Perception, 1999, volume 28, pages 965 – 979

Hierarchical organisation in perception of orientation

Donatella Spinelli¶, Gabriella Antonucci¶, Roberta Daini, Maria Luisa Martelli, Pierluigi Zoccolotti¶
Dipartimento di Psicologia, Università degli studi di Roma "La Sapienza", via dei Marsi 78, 00185 Rome, Italy; e-mail: dippsi39@caspur.bitnet; ¶ also at the Research Center, IRCCS Ospedale S Lucia, Rome, Italy
Received 26 July 1996, in revised form 27 May 1999

Abstract. According to Rock [1990, in *The Legacy of Solomon Asch* (Hillsdale, NJ: Lawrence Erlbaum Associates)], hierarchical organisation of perception describes cases in which the orientation of an object is affected by the immediately surrounding elements in the visual field. Various experiments were performed to study the hierarchical organisation of orientation perception. In most of them the rod-and-frame-illusion (RFI: change of the apparent vertical measured on a central rod surrounded by a tilted frame) was measured in the presence/absence of a second inner frame. The first three experiments showed that, when the inner frame is vertical, the direction and size of the illusion are consistent with expectancies based on the hierarchical organisation hypothesis. An analysis of published and unpublished data collected on a large number of subjects showed that orientational hierarchical effects are independent from the absolute size of the RFI.

In experiments 4 to 7 we examined the perceptual conditions of the inner stimulus (enclosure, orientation, and presence of luminance borders) critical for obtaining a hierarchical organisation effect. Although an inner vertical square was effective in reducing the illusion (experiment 3), an inner circle enclosing the rod was ineffective (experiment 4). This indicates that definite orientation is necessary to modulate the illusion. However, orientational information provided by a vertical or horizontal rectangle presented near the rod, but not enclosing it, did not modulate the RFI (experiment 5). This suggests that the presence of a figure with oriented contours enclosing the rod is critical. In experiments 6 and 7 we studied whether the presence of luminance borders is important or whether the inner upright square might be effective also if made of subjective contours. When the subjective contour figure was salient and the observers perceived it clearly, its effectiveness in modulating the RFI was comparable to that observed with luminance borders.

1 Introduction

Visual objects are characterised by a typical structure which can be detailed at different resolution levels. For instance, a human body is an elongated ellipse-shaped vertically oriented visual object; however, at closer viewing, the body is composed of parts (head, arms, etc) with their characteristic shape and orientation defined with respect to the body itself. Overall, visual objects may be defined as a "multilevel hierarchical structure of parts and wholes" (Palmer 1977), and the relative orientation of visual objects with respect to each other is crucial for identifying shape. Thus, the orientation of a figure and its subparts is one of the most elementary types of information extracted from a visual display.

In his studies on ambiguous triangles, Palmer examined how the orientation of a complex figure is determined by the perceived orientation of its subparts and how the orientation of the subparts of the figure is determined by the orientation of the figure itself (Palmer 1980; Palmer and Bucher 1981, 1982). In an extensive analysis of orientation phenomena, Rock (1990) referred to the hierarchical organisation of perception to describe cases in which the orientation of an object is affected by the immediately surrounding elements in the visual field. Rock contrasted this tendency of the perceptual system to establish a relationship between orientations of neighbouring perceptual units with the frame-of-reference class of phenomena, where the most peripheral elements in the visual scene act as coordinates of the scene itself; that is, the orientation of objects within the visual scene and the phenomenal self are judged in relation to these coordinates.

A convenient experimental condition for studying orientational phenomena is the rod-and-frame illusion (RFI) which measures the effect of a tilted frame on the perceived orientation of a vertical rod presented within it. The original findings on this illusion (eg Witkin and Asch 1948) clearly fall into the frame-of-reference category; thus, the observer perceives the visual stimulus (the rod) as well as his own body as tilted (Sigman et al 1978). However, RFI effects are qualitatively different if small displays are used in a lit environment instead of large stimuli presented in the dark, as in the original condition (see Spinelli et al 1991 for a review).

A clear-cut distinction between frame-of-reference and hierarchical organisation effects in the RFI is obtained when a double-frame procedure is adopted: two squares are presented one inside the other with the rod displayed inside the inner frame; the outer frame is tilted, and the inner frame is vertical. In this case, the direction of the rod setting errors varies according to the type of display used. In the case of large inducing displays presented in the dark, the rod is rotated in the direction of the outer frame in order to be perceived as vertical. This finding indicates that the far reference dominates orientation perception (Di Lorenzo and Rock 1982; Zoccolotti et al 1997), consistent with the frame-of-reference hypothesis. In contrast, when two relatively small frames (the outer tilted, the inner vertical) are presented in a lit environment, the illusion is reversed, ie to be perceived as vertical the rod is set in the direction opposite that of the tilt of the outer square. This result was interpreted on the basis of the hierarchical organisation hypothesis (Zoccolotti et al 1997). Owing to the influence of the outer frame, the vertical inner frame is perceived as tilted in the opposite direction. Thus, for example, with an outer frame tilted clockwise (CW), the inner vertical frame is perceived as tilted counterclockwise (CCW). The latter influences the rod and, consequently, to appear vertical the rod has to be set in the direction of the perceived tilt of the inner frame; in our example the rod was set CCW (Zoccolotti et al 1997). Thus, the rod is immune to the direct influence of the outer frame and is most affected by the immediately surrounding frame.

This interpretation was supported in Zoccolotti et al (1997) by the observation that subjects judged the inner square tilted in the direction opposite the tilt of the outer frame. However, the size of this effect was not measured. Thus, the interpretation that the rod was affected only by the immediately surrounding square was open to criticism. One aim of the present study was to support the proposed hierarchical interpretation with a quantitative analysis. Thus, experiments 1 to 3 were designed to establish whether the size of the illusion on the rod was compatible with that expected from the illusory tilt of the inner square. In experiment 1 we measured the size of the effect of the outer tilted square on the setting to vertical of the inner square. In experiment 2 we measured the effect on the perceived vertical of small tilts of the inducing frame. Experiment 3 replicated the double-square experiment (Zoccolotti et al 1997) to compare the actual size of the effect with that expected on the basis of the joint measurements of experiments 1 and 2 with reference to the hierarchical organisation hypothesis. To assess the reliability of the hierarchical effect we also performed an analysis of published and unpublished data to examine the possible confounding effects of individual differences in the RFI. Hierarchical effects obtained in subjects with large RFI were compared with those measured in observers with small RFI.

