference should only be found for stimuli projected to the nasal hemi-retinae,

and should be absent when projected to the temporal hemi-retinae. It is a strong prediction but, unfortunately, as was seen in the results section, it is not supported by the data. If anything the effect is slightly larger for the temporal retina than the nasal retina.

To summarise, although the locus of the ''left-eye larger'' effect is far from clear, either empirically or theoretically, there seems little doubt of its existence, or of the robust finding that the effect is reversed in left-handers. It clearly requires some sort of explanation.

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