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# Is light in pictures presumed to come from the left side?

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**Abstract.** For good ecological reasons humans assume that the illumination in pictures comes from overhead rather than from below. Recent work has also raised the possibility that the preferred angle of illumination is between  $20^\circ$  and  $30^\circ$  to the left of vertical, although the ecological basis for that is obscure. We describe two studies of this question. In study 1, twenty subjects looked in free, unrestricted vision, at a picture of a single 'bubble' which appeared either convex if the illumination was from above, or concave if the illumination was from below. There was no evidence in study 1 that illumination from the left produced a different appearance from illumination from the right, the preferred angle of illumination being  $0.5^\circ$  to the right of vertical. In study 2, on forty subjects, there was fast presentation (200 ms) of an array of 16 bubbles, one of which, the target, was illuminated from the opposite direction to the others, and hence 'popped out' from the display, appearing concave if the others were convex, or vice-versa. The preferred angle of illumination for detection of the target was about  $14^\circ$  to the left of vertical in study 2. The estimates from studies 1 and 2 did not differ significantly, and when combined gave a preferred angle of  $9^\circ$  to the left of vertical. The reasons for the seeming discrepancy between studies 1 and 2, or the smaller overall effect than that found in previous studies are not clear since the methodologies seem equivalent. In both studies 1 and 2 there was a highly significant association between the direction of spontaneous head tilt and preferred direction of illumination, and this factor has not previously been taken into account in studies of the phenomenon. Contrary to the study of Sun and Perona (1998, *Nature Neuroscience* 1 183–184), there was no association with handedness or other measures of functional lateralisation.

## 1 Introduction

Illumination not only lights objects but it also creates shading and shadows. Light from a single point source, or a small number of extended sources produces shading of objects, those parts at a more oblique angle to the light source(s) appearing darker. Objects also create shadows, light from the source being prevented from reaching other areas by the interposition of the object itself, those other areas being either on the object (self-shading), or on background areas (cast shadows) (Baxandall 1995).

The representation of three-dimensional scenes in two-dimensional pictures, be they photographic or artistic representations (drawings, paintings, etc) or computer-generated images, is problematic because of a fundamental ambiguity whereby many different three-dimensional objects could in principle be responsible for the particular two-dimensional pattern of light and shade in an image (and this is the basis for many visual illusions). Shadows and shading can help to reduce the ambiguity of images (Gombrich 1960), and have been much exploited by Western artists [for overviews see Gombrich (1995), Stoichita (1997), and Casati (2003)].

On the surface of Earth the most common source of illumination is the Sun, and geometry constrains the light source to be from above, except in unusual circumstances, such as at sunset on a mountain top, or when light is reflected from water. This ecological constraint appears to be exploited by the visual system, so that, if three-dimensional objects are illuminated from below rather than above, concave appears convex, and vice-versa (Gibson 1950; Rock 1983). Detailed analysis of this phenomenon shows that the presumption applies not to gravitational coordinates but

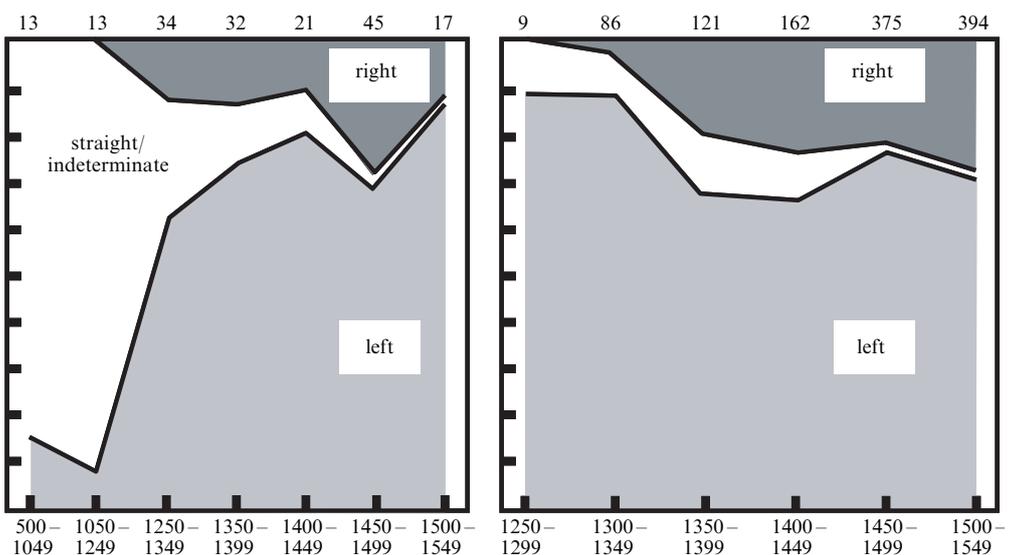
to retinal coordinates, so that rotation of the head alters the apparent concavity or convexity of objects (Ramachandran 1988a, 1988b).

As well as light being presumed to come from above, there is also a suggestion in the literature that light is assumed to come from above and to the left. That claim is far more controversial, and has few obvious ecological arguments in its favour, since, as Mamassian and Goutcher (2001) point out, “it is ... counter-intuitive to believe that human beings would spend more time with the light source on their left rather than on their right”, an observer on the surface of the Earth who can look in any direction being as likely to have light coming from their right as from their left.

Perhaps the most prominent source of the idea that light might come from the left is Sir Ernst Gombrich, who commented in his *Art and Illusion* that:

“Psychologists have found that in the absence of other clues, Western observers have settled for the probability that the light falls from high up and from the left-hand side. It is the position most convenient for drawings and writing with the right hand, and it therefore applies to most paintings.” (Gombrich 1960, page 229)

Gombrich’s argument suggests that the bias is found mainly in works of art, and is secondary to the handedness of the artist, since, like most other people, artists are mostly right-handed (Lanthyony 1995). As a result, light from the left provides the clearest view of the working surface, whereas light from the right causes the right hand to cast a shadow over the paper or canvas. Certainly, there seems little doubt that paintings in the Western tradition usually show light coming from the left side. Figure 1 shows data from Byzantine and Italian Renaissance paintings (McManus 1979), and a similar effect was found in a more general selection of paintings by Sun and Perona (1998).



**Figure 1.** Proportions of Byzantine and Italian Renaissance paintings of the Crucifixion (left) and Madonna and Child (right) with light from the right or the left, according to the date of production. Numbers along the top indicate the sample size. Further details are available in McManus (1979).