More generally, the study was aimed at identifying the perceptual conditions critical for obtaining a hierarchical organisation effect. As stated above, in the double-frame condition a small upright frame surrounding the rod produced hierarchical organisation effects. This inducing stimulus has three main properties: (a) it surrounds the rod, (b) has vertical and horizontal luminance contours, and (c) has a specific configuration (a square). In the present work, we aimed to study which of these factors (enclosure, orientation, and configuration) are critical for determining hierarchical perceptual organisation. First, we tested whether enclosure per se is enough to modulate the RFI. Thus, in experiment 4 the effect of an inner circle was examined. In experiment 5, we investigated whether orientation per se is a sufficient condition to modulate the illusory effect of the tilted outer frame. Thus, we tested the effectiveness of a vertical (or horizontal) rectangle located near the stimulus test but not enclosing it. Experiments 6 and 7 were intended to examine whether hierarchical effects can be produced in the absence of luminance borders. In this case, the configurational properties of the inner figure (a vertical square) were obtained by means of subjective contours. Inducers producing subjective contours of different salience were tested in the two experiments.

2 Experiment 1: Frame illusion measured on a central test square

In the traditional RFI, the subject is asked to set a rod to vertical. In this experiment, we measured the size of the illusion obtained when the adjustments are made on an inner square. For comparison, data with a test rod were also obtained.

In this as well as in all following main experiments, the frame tilt used was 11°; this produces the peak of the illusion in the case of small centrally fixated displays (Antonucci et al 1995). Also, the test and the inducer stimuli were always at least 2 deg apart to avoid the intervention of local contrast mechanisms (Carpenter and Blakemore 1973) that could complicate the interpretation of results. Previous findings on the RFI have shown that the effects of local mechanisms are present only for gaps smaller than 1 deg (Zoccolotti et al 1993).

2.1 *Method*

2.1.1 *Subjects.* Eighteen 20 – 30-year-old volunteers (eight males and ten females) participated in the experiment. In this and in all other experiments the subjects were naive to the purpose of the study. They had normal or corrected-to-normal vision and were in the same age range.

2.1.2 *Apparatus and stimuli.* Stimuli were generated with the Adobe Photoshop package and were presented through Oracle Media Objects software on a high-resolution (1024 × 768 pixels) Apple Multiple Scan 20 monitor controlled by a power Macintosh 8200.

All stimuli were black on a white background. The inducing stimulus was a single tilted square. The side of the inducing square subtended 12 deg at a viewing distance of 86 cm and was 1 mm wide. In one condition, the test stimulus was a rod and in the other a square. The side of the inner square subtended 6 deg and the rod subtended 6 deg. In both cases, stimuli were 1 mm wide. They were presented in a dimly lit environment, with other relevant orientation cues out of sight. The test stimuli (square or rod) were presented at nine different orientations (4° CW, 3° CW, 2° CW, 1° CW, 0°, 1° CCW, 2° CCW, 3° CCW, 4° CCW). The outer frame could be tilted either at 11° CW or 11° CCW. The combination of two different experimental conditions (square or test rod), nine rod tilts, and two outer frame orientations (CW, CCW) produced a total of 36 trials.

2.1.3 *Procedure.* Each subject took part in a single 15-min session. The subject was seated on a chair in front of the display, with head leaning in a head-rest and gaze approximately at the centre of the stimulus. The observer saw the stimuli through a circular window with a diameter of 18 deg. The stimuli were presented to all subjects in the same quasi-random sequence. The subject's task was to judge whether the test stimulus was tilted in a CW or CCW direction. No time limit was given.

2.1.4 *Data analysis.* As in to Coren and Hoy (1986), data were analysed by using the unidimensional Guttman Scale. This allowed establishing the breaking point between CW and CCW perceived rod tilts, which was taken as the measure of the apparent vertical. Reliability of measures was assessed by the coefficient of reproducibility.

Coefficients around or above 0.90 indicate that the observed values are a good approximation of a perfect scale (Dunn-Rankin 1983).

Rod settings were marked positive when they were in the same direction as the frame tilt, and negative when they were in the opposite direction. Since no effect of frame direction (CW or CCW) was detected in this experiment or in the following ones, data from these conditions were pooled together.

2.2 *Results and comments*

In the square test condition, the coefficients of reproducibility were 0.87 and 0.94 for the CW and CCW square test trials, respectively; in the rod test condition, they were 0.94 and 0.94.

Mean settings were 1.4° in the case of the square and 1.3° in the case of the rod test stimulus (see figure 1a). The difference between these two conditions was not significant ($t = 0.3$, ns). When tested against zero, a reliable effect was present for both the square ($t = 4.1$, $p < 0.0001$) and the rod ($t = 4.3$, $p < 0.0001$) test stimuli.

The results of this experiment indicate that a tilted frame produces a reliable error in adjusting an inner square to vertical. The direction and size of this illusion are similar to those of the more commonly used test rod.

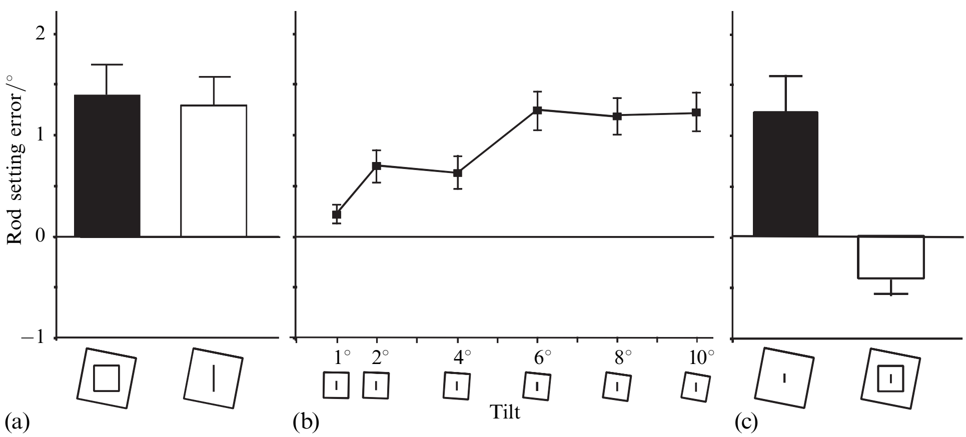

Figure 1. (a) Comparison of setting errors to the vertical with a square or a rod used as test stimulus (experiment 1). The outer frame was tilted 11° CW or CCW. A sketch of the display is presented in the lower part of the figure. (b) Mean rod setting errors (and SEs) as a function of the tilt of the square (experiment 2). (c) Mean rod settings (and SEs) in the control and additional-upright-square condition (experiment 3).

