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Testing the tilt-constancy theory of visual illusions

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Abstract. Prinzmetal and Beck (2001) *Journal of Experimental Psychology: Human Perception and Performance* **27** 206 – 217) argued that a subset of visual illusions is caused by the same mechanisms that are responsible for the perception of vertical and horizontal—a theory they referred to as the tilt-constancy theory of visual illusions. They argued that these illusions should increase if the observer's head or head and body are tilted because extra reliance would then be placed on the illusion-inducing local visual context. Exactly that result had previously been reported in the case of the tilted-room and the rod-and-frame illusions. Prinzmetal and Beck reported similar increases in the tilt illusion (TI), as well as the Zöllner, Poggendorff, and Ponzo illusions.

In two experiments, we re-examined the effect of head tilt on the TI. In experiment 1, we used more conventional TI stimuli, more standard experimental methods, and a more complete experimental design than Prinzmetal and Beck, and additionally extended the investigation to attraction as well as repulsion effects. Experiment 2 more closely replicated the Prinzmetal and Beck stimuli. Although we found that head tilt did increase TIs in both experiments, the increases were of the order of 1° – 2°, more modest than the 7° reported by Prinzmetal and Beck. Significantly, the TI increase was larger when inducing tilts and head tilts were in the same direction than when they were in opposite directions, suggesting that the tilt-constancy theory may be oversimplified. In addition, because previous evidence renders unlikely the claim that the Poggendorff illusion can be explained simply in terms of misperceived orientation of the transversals, the question arises whether there might be some other explanation for the increase in the Zöllner, Poggendorff, and Ponzo illusions with body tilt that Prinzmetal and Beck reported.

1 Introduction

It has recently been argued that many visual illusions are "caused by the same mechanisms that are responsible for the perception of vertical and horizontal" (see Prinzmetal and Beck 2001, page 206). Because these mechanisms often enable observers to perceive orientation as relatively constant, despite changes in other properties such as retinal orientation when the head or body is tilted, the authors referred to their theory as the tilt-constancy theory of visual illusions. For reasons that we elaborate in what follows, Prinzmetal and Beck predicted and found that the tilt-induction effect, and the Zöllner, the Poggendorff, and the Ponzo illusions increased in magnitude with body tilt. They argued (page 214) that previous theories of these illusions, such as the lateral inhibition theory of the tilt illusion proposed by Blakemore et al (1970) and Carpenter and Blakemore (1973), could not explain their findings because no other extant theory of illusions predicts an increase in illusion with body tilt.

The tilt-constancy theory has its genesis in studies of the tilted-room illusion (Asch and Witkin 1948) and a similar, but less complex version, the rod-and-frame illusion (Witkin and Asch 1948). In both cases and for certain room or frame tilts, an upright observer incorrectly perceives a gravitationally and retinally upright rod to be tilted in the direction opposite to the tilt of the surrounding visual context, either the room or the outline frame. The key observation for the theory is that, in both cases, it has been found that such illusory errors in misjudgment of vertical (and horizontal) increase when the observers' head or head and body are tilted (Asch and Witkin 1948; DiLorenzo and Rock 1982; Witkin and Asch 1948). Prinzmetal and Beck claimed that this increase in errors occurs because a tilted observer is forced to place increased reliance on visual context cues in judging vertical or horizontal, at the expense of gravity-based information that otherwise mitigates the effect of the tilted visual context when the observer is upright.

To test the tilt-constancy theory, Prinzmetal and Beck first presented arguments that each member of a subset of visual illusions can be understood in terms of orientation misperception. Prinzmetal and Beck note that Day (1972) had previously suggested that the TI, the Zöllner, and the tilted-room illusions all had common mechanisms, whereas Howard (1982) disagreed. The illusions Prinzmetal and Beck included in their subset were: the tilt illusion (TI), which they termed the tilt-induction effect, the Zöllner, the Poggendorff, and the Ponzo illusions. Examples of these four illusions are shown in figure 1, which is adapted from figures 1 and 2 in Prinzmetal and Beck (2001).

Figure 1a is a version of the TI first reported by Gibson (1937): the counterclockwise (CCW) tilted context lines induce a clockwise (CW) tilt (dashed line) in the truly vertical test line. Consequently, observers asked to set the test line to vertical would set it in error in the same direction as the context lines to compensate for the perceived tilt, a positive or repulsion effect. A similar effect occurs in the Zöllner illusion (figure 1b): the shorter and superimposed context inducing lines induce a perceived CW tilt in the long vertical test line. Figure 1c shows the Poggendorff illusion, in which the parallel, vertical context lines cause the truly aligned solid test transversal lines to appear misaligned: the upper right transversal appears too high, as if the vertical context lines induced an additional repulsive tilt in the test segments (dashed lines). It is important to note that Prinzmetal and Beck (2001, page 207) stress that the effect shown in figure 1c is a change in perceived transversal *orientation*, not an *angle expansion*, although in this case the two are operationally indistinguishable. Finally, in figure 1d, the thick lines show the Ponzo illusion in which the upper of the two physically equal horizontal test lines appears longer than the lower line. Prinzmetal and Beck superimposed the Ponzo figure on a thin-line version of the Zöllner illusion,