Even if artists do consistently paint light in pictures as coming from the left side, that may be secondary to motor asymmetries, rather than resulting from any perceptual tendency to assume that light from the left is more likely than is light from the right. However, in the endnotes to *Art and Illusion*, Gombrich cites Wolfgang Metzger’s *Gesetze des Sehens* (1953). Metzger provided an interesting demonstration which suggests that

light from the left and right are not equivalent. Figure 2 (figure 438 in Metzger) shows a photograph of a fossil ammonite, the top left image showing the original photograph. The top right image is Metzger's left–right reversal of the original photograph, and it seems that the depth has been reversed, the convexities in the original appearing as concavities, and vice-versa. Since left–right reversal alters only the left–right direction

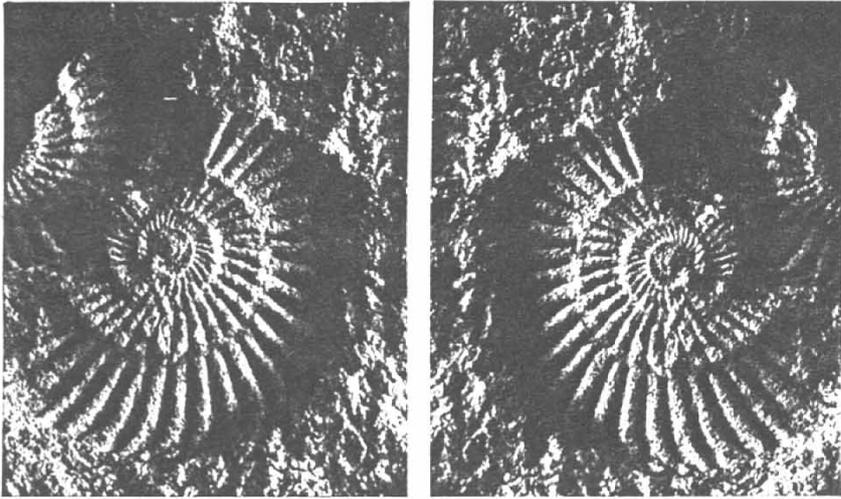


Bild 438. Zweimal dieselbe Aufnahme des Abdrucks von einem Ammonshorn (*Parkinsonia spec.*, brauner Jura), rechts: richtig abgezogen, links: rechts-links-verkehrt abgezogen; so hat der Lichtbildner — absichtlich — erreicht, daß das Bild links wie der Steinkern zu dem Abdruck rechts aussieht; besonders zwingend, wenn man den rechten Rand nach unten nimmt. (Photo HUT, Basel [Leica]; von Priv.-Doz. Dr. RITTMANN, Basel, freundlichst zur Verfügung gestellt.)

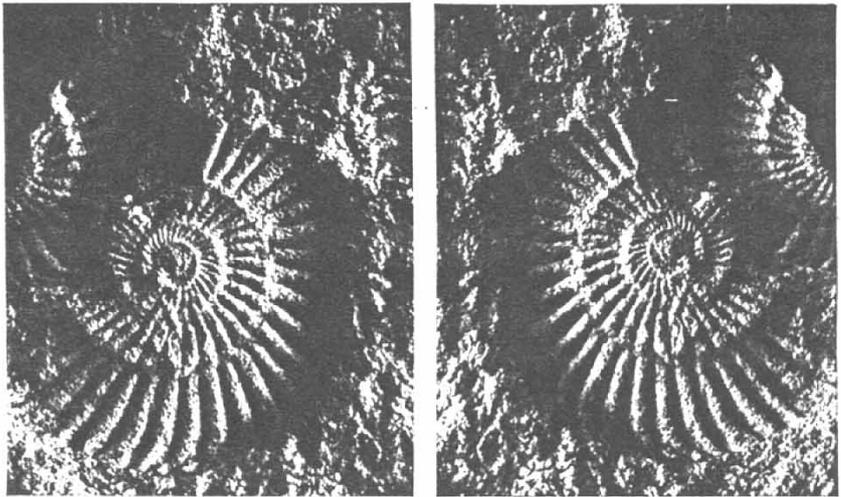


Bild 438. Zweimal dieselbe Aufnahme des Abdrucks von einem Ammonshorn (*Parkinsonia spec.*, brauner Jura), rechts: richtig abgezogen, links: rechts-links-verkehrt abgezogen; so hat der Lichtbildner — absichtlich — erreicht, daß das Bild links wie der Steinkern zu dem Abdruck rechts aussieht; besonders zwingend, wenn man den rechten Rand nach unten nimmt. (Photo HUT, Basel [Leica]; von Priv.-Doz. Dr. RITTMANN, Basel, freundlichst zur Verfügung gestellt.)

**Figure 2.** Metzger's illustration of the different effect of light from the left or the right. See text for details.

of the light, the implication has to be that light from the left is not equivalent perceptually to light from the right.

Although Metzger assures us that the top right image in figure 2 has only been left–right reversed, it is nevertheless possible that some other minor differences have been introduced. That hypothesis can, however, be rejected, since the lower part of figure 2 shows Metzger's figure 438 left–right reversed in its entirety (as seen in the mirror-inverted text). Still the image on the left has reversed depth compared with that on the right.

In late 1997, two of us (JB and ICM) were interested in whether light from the left and right sides was perceptually equivalent, and we carried out the experiment described below as study 1, in which observers reported whether a single hemispherical 'bubble' viewed in free vision appeared concave or convex. After study 1 was completed, but not submitted for publication, Sun and Perona (1998) published an experiment in which they claimed that light was presumed to come from the left. The Sun and Perona study used a 'pop-out' technique in which the observer viewed an array of hemispherical bubbles in which on half the occasions there was a target with the opposite concavity. Subsequently Mamassian et al published a series of studies in which they also found that light was preferentially assumed to be coming from the left side of an image (Mamassian and Goutcher 2001; Mamassian and Landy 2001; see also Bacon and Mamassian 2002). The experimental method used in these experiments is more similar to that of our study 1, observers reporting as concave or convex a single target consisting of alternating black and white wavy lines. In view of the discrepancies between our study 1 and the studies of Sun and Perona and of Mamassian et al, we therefore carried out study 2 in which a pop-out technique was used, with subjects searching for a single target in reversed depth in an array of bubbles.

Sun and Perona used stimuli with a fast presentation time, and in the discussion of their paper also noted that "quantitative measurements of the perception of shape from shading using static displays have revealed no asymmetry between left- and right-lighting conditions", citing two papers in support of the latter finding (Bülthoff and Mallot 1988; Todd et al 1996). Similar findings of no left–right differences in illumination can be found in the studies of Tarr et al (1998), and Langer and Bülthoff (2000). Sun and Perona inferred that "the preference for left lighting we observe with our fast presentation paradigm is confined to the earlier stages of visual processing, and that this effect may become negligible under ecological viewing conditions". They then, however, contradicted their own hypothesis and suggested that a left-lighting preference may be responsible for the predominance of left-sided light in art, which they say is unlikely to result from "accidental artistic convention" as it is "found across schools and periods". However, the viewing of paintings is surely "under ecological viewing conditions", and therefore is with unrestricted time.