3 Experiment 2: The RFI at small tilts of the inducing frame

As shown above, when the outer frame is tilted 11° the perceived orientation of the inner stimulus is made to deviate from the vertical by 1.4° in the direction opposite to that of the frame tilt. The question was whether an inducer of such a small tilt from the vertical can exert detectable effects on the orientation of an inner test stimulus. The amplitude of the RFI has not been measured before in this range. This was the purpose of the present experiment.

3.1 *Method*

3.1.1 *Subjects.* Fifteen new volunteers (six males and nine females) participated in the experiment.

3.1.2 *Apparatus and stimuli.* The apparatus and stimuli were the same as in experiment 1, except for the following: (a) the inducing square subtended 6 deg and was tilted at six different orientations (1°, 2°, 4°, 6° 8°, and 10°) in the CW and CCW directions;

(b) the test stimulus was a rod subtending 2 deg; (c) the combination of six square tilts, two frame orientations (CW, CCW), and nine rod positions produced a total of 108 trials.

3.1.3 *Procedure and data analysis.* These were as in experiment 1.

3.2 *Results and comments*

The coefficients of reproducibility were high for all frame tilts both in the CW (0.93, range 0.87 – 0.97) and CCW (0.93, range 0.88 – 0.90) trials.

The mean rod settings as a function of frame tilt are plotted in figure 1b. A one-way ANOVA with frame tilt (1°, 2°, 4°, 6°, 8°, and 10°) as repeated factor indicated an effect of tilt ($F_{5,70} = 7.44$, $p < 0.0001$): settings were in the direction of frame tilt and increased with increasing frame tilt. A posteriori Duncan comparisons indicated significant increases from 1° to 2° and from 4° to 6° ($p < 0.05$); no further increase was detected beyond this tilt.

All conditions were significantly different from zero (1° frame: coefficient of reproducibility 0.22, $t = 1.9$, $p < 0.05$; 2° frame: coefficient of reproducibility 0.69, $p < 0.001$; 4° frame: coefficient of reproducibility 0.63, $t = 3.4$, $p < 0.005$; 6° frame: coefficient of reproducibility 1.24, $t = 5.7$, $p < 0.0001$; 8° frame: coefficient of reproducibility 1.19, $t = 5.8$, $p < 0.0001$; 10° frame: coefficient of reproducibility 1.23, $t = 5.6$, $p < 0.0001$).

The results indicate that the illusion grows as a function of frame tilt up to 6° where it reaches a plateau. It should be noted that reliable rod setting errors were observed even in the case of very small frame tilts (1° and 2°).

4 Experiment 3: A replication of the hierarchical organisation effect

The hierarchical organisation hypothesis posits that the orientation of an object is determined by the immediately surrounding objects in the visual field. In the case of two squares surrounding a rod (the outer tilted, the inner upright), it was proposed that the inner square would induce errors in the perceived vertical to the extent to which it was perceived tilted (Zoccolotti et al 1997). In contrast, no direct effect of the outer frame on the rod is expected. The joint results of the first two experiments permit estimating of the expected size of the hierarchical organisation effect, on the basis of this hypothesis. If we consider the case of an outside square tilted at 11°, errors in adjusting an inner square to the vertical were 1.4° (experiment 1). In the case of an inducer of this tilt, the effect on verticality ranged from 0.2° to 0.6° (experiment 2; see figure 1b). The actual effects obtained in our previous study, with a different method of stimulus presentation, fell within this range (Zoccolotti et al 1997, experiment 2: 0.5°; experiment 3: 0.4°). The aim of the present experiment was to evaluate the size of rod setting errors in a double-frame condition with the same stimulus presentation as that used in experiments 1 and 2.

4.1 *Method*

4.1.1 *Subjects.* Sixteen new volunteers (five males and eleven females) took part in this experiment.

4.1.2 *Apparatus and stimuli.* The apparatus was the same as in experiment 1. In the experimental condition (additional-square condition) a rod was surrounded by an inner upright square and this was surrounded by a tilted (11°) square frame (see figure 1c). In the control condition the rod was surrounded only by the tilted square. The side of the outer frame was 12 deg. The side of the inner square measured 6 deg. The rod was 2 deg long. Rod tilts were the same as in experiment 1. The combination of two different experimental conditions (additional-square and control conditions), nine rod tilts and two outer frame orientations (CW, CCW) produced a total of 36 trials.

4.1.3 *Procedure and data analysis.* These were as in experiment 1.

4.2 *Results and comments*

In the control condition, the coefficients of reproducibility were 0.93 and 0.94 for the CW and CCW frame orientation trials, respectively; in the additional-square condition, they were 0.92 and 0.94.

The mean rod setting in the control condition was 1.21°; in the additional-square condition the effect was reversed, as expected from previous results (Zoccolotti et al 1997) (−0.42°; see figure 1c). The difference between the two conditions was statistically reliable ($t = 4.4$, $p < 0.001$). Both conditions were significantly different from zero (additional square: $t = -3.03$, $p < 0.01$ and control: $t = 3.35$, $p < 0.005$).

The results confirm the presence of an inversion of the illusory effect in the double-frame condition (Zoccolotti et al 1997). As stated above, on the basis of experiments 1 and 2, if the illusion can be explained solely as the result of the influence of the (perceived) tilt of the inner frame, an effect between 0.2° and 0.6° would be produced in the additional-frame condition. The size of the effect found (0.42°) agrees with this prediction. Therefore, the size of the effect is compatible with the hypothesis that rod settings in the double-frame condition are due to the influence of the perceived tilt of the inner frame with negligible direct influence of the outer frame on the rod.

4.3 *Individual differences and hierarchical effect*

A possible limitation of the above conclusion is that the size of the effect of the outer frame on the rod in the control condition may be different in different groups of subjects and this may influence the hierarchical effect.

Differences between subjects in the amplitudes of the RFI are well known (eg Witkin and Asch 1948). Although the use of small frames and a large gap reduces these variations (Spinelli et al 1995a), differences between subjects are present. The data in the black columns of figures 1c and 3, collected for different groups in the control condition (experiments 3 to 7), confirm that the averaged RFI has different sizes in different groups. Moreover, within each group, individual differences may be large. To see whether the size of the RFI in the control condition affects the direction of the hierarchical effect, we re-examined our previously published data (Zoccolotti et al 1997) as well as other unpublished data, separating results of subjects according to the size of the RFI.

Figure 2 reports the data obtained across five studies (including the present experiment 3) for a total of seventy-eight subjects tested in the RFI control condition and in the double-frame condition. The stimuli and procedure were similar but not identical in all cases. This large population was segregated into five groups, according to the size of the RFI (based on the distribution plot). The RFI ranged from fractions of 1° to 3°. It will be appreciated that the direction and size of the illusion in the double-square condition was independent of the size of the RFI.

5 Experiment 4: Modulation of the RFI by an inner circle

In experiments 4 to 7 we evaluated the role of different perceptual characteristics under which a hierarchical organisation effect may be observed.

The aim of this experiment was to test whether enclosure per se is a sufficient condition for producing hierarchical organisation effects. Thus, we measured whether a circle enclosing the rod is sufficient to block or reduce the orientation influence of the outer frame. Using a large inducing display (presented in the dark), Ebenholtz and Utrie (1983) found no reduction in the effect when an inner circle was added. However, in view of the considerable differences between the RFI in large and small displays (Ebenholtz and Glaser 1982) we thought it would be interesting to examine this stimulus condition with small centrally fixated displays.

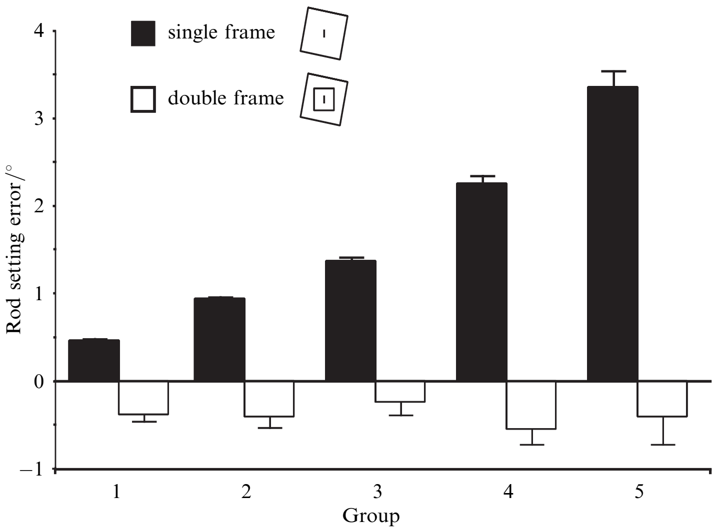

Figure 2. Mean rod settings (and SEs) in the control and additional-upright-square condition for five separate groups of subjects divided according to the amplitude of the RFI in the control condition. Group 1: $N = 26$; Group 2: $N = 22$; Group 3: $N = 14$; Group 4: $N = 8$; Group 5: $N = 8$.

5.1 *Method*

5.1.1 *Subjects.* Seventeen new volunteers (nine males and eight females) participated in this experiment.

5.1.2 *Apparatus and stimuli.* The stimuli in this and in the following experiments were printed in black ink on white sheets of paper (29.5 cm × 21 cm). In the control condition, a rod was surrounded by a tilted square frame; in the additional-circle condition, an inner circle (with a diameter of 6°) was added (see figure 3a). Except for the presence of the circle, the stimuli were the same as those in experiment 3.

5.1.3 *Procedure and data analysis.* These were as in experiment 1.

5.2 *Results and comments*

The coefficients of reproducibility for the control condition were 0.95 and 0.97 for the CW and CCW frame tilts, respectively; in the additional-circle condition, they were 0.94 and 0.91.

The mean rod setting in the control condition was 0.84°, and in the additional-circle condition 0.72° (see figure 3a). The difference between these two conditions was not statistically reliable ($t = 0.56$, ns).

Both conditions were significantly different from zero (additional-circle: $t = 3.44$, $p < 0.005$ and standard: $t = 2.56$, $p < 0.05$).

The results clearly indicate that a circle inside a tilted square does not modulate the RFI. This finding parallels that obtained with a large inducing display by Ebenholtz and Utrie (1983). Therefore, it appears that the isolation of an element by luminance contours is not sufficient per se to interrupt the orientation influences of the outer frame. Rather, it seems necessary that the immediate surrounding frame carries definite orientation information to affect the orientation perception of the unit within it, as observed in experiment 3.

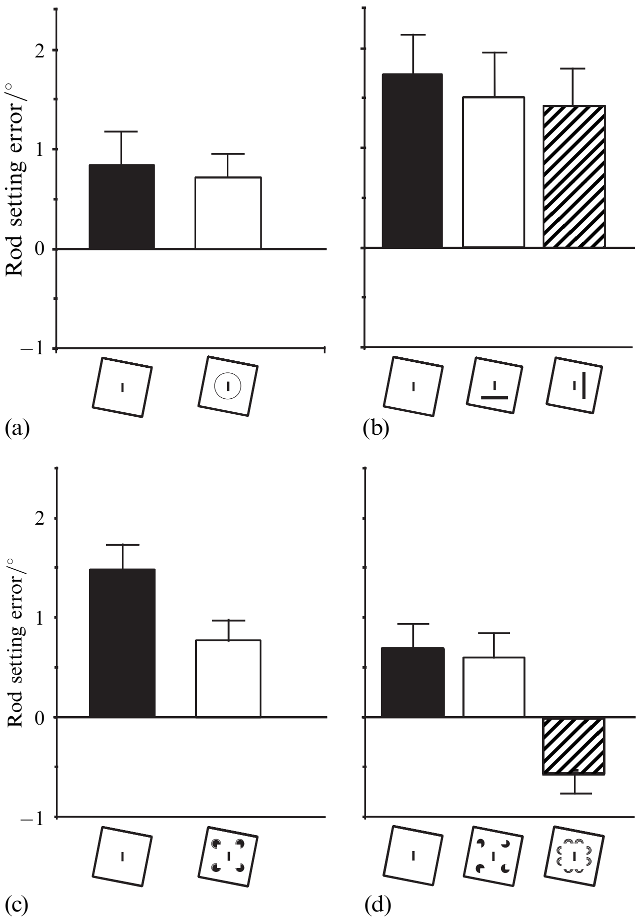

Figure 3. Mean rod settings (and SEs) in the control and additional-frame conditions. (a) Experiment 4 (double frame with an inner circle), (b) experiment 5 (inner horizontal or vertical rectangle), (c) experiment 6 (inner frame composed of subjective contours), and (d) experiment 7 (inner frame composed of subjective contours versus scrambled pacmen figure).