Irrespective of the validity of Sun and Perona's argument on light in paintings (which also seems to take no note of the predominant right-handedness of artists), Sun and Perona in their experiment did use a fast presentation, as did Mamassian et al, whereas in our study 1 we used free viewing. In study 2 we therefore used slow (1 s), medium (500 ms), and fast (200 ms) presentation.

Sun and Perona also looked at individual differences in their twelve subjects, and found a very strong correlation (0.83) between extent of right-handedness and a preference for light being presumed to come from the left, which they explained in terms of "left-handers [living] in a right-handers' world and [being] often forced to function in environments that are designed for right-handers". Mamassian and Goutcher (2001) speculated that observers might "consistently orient their body relative to the light source while manipulating an object" and that "if this explanation holds, there should be a relationship between handedness and the strength of the illumination position bias".

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However, in their data they found no relationship between handedness and a preference for light from the left. If the presumption of light from the left does relate to individual lateralisation, then that would constrain the possible interpretations of the phenomenon, and the question therefore needs investigating further.

Humans show many different lateralisations, not all of which are related to handedness [for a general overview, see McManus (2002)]. In our study 2 we have looked at detailed measures of handedness and eye dominance, and in particular in both studies 1 and 2 we have looked at spontaneous head tilt. Although to a first approximation the head of most individuals appears to be upright, with the eyes on a horizontal axis, in practice most people show a consistent spontaneous head tilt, one eye being higher than the other (Greenberg 1960; Previc 1994; Putnam et al 1996), in part because of the well-known asymmetries of the legs, pelvis, and spinal column on which the skull is perched (Gaupp 1909; Ludwig 1932). That has potential implications for the interpretation of shading, not least because of Ramachandran's findings that the assumption of light coming from above depends on retinal rather than gravitational coordinates. It also potentially affects binocular vision, since it introduces a vertical disparity between the eyes.

## 2 Study 1

### 2.1 Method

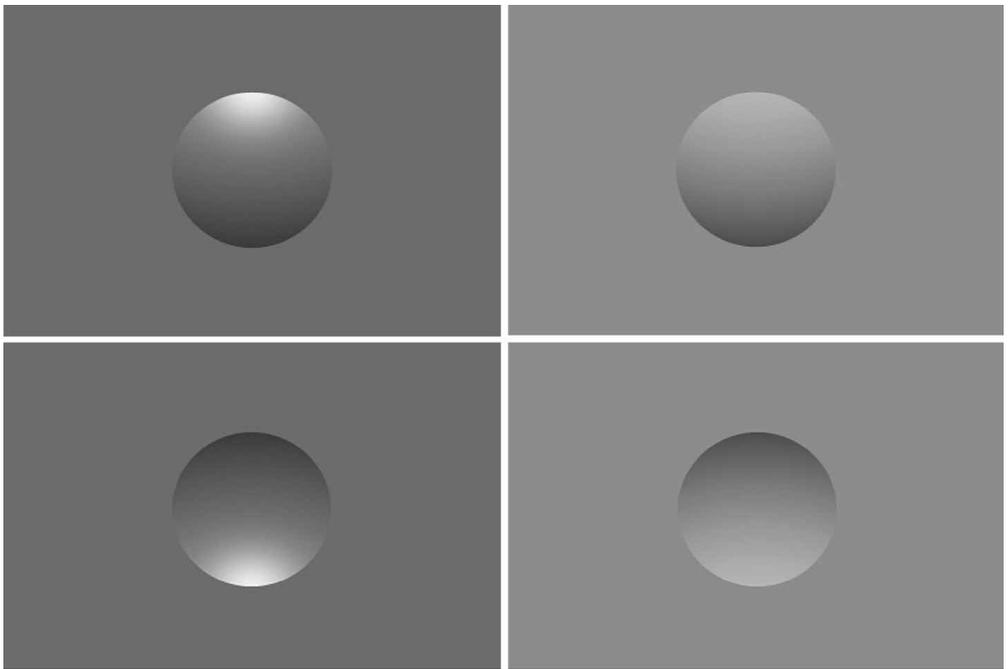
2.1.1 *Subjects.* Twenty subjects (twelve male, eight female) took part in the experiment, all of whom were psychology undergraduates at University College London. None was aware of the purpose of the study. All but two subjects were right-handed. Ages ranged from 19 to 49 years (mean, 22.5 years).

2.1.2 *Apparatus.* Stimuli were presented to subjects on a personal computer in purpose-built experimental cubicles, in which a 20 W bulb provided dim background lighting. The computer display was viewed at a distance of 1.6 m. No head fixation was provided.

2.1.3 *Stimuli.* The stimuli consisted of a set of concave and convex 'bubbles'. Each was created with the use of Microstation 95, which runs on Macintosh computers and is used by architects and has a sophisticated lighting model. Each stimulus consisted of a white sphere in front of a grey vertical wall, illuminated by a point source simulating the Sun. Two versions of the stimuli were created, one with high reflectiveness in which there were specular highlights, and the other with low reflectiveness, in which there were no specular highlights (see figure 3). There were no cast shadows. Stimuli were presented with the illumination source at angles of  $0^\circ$ ,  $22.5^\circ$ ,  $45^\circ$ ,  $67.5^\circ$ ,  $90^\circ$ ,  $112.5^\circ$ ,  $135^\circ$ ,  $157.5^\circ$ ,  $180^\circ$ ,  $-22.5^\circ$ ,  $-45^\circ$ ,  $-67.5^\circ$ ,  $-90^\circ$ ,  $-112.5^\circ$ ,  $-135^\circ$ , and  $-157.5^\circ$  to the vertical,  $0^\circ$  indicating directly above, and positive angles indicating light from the left [as in Sun and Perona (1998)]. The visual angle subtended by each bubble was 1 deg.

2.1.4 *Procedure.* On each trial the subjects were shown a single stimulus, and were asked to indicate, by pressing one of two keys on a computer keyboard, whether it appeared to be concave or convex ('in' or 'out'). Stimulus presentation was controlled by the program MEL 2.01 running on the PC. Subjects worked at their own speed, although they were asked to work as quickly as possible. Subjects were allowed to scan around the stimuli visually if they wished. Reaction times were recorded. Stimuli for each subject were presented in a  $16 \times 2$  design, in which there were 16 light orientations and 2 stimulus types (specular versus non-specular), with 8 eight replications in each condition, so that each subject carried out 128 trials. Subjects were also given 10 practice trials before the experiment proper in order to familiarise themselves with the apparatus.