6 Experiment 5: Modulation of the RFI by an inner rectangle not enclosing the rod

In this experiment we examined the effect of orientational information per se in modulating hierarchical organisation effects. In particular, we tested whether the presence of veridical vertical (or horizontal) information in the proximity of the test rod is sufficient to modulate the RFI (see figure 3b).

If the critical element determining the modulation of the effect of the outer tilted frame is the presence of orientational information in the proximity of the rod, clear modulation should be expected.

6.1 *Method*

Sixteen new volunteers (eleven females and five males) participated in this experiment.

6.1.1 *Stimuli.* Three different conditions were tested: control condition, the horizontal-rectangle condition (a thin inner rectangle subtending 6 deg × 1 deg not enclosing the rod was positioned under the rod; see figure 3b) and the vertical-rectangle condition (the same rectangle as in the previous condition, but displayed vertically, was positioned on the right side of the rod, see figure 3b). As in the other experiments, the distances between the frame, the rod, and the rectangle were always more than 2 deg to avoid unwanted local orientation interactions. The combination of three different conditions (control, horizontal rectangle, and vertical rectangle), nine rod tilts and two frame orientations (CW, CCW) produced a total of 54 trials. Except for these specifications, the stimuli and procedure were the same as in experiment 4.

6.2 *Results and comments*
The coefficients of reproducibility for the control condition were 0.95 and 0.90 for the CW and CCW frame tilts, respectively; in the horizontal-rectangle condition, they were 0.92 and 0.90; and in the vertical-rectangle condition they were 0.94 and 0.94.

Mean rod settings were submitted to an ANOVA with condition (control, horizontal rectangle, and vertical rectangle) as repeated factor. The condition factor was not significant ($F_{2,15} = 0.71$, ns): mean rod setting error was 1.73° in the control condition, 1.51° in the horizontal-rectangle condition, and 1.43° in the vertical-rectangle condition (see figure 3b).

All conditions were significantly different from zero (control: $t = 4.29$, $p < 0.001$; horizontal rectangle: $t = 3.39$, $p < 0.005$; vertical rectangle: $t = 3.96$, $p < 0.005$).

The results of the experiment indicate that the presence of orientation information in the proximity of the rod is not sufficient to modulate the illusory effect of the outer frame. Thus, in spite of the vertical or horizontal veridical information provided by the rectangle in proximity of the test rod, rod setting errors were almost as great as those of the standard condition. Thus, the orientation information conveyed by the non-inclusive rectangle was not used as a reference. Subjects' verbalisations indicated that observers did not consider this stimulus in their judgment because it seemed tilted (in the direction opposite to that of the outer frame). However, it should be remembered that also in the case of the square (see figure 1c) the observers perceived the inner frame as tilted, but they were influenced by it in the rod setting (Zoccolotti et al 1997).

7 Experiment 6: Modulation of the RFI by a subjective contour inner vertical square
Overall, it appears from experiments 3, 4, and 5 that hierarchical perceptual organisation of the illusion requires that a figure with oriented luminance borders surrounds the test. In this and in the following experiments, we studied whether the presence of luminance borders is critical or whether hierarchical organisation might also take place with oriented subjective contours.

In the RFI literature, only in one study has the effectiveness of an inducing square made of subjective contours been examined; however, in this case, a large display presented in the dark was used (Streibel et al 1980). Under these circumstances, the subjective contours were relatively ineffective in producing the illusion. However, recent evidence indicates that purely subjective contours may generate reliable and robust orientation interactions in the case of small central displays (van der Zwan and Wenderoth 1995). Taking into account the different mechanisms involved in large and small displays (Ebenholtz and Glaser 1982), we performed a preliminary experiment with a single-frame procedure to examine whether reliable rod setting errors can be obtained with displays made up of subjective contours. The angular shape of rod setting errors as a function of the tilt of the visual display in the case of the subjective-contour single frame was compared with that obtained in the standard single-frame condition.

Preliminary experiment: The RFI induced by subjective-contour square

7.1 *Method*
7.1.1 *Subjects.* Twenty-six volunteers (eleven males and fifteen females) participated in the experiment.

7.1.2 *Apparatus and stimuli.* The inducing stimulus was a single tilted square. In one condition, the square was defined by real contours and in the other by subjective contours (as in the inner drawing in figure 3d). The side of the square (whether real or subjective) was 6 deg. The diameter of the four black incomplete circles or 'pacmen' was 2 deg. The square could appear tilted at three different angles (11°, 22°, and 33°) in both CW and CCW directions. In order to maintain the gap constant across frame tilts (Antonucci et al 1995), the length of the rod varied between 1.8 deg (at the 11 deg frame tilt) and 2.8 deg (at the 33 deg frame tilt). As in the previous experiments, nine different rod tilts were used. The combination of two different conditions (standard and subjective contours), three square tilts, nine rod tilts and two frame orientations (CW, CCW) produced a total of 108 trials.

7.1.3 *Procedure and data analysis.* These were as in experiment 1.

7.2 *Results and comments*
Coefficients of reproducibility were high both for the real-contour condition (0.91; range 0.88 – 0.94) and the subjective-contour condition (0.91; range 0.86 – 0.95). An ANOVA with condition (standard versus subjective contours) and square tilt (11°, 22°, and 33°) as repeated factors indicated a main effect of square tilt ($F_{2,50} = 34.21$, $p < 0.0001$) and the condition by square tilt interaction ($F_{2,50} = 16.09$, $p < 0.0001$; see figure 4). As expected, rod setting errors were in the direction of frame tilt for a square tilted at 11° and in the opposite direction for a square tilted at 33°. An analysis of simple effects indicated that both of these effects were larger for the standard than for the subjective-contour condition (11° square tilt: $F_{1,25} = 23.39$, $p < 0.001$; 33° square tilt: $F_{1,25} = 5.52$, $p < 0.05$); no difference between the two conditions was present for a 22° square tilt ($F = 1.07$, ns).

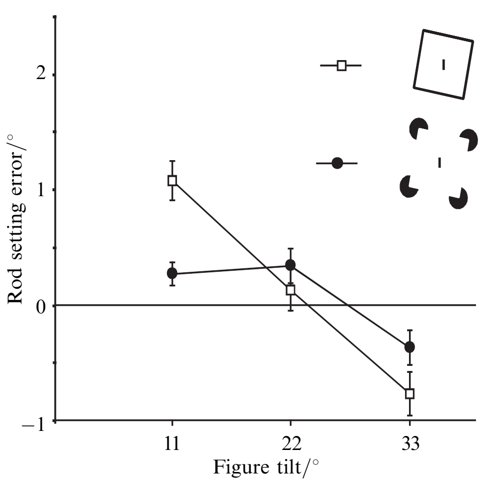

Figure 4. Mean rod settings (and SEs) as a function of frame tilt in the control condition and in the subjective-contour condition (preliminary experiment to study 3).

When tested against zero, a reliable effect was present at 11° ($t = 6.29$, $p < 0.0001$) and at 33° of square tilt ($t = -4.08$, $p < 0.0001$) in the standard condition; no effect was present for a 22° square tilt. In the subjective-contour condition, a positive effect was present at 11° square tilt ($t = 2.66$, $p < 0.01$) and at 22° square tilt ($t = 2.22$, $p < 0.05$), and a negative one at 33° ($t = -2.47$, $p < 0.05$).

The results indicate that reliable rod setting errors are produced by an inducing stimulus made of subjective contours and that the direction of the illusion as a function of frame tilt is similar to that obtained in the control condition and described in the literature (eg Wenderoth 1974). Errors in the direction of frame tilt and errors in the direction opposite to frame tilt are obtained according to degree of frame tilt. This is typical of the visual mechanisms responsible for global analysis of the figure (Wenderoth and Beh 1977). In fact, vertical judgment is influenced by the symmetry axis of the figure nearest to vertical (Wenderoth and van der Zwan 1991). When the frame is tilted 11° CW, the rod setting is dominated by the symmetry axis tilted 11° CW. When the frame is tilted 33° CW the axis nearest to vertical is the diagonal of the square, tilted 12° CCW, thus yielding indirect effects. Unlike what is commonly found for the 22° square tilt condition (ie no illusory effect), a small positive effect was observed. No clear explanation of this finding is available at present.

It is interesting to note that, although similar in direction, the illusory effect produced by the subjective contour frame was smaller than that produced by the real contour frame. There have been similar reports with other illusory conditions [eg the Poggendorff illusion; see Goldstein and Weintraub (1972)].

Main experiment (experiment 6)

After showing that the illusory contours could produce the RFI, we addressed the question of hierarchical organisation of perception through the use of a double frame paradigm with an inner subjective contour frame.

7.3 *Method*

The same general method was used as in experiment 4, except for the following: (a) sixteen volunteers (six males and ten females) participated in the experiment; (b) in the additional-square condition, the inner stimulus was a subjective contour-square (see figure 3c).

7.4 *Results and comments*

All coefficients of reproducibility were high: in the control condition, they were 0.94 and 0.94 for CW and CCW frame tilt; in the additional-square condition they were 0.89 and 0.90, respectively.

The mean rod setting in the control condition was 1.48°, and in the additional-square condition 0.77° (see figure 3c). The difference between these two conditions was statistically reliable ($t = 2.29$, $p < 0.05$). Both conditions were significantly different from zero (additional subjective-contour square: $t = 3.82$, $p < 0.005$; and standard: $t = 5.97$, $p < 0.0001$).

The results indicate a modulation of the inner subjective contour square on the RFI: rod settings were considerably smaller in the subjective-contour condition compared to the control condition. However, the illusory effect was not reversed as expected on the basis of the hierarchical organisation hypothesis. Thus, the inner subjective-contour figure does not completely block the influence of the outer frame on the rod. It is possible that this was due to the 'relative weakness' of subjective versus real contours, as found in the single-frame experiment described above. Thus, orientation information conveyed by weak contours is more 'noisy' and its influence on the rod less effective. Experiment 7 was devised to test this and another possible interpretation.

8 Experiment 7: Modulation of the RFI by an inner subjective-contour inner vertical square (more salient than in experiment 6 and lacking oriented contours)

As stated above, one possibility is that the partial modulation of the illusion observed in experiment 6 was due to the relative weakness of the subjective borders of the specific stimulus used. Indeed, these appeared strong near the pacmen, but less evident and homogeneous at increasing distances. Therefore, in this experiment we decided to use a figure with more evident second-order subjective contours. Further, one factor that may have contributed to the weakness of the effect in experiment 4 concerns subjects' characteristics; therefore to promote the emergence of subjective-contour effects, we also preselected subjects sensitive to this type of illusion (see method).

The new figure, a square produced by semicircular borders, is presented in figure 3d. The image has luminance contours lacking definite orientation in both space and frequency domains (as assessed by Fourier spectrum). The reader can appreciate the salience of contours and consistent change in surface luminance. To confirm the different strength of the two subjective-contour figures (the 'pacmen' stimulus versus the semicircular-border square), these were presented to a group of subjects (six males and twenty-four females). The subjects first viewed one example of a figure with strong illusory contours (Kanizsa 1980, figure 10.10, page 283) and one of a figure with very weak subjective borders (the same stimulus transformed, as suggested by Kanizsa, page 284). They were requested to evaluate the salience of the squares on a 5-point scale using these two stimuli as anchorage points for strong (value 5) and weak (value 1) subjective contours, respectively. The two squares (the pacmen and the semicircular-border square) were presented upright without the test-rod stimulus. Median salience was 3 (range 1 – 5) for the pacmen and 4 (range 1 – 5) for the semicircular-border square. The difference was statistically reliable (Wilcoxon test: $z = 2.31$, $p < 0.05$). These results confirm that the semicircular-border square has more salient subjective borders.

A second interpretation of the limited but measurable modulation reported in experiment 6 might be the presence of short vertical and horizontal luminance borders of the inner stimulus (see figure 3c). In fact, the pacmen used to generate the subjective contours did carry such orientational information. This interpretation was persuasively used in the case of large inducing displays made of subjective contours presented in the dark (Streibel et al 1980). The presence of these short oriented real borders and corners (not the analysis of the shape of the inducing display) was critical for producing the residual RFI. To test this interpretation, we used an inner figure generated by four pacmen arranged so that they did not generate a subjective-contour square (see figure 3d) but provided the same orientation information as in the previous experiment.