2.1.5 *Background measures.* Handedness was assessed by self-report as right or left. Eye dominance was assessed with a monocular symmetrical assessment (Bourassa et al 1996),



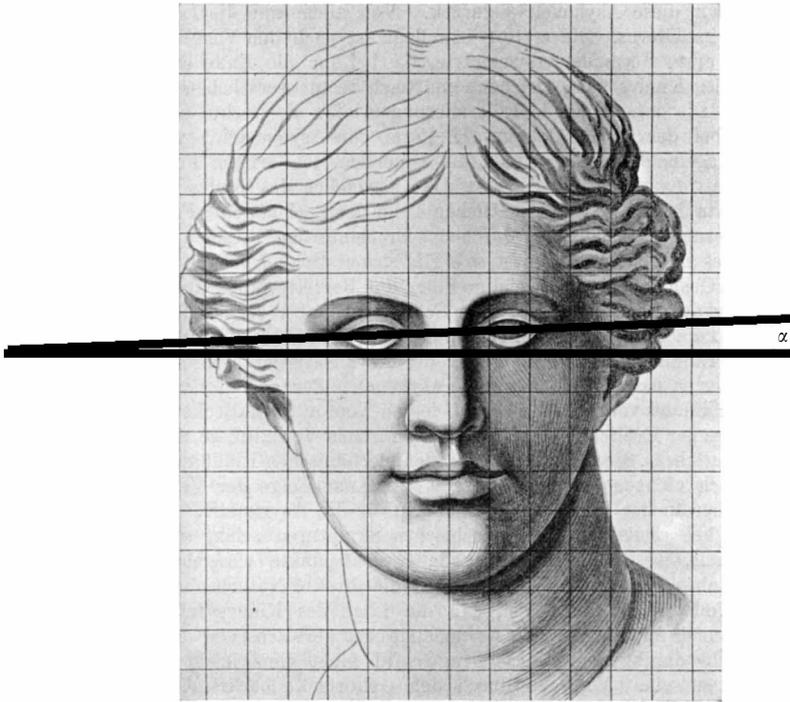
**Figure 3.** The stimuli in study 1. The upper bubbles are illuminated from above and should appear convex in a normal reading position, whereas the lower bubbles are illuminated from below and should normally appear concave. Stimuli for other illumination angles were created by rotating the bubbles in these stimuli, and can be visualised by rotating the page. On each experimental trial a subject saw only a single bubble. Specular bubbles with high reflectance are shown to the left and non-specular bubbles with low reflectance to the right.

in which the subject held a narrow cardboard tube with both arms outstretched in front of her/him and then brought the tube to the eye, reporting what could be seen on a tiny piece of translucent paper pasted at the end of the tube. The eye used for looking was recorded by the experimenter. Spontaneous head tilt was assessed by photographing subjects while they stood upright against a wall on which was placed a grid of vertical and horizontal lines. Tilt was measured by drawing a line through the centres of the two eyes, and calculating its angle with the horizontal background lines (Previc 1994)—see figure 4 for an example, based on the illustration of the Venus de Milo in Gaupp (1909).

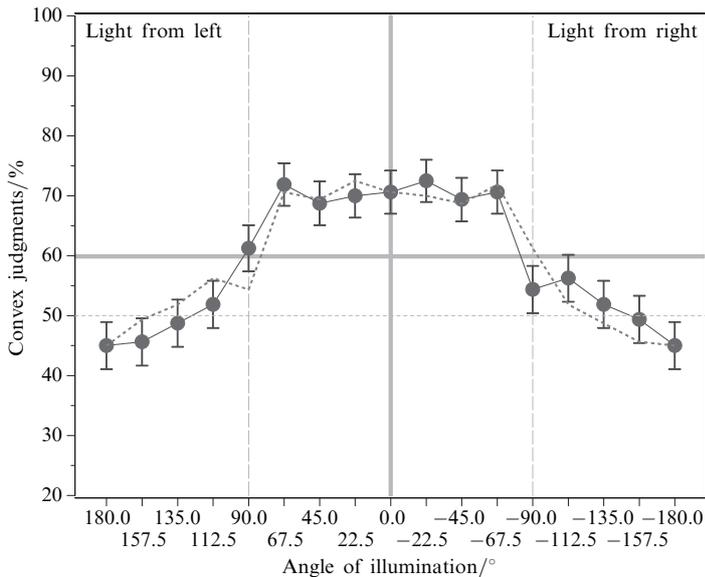
## 2.2 Results

Overall the twenty subjects made a total of 2560 judgments. Mean reaction time was 2068 ms (SD = 2393 ms), with a significant trend on trial number ( $p < 0.001$ ), the first 10 stimuli having a mean reaction time of 3157 ms, compared with 1256 ms for the last 10 stimuli. Despite the experiment being entirely balanced, 59.9% of judgments overall were 'convex' and only 40.1% were concave; this bias towards reporting bubbles to appear convex has been reported elsewhere (Woodworth and Schlosberg 1954; Bacon and Mamassian 2002).

Figure 5 shows the percentage of convex judgments in relation to the orientation of the light. The data were modelled with a cosine wave,  $p(\text{convex}) = k + A \cos(\theta - \phi)$ , where  $p(\text{convex})$  is the probability of a convex judgment,  $A$  is the amplitude of the cosine wave,  $\theta$  is the angle of the illumination,  $\phi$  is the phase of the cosine wave, and  $k$  is a fixed constant representing the bias towards reporting convex rather than concave.



**Figure 4.** Measurement of head tilt. A line is drawn between the centre of the two eyes and the angle of head tilt calculated as the angle made against the background lines, which are aligned with gravitational vertical and horizontal. When  $\alpha$  is positive, as here, the head is tilted to the subject's right. The original drawing is from Gaupp (1909).