8.1 *Method*

8.1.1 *Selection of subjects.* Prior to the experiment, twenty-two new subjects were shown three pairs of subjective-contour stimuli obtained from various sources (Kanizsa 1980, figure 10.6 versus 10.7, pages 279 – 280; and figure 10.11 versus 10.12, pages 284 – 285; Purghé 1993, figure 5b versus 5a, page 818). Each pair depicted one version with 'strong' and one with 'weak' subjective contours. The subject's task was to indicate the 'strong' illusion in each pair. Eighteen subjects (nine males and nine females) discriminated all pairs correctly and were admitted to the experiment.

8.1.2 *Stimuli.* Three different conditions were tested: control condition, subjective-contour condition (the inner square was produced by semicircular contours; see figure 3d), and the no-subjective-contours condition (the inner structure was formed by four pacmen, see figure 3d). The combination of three different conditions (control, subjective contours, and no subjective contours), nine rod tilts, and two frame orientations (CW, CCW) produced a total of 54 trials. Apart from these specifications, the method was the same as in experiment 4.

8.2 *Results and comments*

In the control condition, the coefficients of reproducibility were 0.88 and 0.96 for CW and CCW frame tilt, respectively; in the no-subjective-contours condition, they were 0.93 and 0.95, in the subjective-contour condition, 0.93 and 0.93.

Mean rod settings were submitted to an ANOVA with condition (control, subjective contours, and no-subjective contours) as repeated factor. The condition factor proved significant ($F_{2,34} = 23.11$, $p < 0.0001$): mean rod setting error was 0.68° in the case of the control condition, 0.61° in the case of the no-subjective-contours condition and −0.57° in the case of the subjective-contour condition (see figure 3d). A posteriori comparisons with the Duncan test indicated that the first two conditions did not differ from each other and they both differed from the subjective-contour condition ($p < 0.01$).

All conditions were significantly different from zero (control: $t = 2.70$, $p = 0.01$; no-subjective contours: $t = 2.51$, $p < 0.05$; subjective contours: $t = -3.00$, $p < 0.01$).

In the subjective-contour condition, clear hierarchical organization effects were shown. Rod setting errors were in the direction of the perceived tilt of the inner square. In fact, the size and direction of the hierarchical effect were very much the same as those observed for inner squares with real contours (reported in figure 1c). The presence of similar orientation effects for both luminance and purely subjective contours was reported by van der Zwan and Wenderoth (1955) in the case of tilt aftereffects. Thus, the effectiveness of a vertical-subjective-contour square in modulating the illusion depends on its perceived strength. When powerful stimuli and 'good' observers are selected, the effectiveness is high; when observers are not preselected and subjective contours are less evident, effectiveness is lower.

No modulating effect was present for the small borders of the four pacmen on the illusion. This is different from what happens in the case of large inducing displays presented in the dark, where the illusory effect is due to the presence of short portions of luminance borders, not to the global action of the figure composed of subjective contours (Streibel et al 1980).

9 General discussion

The aims of the present study were twofold. First, an attempt was made to support the hypothesis of hierarchical organisation applied to the RFI with a quantitative analysis. Second, the characteristics of the display necessary for producing this effect were examined.

According to hierarchical organisation of perception, the orientation of an object is affected by the immediately surrounding elements in the visual field (Rock 1990). When applied to the double-frame presentation of the RFI, this interpretation posits that the rod will be influenced by the inner frame while no direct effect of the outer frame will be present. The errors produced by the outer frame are expected to be in the same direction as the tilt of this inducer. When the inner frame is objectively upright, it appears tilted in the direction opposite to that of the outer inducer (Zoccolotti et al 1997). Therefore, if the inner frame exerts an effect on the rod, this consists of rod setting errors in the direction of its perceived tilt (ie away from the tilt of the outer frame). Thus, errors in the direction opposite to that of the outer square detect hierarchical perceptual organisation. Of course, intermediate results may also be conceivable if both frames exert some influence on the test stimulus. The results of experiments 1 and 2 allowed making an estimate of the range of the expected size of the hierarchical effect, if the illusory effect is entirely mediated by the influence of the inner frame. The actual value observed in experiment 3 is close to this estimate. Moreover, an analysis of data collected on a large number of subjects, segregated according to their size of the RFI, allowed us to exclude the possibility that the effect measured on the rod in the double-frame condition is a linear sum of the outer and inner frame influences on the rod itself. In fact, subjects with small and large RFI showed effects in the same direction in the double-frame test. Overall, these results support the view that the perceived orientation of the rod is dominated by the influence of the inner frame, as expected from the hierarchical hypothesis.

The more general aim of the present experiments was to specify some of the perceptual determinants of hierarchical organisation effects in the RFI. A first finding is that the incapsulating effect observed with an inner upright square (Zoccolotti et al 1997) is not a consequence of enclosure per se. A circle does not consistently modulate the effect of the outer frame. Rather, enclosure by luminance borders is not even a necessary condition, since hierarchical effects may be shown with subjective-contour figures.

However, oriented contours are not sufficient either. Indeed, the effect of a salient vertical rectangle presented near the test rod was virtually null. Similarly, when the pacmen containing vertical and horizontal borders were arranged so as not to produce subjective contours, their effect was negligible. Further, the very effective stimulus (with semicircular borders) used in experiment 7 does not even possess vertical or horizontal luminance borders and has no power at these orientations (as assessed by Fourier analysis). Therefore, the presence of orientational information conveyed by luminance contours is neither necessary nor a potentiating factor for the modulation of the RFI. It may be noted that similar observations were made by Hartley (1982), who found that orientation illusions could be generated both by rectilinear and curvilinear inducing displays, the critical factor being the presence and orientation of the bilateral-symmetry axis of the figure. It is not necessary that the latter be defined by luminance contours surrounding the test but it is necessary that the inducing figure be perceived as a reference for the test stimulus.

The lack of modulation in the case of the rectangle presented near the rod suggests that the inner stimulus acts on the rod only if one element is perceived as a reference for the other. When the rectangle and the rod are perceived as two separate elements, hierarchical organisation does not occur. This is in line with proposals already present in the literature. For instance, examples of hierarchical organisation produced by Palmer (1977) and Marr (1982) always depict structural connections of elements apt to produce this perceptual result. This is obtained through enclosure, as in the case of ambiguous pointing triangles surrounded by a rectangle (Palmer and Bucher 1981, 1982) or through spatial continuity of elements as in Marr's (1982) example of the human figure (the perceived arm orientation depends on the trunk orientation).