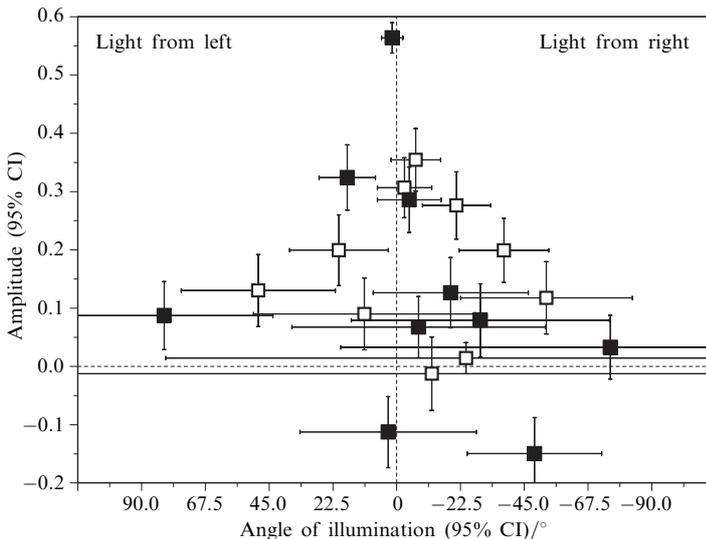


**Figure 5.** The overall percentage of convex judgments made by subjects in relation to the angle of illumination of the bubble. For clarity, the 180° data have been plotted twice, once at each end. The data are plotted as solid points with error bars, joined by a solid line. The dashed line with the data is the line of the data mirror-reflected around zero, so that the symmetry of the data can be assessed. The vertical lines are plotted at 90°, 0°, and -90°. The dashed horizontal line represents equal numbers of concave and convex judgments, and the solid horizontal line shows the average proportion of convex judgments (which is greater than 50%).

The constant alone accounted for 59.88% of the variance (model SS = 918.00352; total SS = 1533).<sup>(1)</sup> Adding in the cosine wave with  $\phi = 0$  (ie the peak at  $0^\circ$ ) increased the explained variance to 61.44% (model SS = 941.84429), a significant increase ( $F_{1,2560} = 99.2$ ,  $p < 0.001$ ). Fitting a model in which  $\phi \neq 0$  (ie the peak is at some non-zero position) increased the accounted variance by only 0.0000014% (model SS = 941.84652) which is non-significant ( $F_{1,2557} = 0.0096$ , ns). The fitted value of the phase parameter,  $\phi$ , is  $-0.554^\circ$  (95% CI =  $-11.61^\circ$  to  $+10.51^\circ$ ).<sup>(1)</sup>

Individual differences in spontaneous head tilt were assessed in relation to whether overall the head was tilted to the right or the left. For the ten subjects with right head tilt, the estimate of  $\phi$  was  $-7.14^\circ$  (95% CI =  $-21.05^\circ$  to  $+6.77^\circ$ ), whereas for the ten subjects with left head tilt the estimate of  $\phi$  was  $7.52^\circ$  (95% CI =  $-9.93^\circ$  to  $+25.06^\circ$ ). Fitting a single model to all the data, and using an additional parameter for right or left tilt, gave an estimate of the difference in  $\phi$  between left and right tilters of  $14.70^\circ$  (95% CI =  $-7.24^\circ$  to  $+36.64^\circ$ ).

As well as modelling the entire data set, the responses of the individual subjects were also modelled with the function  $p(\text{convex}) = k + A \cos(\theta - \phi)$ , with  $A$  and  $\phi$  estimated for each subject. Figure 6 shows the estimates of  $A$  and  $\phi$ , along with their standard errors. There is a clear difference in overall effect between subjects, some showing a value of  $A$  which does not differ significantly from zero. The estimated values of  $\phi$  also differ from one another, but the standard errors are wide, particularly when the estimates of  $A$  are low (and the standard errors of  $A$  are high). No individual estimate of  $\phi$  is more than two standard errors from an illumination angle of zero.



**Figure 6.** Results for the twenty individual subjects in study 1. A cosine curve was fitted separately for each subject. The abscissa shows the phase of the best-fitting curve, and the ordinate shows the amplitude of the best-fitting curve. Error bars show one standard error either side of the estimates for phase and amplitude. Subjects with a spontaneous head tilt to the right are shown as open squares, and subjects with a head tilt to the left are shown as solid squares. The vertical dashed line shows a phase of zero (ie preferential light direction from directly overhead), and the horizontal dashed line shows an amplitude of zero (ie no evidence of a preferential lighting direction).

<sup>(1)</sup> SD = standard deviation, SS = sum of squares, CI = confidence interval, ns = non-significant.

### 2.3 Discussion

Overall, in study 1 we found no evidence that the preferred direction of light is shifted significantly to the left, the 95% confidence interval for the preferred direction of illumination not differing significantly from zero. Furthermore, the confidence interval does not include the value of  $23.3^\circ$  reported by Sun and Perona for their right-handed subjects nor the  $21.8^\circ$  which would be expected for our 9 : 1 mixture of right-handed and left-handed subjects. Likewise, the confidence interval does not include the mean illumination angles of  $24^\circ$  and  $28.8^\circ$  reported by Mamassian and Goutcher (2001) for left-handed and right-handed observers, respectively.

We did find a trend in study 1 whereby subjects who spontaneously tilted their heads to the right had a negative preferred illumination angle, with a reverse effect for those who tilted their heads to the left. However, the difference was not significant. Nevertheless, the effects are as expected if retinal rather than gravitational vertical determines convexity judgments, and head tilt is also occurring during the experiment. It should be emphasised once again that we did not control head tilt experimentally in the study, and neither was it monitored during the experiment.

Overall our study 1 revealed no tendency for light to be assumed to be coming from the left, in contradiction to other studies. An important difference in our methodology is that the stimuli were presented in free vision, whereas Sun and Perona used an adaptive procedure with typical presentation times between 20 and 450 ms, and Mamassian and Goutcher (2001) presented stimuli for 120 ms. We therefore ran study 2 using fast presentations (200 ms), and also using a similar 'pop-out' design to that used by Sun and Perona.

## 3 Study 2

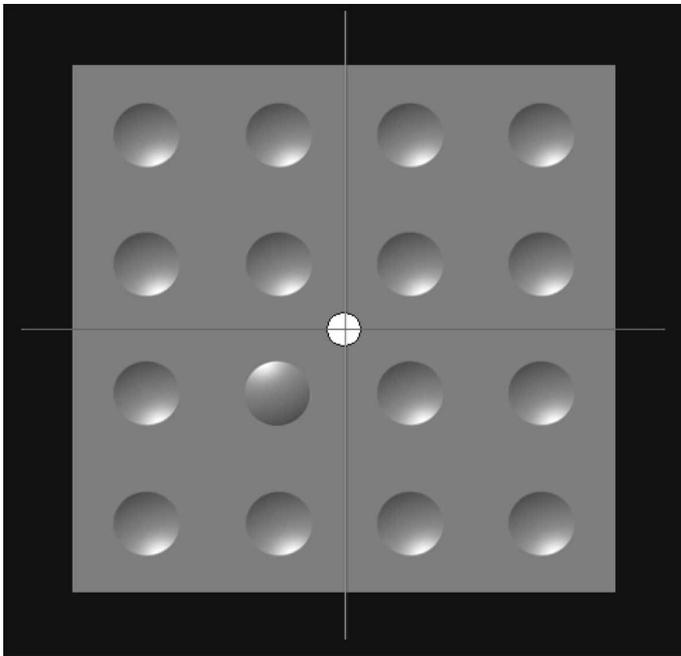
### 3.1 Method

3.1.1 *Subjects.* Forty subjects participated in the experiment, seventeen male and twenty-three female. All were undergraduates at University College London. Four of the subjects (10%) were left-handed for writing (see below).