Squares composed of subjective contours varied in their effectiveness of modulating the effect of the outer frame, depending on the perceived salience of their borders. The effects were clearer for figures with salient contours and when it was pre-assessed that subjects easily perceived subjective contours. When the subjective contours were absent (as in the case of the figure with scrambled inducing elements) the modulation of the effect of the outer frame was absent. These findings suggest that hierarchical organisation in orientation perception depends on the orientation properties of the inducing figure. As mentioned above, Streibel et al (1980) reported that the configurational analysis of the figure is relatively unimportant in the case of large frames presented in the dark. In this condition, the illusory effect appears largely mediated by the presence of high contrast borders and corners presented in the far periphery. These findings are in keeping with the idea of different processes in the case of large and small displays (Ebenholtz and Glaser 1982). Hierarchical organisation effects are predominant in the case of small central stimuli presented in daylight; in the case of large inducing stimuli presented in the dark, these effects may still be present but they are masked by the much larger illusory effects produced by the frame of reference (Spinelli et al 1995b; Zoccolotti et al 1997).

Acknowledgements. This study was supported by grants from CNR and MURST. We would like to thank Franco Purghé for his advice on the subject selection procedure in experiment 3, and Stuart Smith for his help with the semicircular-subjective-contours figure.

References

Antonucci G, Fanzon D, Spinelli D, Zoccolotti P, 1995 "Visual factors affecting the rod-and-frame illusion: role of gap size and frame components" *Perception* **24** 1119 – 1130

Carpenter R H S, Blakemore C, 1973 "Interactions between orientation in human vision" *Brain Research* **8** 287 – 303

Coren S, Hoy V S, 1986 "An orientation illusion analog to the rod and frame: Relational effects in the magnitude of the distortion" *Perception & Psychophysics* **39** 159 – 163

Di Lorenzo J R, Rock I, 1982 "The rod-and-frame effect as a function of the righting of the frame" *Journal of Experimental Psychology: Human Perception and Performance* **8** 536 – 546

Dunn-Rankin P, 1983 *Scaling Methods* (Hillsdale, NJ: Lawrence Erlbaum Associates)
Ebenholtz S M, Glaser G W, 1982 "Absence of depth processing in the rod-and-frame effect" *Perception & Psychophysics* **32** 134 – 140
Ebenholtz S M, Utrie J W, 1983 "Peripheral circular contours inhibit the visual orientation control system" *Aviation, Space, and Environmental Medicine* **54** 342 – 346
Goldstein M B, Weintraub D J, 1972 "The parallel-less Poggendorf: Virtual contours put the illusion down but not out" *Perception & Psychophysics* **11** 353 – 355
Hartley A A, 1982 "The roles of axes of symmetry in orientation illusions" *Perception & Psychophysics* **31** 367 – 375
Kanizsa G, 1980 *Grammatica del Vedere* (Bologna: Il Mulino)
Marr D, 1982 *Vision* (San Francisco, CA: Freeman)
Palmer S E, 1977 "Hierarchical structure in perceptual representation" *Cognitive Psychology* **9** 441 – 474
Palmer S E, 1980 "What makes triangles point: Local and global effects in configurations of ambiguous triangles" *Cognitive Psychology* **12** 285 – 305
Palmer S E, Bucher N M, 1981 "Configural effects in perceiving pointing of ambiguous triangles" *Journal of Experimental Psychology: Human Perception and Performance* **7** 88 – 114
Palmer S E, Bucher N M, 1982 "Textural effects in perceiving pointing of ambiguous triangles" *Journal of Experimental Psychology: Human Perception and Performance* **8** 693 – 708
Purghé F, 1993 "Illusory contours from pictorially three-dimensional inducing elements: Counter-evidence for a Parks and Rock's example" *Perception* **22** 809 – 818
Rock I, 1990 "The frame of reference", in *The Legacy of Solomon Asch* Ed. I Rock (Hillsdale, NJ: Lawrence Erlbaum Associates) pp 243 – 268
Sigman E, Goodenough D R, Flannagan M, 1978 "Subjective estimates of body tilt and the rod-and-frame test" *Quarterly Journal of Experimental Psychology* **31** 155 – 165
Spinelli D, Antonucci G, Daini R, Zoccolotti P, 1995a "Local and global visual mechanisms underlying individual differences in the rod-and-frame illusion" *Perception & Psychophysics* **57** 915 – 920
Spinelli D, Antonucci G, Daini R, Fanzon D, Zoccolotti P, 1995b "Modulation of the rod-and-frame illusion by additional external stimuli" *Perception* **24** 1105 – 1118
Spinelli D, Antonucci G, Goodenough D R, Pizzamiglio L, Zoccolotti P, 1991 "Psychophysiological mechanisms underlying the Rod and Frame illusion", in *Field Dependence – Independence: Cognitive Style across the Life Span* Eds S Wapner, J Demick (Hillsdale, NJ: Lawrence Erlbaum Associates) pp 37 – 60
Streibel M J, Barnes R D, Julness G D, Ebenholtz S M, 1980 "Determinants of the rod-and-frame effect: Role of organization and subjective contour" *Perception & Psychophysics* **27** 136 – 140
Wenderoth P, 1974 "The distinction between the rod-and-frame illusion and the rod-and-frame test" *Perception* **3** 205 – 212
Wenderoth P, Beh H, 1977 "Component analysis of orientation illusions" *Perception* **6** 57 – 75
Wenderoth P, Zwan R van der, 1991 "Local and global mechanisms of one- and two-dimensional orientation illusions" *Perception & Psychophysics* **50** 321 – 332
Witkin H A, Asch S E, 1948 "Studies in space orientation. IV. Further experiments on perception of the upright with displaced visual fields" *Journal of Experimental Psychology* **38** 762 – 782
Zoccolotti P, Antonucci G, Daini R, Martelli M L, Spinelli D, 1997 "Frame-of-reference and hierarchical-organisation effects in the rod-and frame illusion" *Perception* **26** 1485 – 1494
Zoccolotti P, Antonucci G, Spinelli D, 1993 "The gap between the rod and frame influences the rod-and-frame effect with small and large inducing displays" *Perception & Psychophysics* **4** 14 – 19
Zwan R van der, Wenderoth P, 1995 "Mechanisms of purely subjective contour tilt aftereffects" *Vision Research* **35** 2547 – 2557