3.1.2 *Apparatus.* Subjects were tested in groups of five to ten subjects in a lecture theatre, with stimuli presented on a screen by means of a video projector which was controlled by the program PowerPoint. Room illumination was dimmed so that the screen could be seen clearly, and response sheets were still visible. Subjects sat comfortably in a normal position without head fixation. Not all subjects were exactly orthogonal to the screen, but position of the subjects was recorded for subsequent analysis. Subjects were seated an average distance of 4.24 m from the screen ( $SD = 0.62$  m). The lecture theatre was underground and had no windows; no doors were visible to a subject seated looking at the screen, and to all intents and purposes the lecture theatre was symmetric.

3.1.3 *Stimuli.* The stimulus display consisted of 16 'bubbles' arranged in a  $4 \times 4$  array, with a fixation point at the centre of the display (see figure 7). The bubbles were the same as the specular bubbles used in study 1, and as in study 1 were presented with the illumination source at angles of  $0^\circ$ ,  $22.5^\circ$ ,  $45^\circ$ ,  $67.5^\circ$ ,  $90^\circ$ ,  $112.5^\circ$ ,  $135^\circ$ ,  $157.5^\circ$ ,  $180^\circ$ ,  $-22.5^\circ$ ,  $-45^\circ$ ,  $-67.5^\circ$ ,  $-90^\circ$ ,  $-112.5^\circ$ ,  $-135^\circ$ , and  $-157.5^\circ$  to the vertical,  $0^\circ$  indicating directly above, and positive angles indicating light from the left [as in Sun and Perona (1998)]. On average, the bubbles subtended a visual angle of 1.06 deg ( $SD = 0.16$  deg), and the matrix of bubbles in the display subtended a visual angle of 7.43 deg ( $SD = 1.14$  deg). We have followed the convention of Sun and Perona that the angle of illumination corresponds to that of the background bubbles rather than the target.

3.1.4 *Procedure.* On each trial the subjects were presented with a single  $4 \times 4$  array in which there was always one target bubble which had an illumination at  $180^\circ$  to the



**Figure 7.** Stimulus display in study 2. The background bubbles are illuminated at an angle of  $-157.5^\circ$ , and the target, which is in the inner part of the left lower quadrant, is illuminated at an angle of  $+22.5^\circ$ .

other bubbles, and as a result appeared to be convex if the other bubbles were concave, or vice-versa. The position of the target was always at one of the 8 positions on the two diagonals, and the subjects' task was to say in which quadrant the target had appeared. Subjects made their responses on a pencil-and-paper response sheet marked with squares corresponding to the four quadrants.

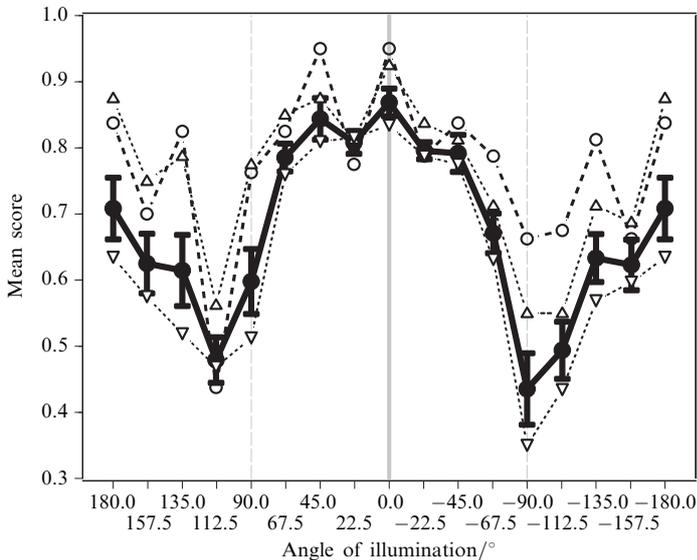
The onset of the target was preceded by the appearance of the fixation point on its own for 1 s, followed by a 1 s presentation of the fixation point with the cross delineating the quadrants. The display with the target was followed by 1 s mask consisting of a dark-grey and light-grey checkerboard pattern of similar contrast to the target display.

The experiment was divided into three parts. In parts A and B each subject carried out 32 trials, and in part C each subject carried out 128 trials. In part A the target was presented for 1 s, in part B the target was presented for about 500 ms, and in part C the target was presented for about 200 ms, the timing being determined by the 'medium' and 'fast' presentations of PowerPoint. Part C consisted of a completely randomised design in which each of the 8 target positions was presented at the 16 different angles of illumination, whereas parts A and B consisted of random subsets of target positions equally dispersed across the 16 illumination angles. Subjects carried out parts A and B first, to some extent as a training and preparation for the more difficult stimuli presented in part C.

**3.1.5 Background measures.** After completion of the experiment proper, subjects completed a handedness questionnaire consisting of questions on hand preference and lateralisation, including eye dominance, some of which were written, and others were photographic for assessing more complex lateralised tasks (McManus and Drury 2004). After completion of the questionnaire, the spontaneous head tilt of subjects was assessed by photographing them against an array of horizontal and vertical lines, with tilt assessed as in study 1 (Previc 1994).

### 3.2 Results

The forty subjects made 7680 judgments overall, 1280 in part A, 1280 in part B, and 5120 in part C. Responses were scored +1 if the subject identified the correct quadrant, 0 if they identified only the correct half (top/bottom or left/right) in which the target was to be found, and -1 if their response was diametrically opposite to the target quadrant. The average score was therefore +1 if subjects could carry out the task perfectly, and 0 if the subjects were scoring at random. Figure 8 shows performance in parts A, B, and C according to the angle of illumination. Error bars are only provided for the overall results in order to avoid the figure becoming too complicated, and since they are wider for parts A and B owing to the sample size being smaller.



**Figure 8.** Responses in study 2 by the angle of illumination of the distractors. The thick line with solid circles and error bars is the mean score for all judgments (blocks A, B, and C). The open circles are the data for block A, the open upright triangles are the data for block B, and the open inverted triangles are the data for block C.

The analysis of the data is slightly different from that in study 1, in which illumination at one orientation will provide a maximum perception of convexity, and illumination  $180^\circ$  from that maximum will provide a maximum sense of concavity. In study 2, where a target is being searched for, the minimum detection rate will be when the direction of illumination is  $90^\circ$  either side of the maximum, with a high target detection rate when the direction of illumination is  $180^\circ$  from the maximum. The data were therefore modelled by using a mixture of two cosine waves, in which  $S = k + A_1 \cos(\theta - \phi) + A_2 \cos[2(\theta - \phi)]$ , where  $S$  is the mean score on the task,  $\theta$  is the angle of the illumination,  $\phi$  is the phase of the cosine waves, and  $A_1$  and  $A_2$  are the amplitudes of the fundamental and the second harmonic. Of greatest interest here is the parameter  $\phi$ , and whether its confidence interval includes zero. The equations were fitted by using the NLR (nonlinear regression) program in SPSS (Statistical Package for the Social Sciences, v11.5).

Table 1 shows the estimated parameters overall, and for the three separate parts of study 2.  $A_2$ , which is always positive and significantly different from zero, represents the main effect of the experiment, and indicates that the minimum and the maximum target detections are separated by  $90^\circ$  (ie they are dependent on the second harmonic). However,  $A_1$ , the first harmonic, is also significantly different from zero, which indicates that targets are better detected when the distractors are illuminated from above ( $0^\circ$ ),

**Table 1.** Fitted parameters for the equation  $S = k + A_1 \cos(\theta - \phi) + A_2 \cos[2(\theta - \phi)]$ , in parts A, B, and C of study 2, and for study 2 as a whole.

	Estimate (standard error)			
	$k$	$A_1$	$A_2$	$\phi/^\circ$
Part A	0.7679 (0.0213)	0.0726 (0.0302)	0.0688 (0.0302)	13.56 (17.32)
Part B	0.7547 (0.0166)	0.0848 (0.0234)	0.0908 (0.0234)	19.66 (10.82)
Part C	0.6295 (0.0114)	0.1470 (0.0161)	0.1205 (0.0161)	13.43 (4.867)
All data from study 2	0.6734 (0.0100)	0.1237 (0.0142)	0.1073 (0.0142)	14.39 (4.95)

rather than from below ( $180^\circ$ ) (ie when the target appears concave and the background convex, rather than vice-versa); this is presumably the equivalent of the predominance of convex over concave judgments in study 1.

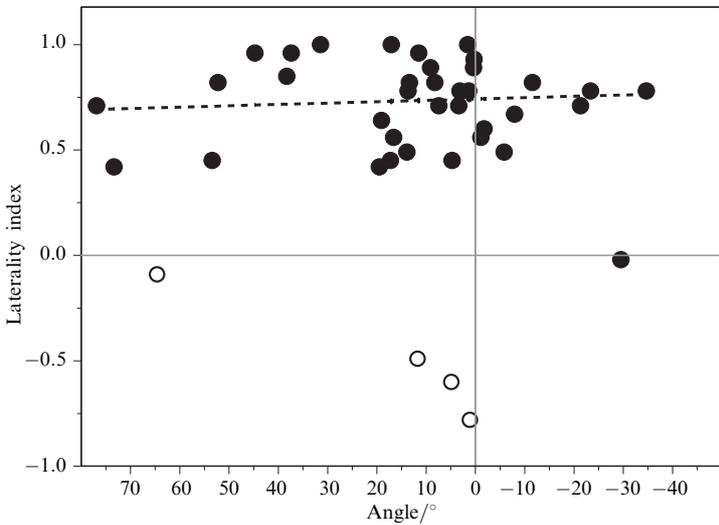
Overall the estimated optimal phase angle is  $+14.39^\circ$ , with a 95% confidence interval of  $+4.62^\circ$  to  $+24.17^\circ$ . The effect is very similar in parts A, B, and C, despite A using slow presentation, B medium, and C fast.

**3.2.1 Individual differences.** Data were modelled for each subject individually by using the equation  $S = k + A_1 \cos(\theta - \phi) + A_2 \cos[2(\theta - \phi)]$ . Estimates of  $A_2$  had a mean of 0.120 (SD = 0.113, range =  $-0.162$  to  $+0.442$ ), and the estimate was more than twice its standard error in sixteen subjects, all of whom had positive values. Estimates of  $A_1$  had a mean of 0.313 (SD = 0.930, range =  $-0.562$  to  $+5.92$ ), and the estimate was more than twice its standard error in twenty-one subjects, all but one of whom had positive estimates. Together, these data demonstrate that many subjects individually showed significant differences in relation to the orientation of the illumination, and many also showed a significant difference between illumination from above and illumination from below.

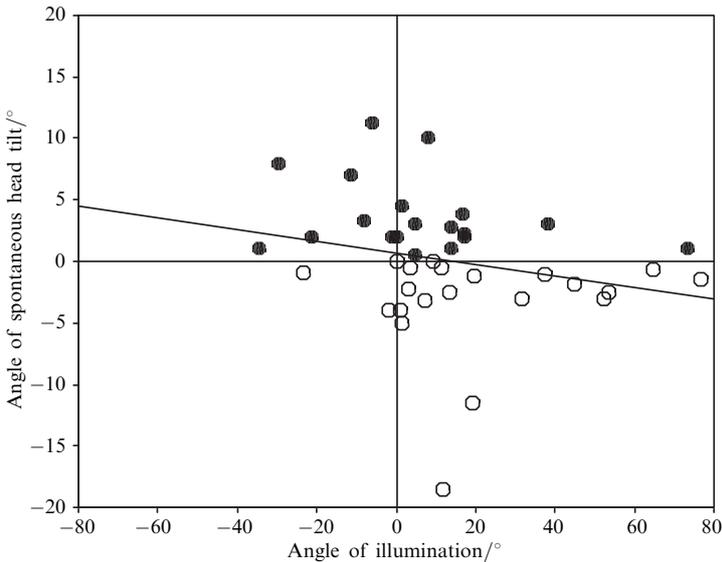
Estimates of  $\phi$  had a mean of  $13.37^\circ$  (SD =  $25.71^\circ$ , range =  $-34.66^\circ$  to  $+76.87^\circ$ ), with eight subjects having an estimate more than twice the standard error, six having positive estimates and two having negative estimates.

Estimated phase angles were used as the dependent variable to assess their relationship to individual measures of laterality. In the first instance, a forward entry multiple regression was used to assess whether any of the 34 individual measures of handedness, footedness, or eye dominance predicted  $\phi$ . Four variables entered the analysis when  $p$  was set at 0.05, with the most significant achieving a significance of only  $p = 0.039$ . A Bonferroni correction to allow for alpha inflation would require a  $p$  value of  $0.05/34 = 0.0015$ , and hence none of the associations can be regarded as significant. In particular, it should be noted that there was no significant difference between those with right-eye or left-eye dominance ( $t$ -test,  $p = 0.762$ ). A conventional laterality index was also calculated on the basis of eleven questionnaire measures of handedness. Figure 9 shows there is no relationship with phase angle ( $r = 0.019$ ,  $p = 0.906$ ).

Nineteen subjects spontaneously tilted their head to the left, nineteen to the right, and two showed no head tilt on the photographic measure. The mean absolute (unsigned) degree of tilt was  $3.5^\circ$  (SD =  $3.75^\circ$ , range =  $0^\circ$  to  $18.6^\circ$ ). There was a highly significant correlation between signed head tilt and  $\phi$  ( $r = 0.684$ ,  $p < 0.001$ ; see figure 10). If we ignore the two subjects with zero head tilt, the mean value of  $\phi$  was  $22.5^\circ$  (SD =  $26.09^\circ$ ) for subjects spontaneously tilting their head to the left, and



**Figure 9.** Relationship between phase angle and degree of lateralisation in study 2. A laterality index of +1 indicates strong right-handedness, and a laterality index of -1 indicates strong left-handedness. Subjects using the right hand for writing are shown as solid points, and those using the left hand for writing as open points. The dashed line shows the regression through all the points.



**Figure 10.** Relationship between phase angle (abscissa) and degree of spontaneous head tilt (ordinate) in study 2. Subjects tilting to the right are indicated with solid points, and those tilting to the left with open points. The solid line shows the regression through all the points.

5.14° (SD = 24.11°) for subjects tilting their head to the right ( $t_{36} = 2.129$ ,  $p = 0.040$ ). The difference in  $\phi$  between right tilters and left tilters was 17.35° (standard error = 8.15°; 95% CI = 0.83° to 33.88°).

The forty subjects were not seated exactly orthogonally to the screen, and we therefore recorded their distance from the screen and the angle they made with the screen. There was no correlation of  $\phi$  with angle or distance from the screen ( $r_{40} = -0.045$ ,  $p = 0.782$ ;  $r_{40} = -0.081$ ,  $p = 0.617$ , respectively). Neither was there a correlation between angle of spontaneous head tilt and seating angle to the screen.

#### 4 General discussion

In contrast to study 1, in study 2 we did find a statistically significant tendency for light to be presumed to come from the left rather than the right. However, the mean effect in study 2 of  $14.39^\circ$  is somewhat less than that reported by Sun and Perona, or by Mamassian and Goutcher; however, the 95% confidence intervals do include their values of between about  $21^\circ$  and  $29^\circ$ . The estimates derived from study 1 and study 2 can be readily combined by using calculations derived from the basic *t*-test. The estimates from study 1 and study 2 are not significantly different ( $t_{58} = 1.84$ , ns), and a combined estimate, weighted by sample size, is  $9.4^\circ$ , which is between a third and a half the size of that described by Sun and Perona and by Mamassian and Goutcher. The 95% confidence interval is about  $1.8^\circ$  to  $17.0^\circ$ , and therefore does not include zero but also does not include the Sun and Perona or Mamassian and Goutcher effects.

In study 1 we used only unlimited presentation time, whereas in study 2 we used fast (200 ms), medium (500 ms), and slow (1 s) presentations, but in study 2 it was clear that there were no differences in effect size in relation to the rate of presentation. The data therefore provide no support for Sun and Perona's suggestion that a bias to the left is only found in fast presentations. Differences in speed of presentation are therefore unlikely to account for the differences between studies (although we accept that precision of timing in PowerPoint is less accurate than with other presentation methods, and our stimuli are still a little slower than those of Sun and Perona).

Our study 2 was similar to that of Sun and Perona in asking subjects to search for a target in an array of stimuli, one of which 'popped out', whereas our study 1 was similar to that of Mamassian and Goutcher in asking subjects to judge the convexity or concavity of a single stimulus. It seems unlikely that any of these methodological differences can explain the much reduced effect size in our study 2 or the absent effect in our study 1.

Sun and Perona claimed that there was a strong correlation (0.83) between preferred angle of illumination and degree of lateralisation, strong right-handers showing a much greater preference for illumination from the left than did left-handers. Despite, however, having many more subjects and looking at many more measures of lateralisation, we were unable to replicate this finding in our study 2. Given the very large effect described by Sun and Perona it should have been easy to replicate; and our absence of replication, coupled with that of Mamassian and Goutcher (2001), means we have to conclude that the original finding of Sun and Perona was probably a type 1 error, particularly given that their sample size was only 12.

Both our study 1 and our study 2 showed a relationship between the angle of spontaneous head tilt to right or left and the angle of the preferred illumination, those tilting their head to the left having a higher value of  $\phi$  than those tilting their head to the right, with the difference between right and left head tilters being similar in both studies ( $14.7^\circ$  and  $17.4^\circ$ , respectively). Our findings therefore confirm the speculation of Mamassian and Goutcher (2001) that observers might "consistently orient their body relative to the light source" and that this would relate to "strength of the illumination position bias", although the intervening variable is not handedness as they suggested, but spontaneous head tilt.

It should be emphasised that in our study we did not attempt to control head tilt by fixation of the subjects' heads, and therefore it is probable that subjects were also spontaneously tilting during the experiment. Whether retinal tilt alone can account for the entire effect that we and others have found is unclear, since the mean absolute head tilt is relatively small (about  $3^\circ$  to  $4^\circ$ ), and equal numbers of people in our studies tilted their head to the left or to the right. Nevertheless, there is probably a strong case for measuring spontaneous head tilt, and for controlling head position more precisely and checking the horizontal alignment of the pupillary centres in future experiments.

We note that Sun and Perona (1998) do not describe any method of head fixation or alignment, and that, although Mamassian and Goutcher (2001) describe the use of a chin cup and head restraint, they do not describe any method for ensuring the eyes are aligned horizontally.

In conclusion, we do find a small tendency for there to be a preferred direction of illumination from the left rather than the right, although the effect was only found in one of our studies. Our demonstration that direction of spontaneous head tilt relates to preferred direction of illumination does raise the important possibility that failure to control retinal orientation may account for some of the results in the literature. Further studies are required with much better experimental control of this factor, particularly given that the difference between right and left tilters (averaging about  $16^\circ$ ) is larger than the average bias to the left (about  $9^\circ$ ).

We remain agnostic whether indeed there is a general tendency for light to be presumed to come from the left. Our methods of measurement are robust, and readily demonstrate a significant tendency, even in individual subjects, for light to be presumed to come from above rather than below. However, the differences from vertical are small, are only found in one of the two studies, and hover on the edges of statistical significance despite reasonable sample sizes and large numbers of trials. If there is a general preference for light to come from the left, then it is perhaps more compellingly shown in the demonstration of Metzger (see figure 2), than in our more systematically collected data.

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