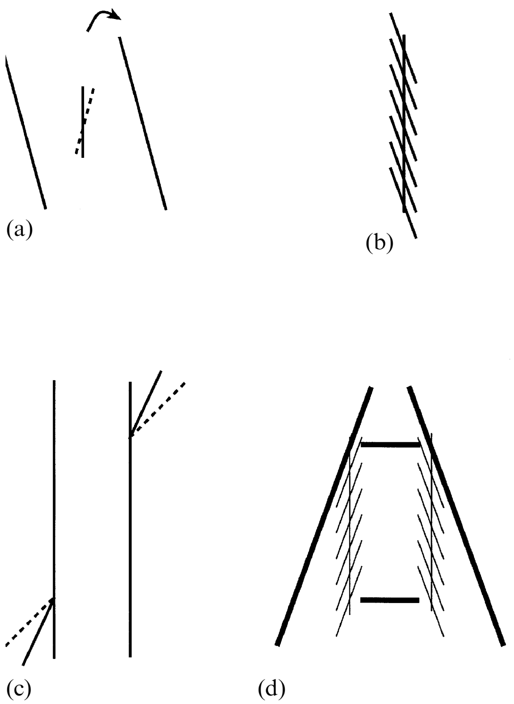


Figure 1. Examples of (a) the tilt illusion, (b) the Zöllner illusion, (c) the Poggendorff effect, and (d) the Ponzo illusion. Adapted from Prinzmetal and Beck (2001), figures 1 and 2. See text for details.

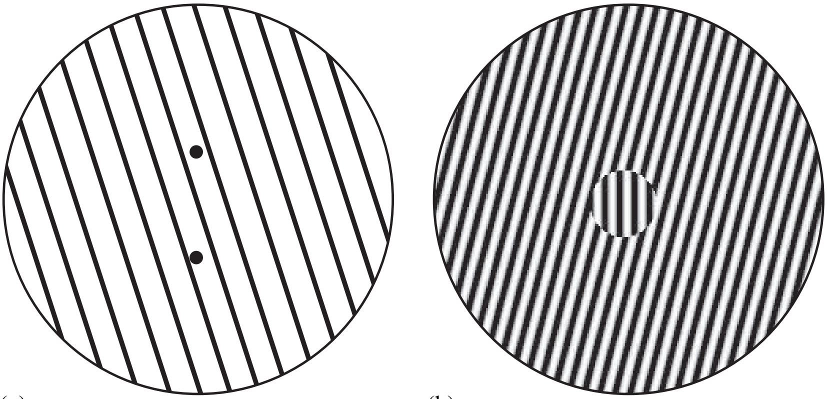
as has been done here. The intention was to show that just as the vertical and parallel Zöllner test lines appear to diverge at the top, so this apparent expansion of space at the top of the Ponzo figure results in the perceptual expansion of the upper horizontal test line.

If Prinzmetal and Beck had simply given this account of the four illusions in terms of misperceived orientation and gone no further, they would simply have joined the ranks of others like Judd (1899), who sought to explain a variety of illusions in terms of other illusions, with little by way of explanation (Wenderoth 1992). However, Prinzmetal and Beck went further and argued (page 209):

> "In summary, the tilt-constancy theory claims that the same mechanism that causes the incorrect perception of orientation in the tilted-room illusion ... is responsible for a variety of illusions, including the Zöllner, the Poggendorff, and Ponzo illusions as well as the tilt-induction effect. .... If the tilt-induction effect and the Zöllner, Poggendorff, and Ponzo illusions are caused by the same mechanism as the tilted-room illusion, they should also increase when observers are seated in a tilted position."

Not only did Prinzmetal and Beck test this proposition, but they also included, in the same experiment, illusions that are believed not to involve orientation perception, like the Müller-Lyer illusion, the prediction being that body tilt would increase only the four illusions hypothesised to involve orientation-constancy mechanisms. The results confirmed their prediction.

There were several reasons for our wanting to re-examine Prinzmetal and Beck's theory and results, especially the TI result. Prinzmetal and Beck used an unusual stimulus to measure the TI (figure 2a): the inducing grating consisted of thin white lines tilted 18° CCW with a duty cycle of about 0.05 on a black background (the inverse of figure 2a), and the test stimulus was a pair of dots.



(a) (b)

Figure 2. Examples of the kinds of tilt illusion stimuli used (a) by Prinzmetal and Beck (2001) and (b) in experiment 1. See text.

Observers "moved the top dot back and forth so that it was vertically aligned, *according to gravity*, with the bottom dot. Specifically, observers were told that if the two dots were tennis balls, the top dot should be placed so that, if dropped, it would land squarely on the bottom dot in the real world" (page 209). It is well known that dots are often perceptually attracted to nearby lines (Wenderoth 1980a) so that dot-to-line attraction effects may have confounded Prinzmetal and Beck's results. Although Prinzmetal and Beck randomly perturbed the vertical position of the dots by ±0.5° so that observers could not use the relative position of a nearby line to make the judgment, this procedure cannot rule out interactions between orientation judgments and dot attraction effects within each trial. Also, no pretest measures were taken (ie in the absence of the inducing grating) and it is thus possible that the subjective vertical with only the dots visible was different for upright and 30° CCW tilted observers. That is, it cannot be known to what extent the upright repulsion TI of +2.4° and the body-tilted repulsion TI of +9.4° reported by Prinzmetal and Beck differed owing to body tilt alone, inducing Aubert–Müller (A− and E−) effects (Day and Wade 1969) or to the authors' postulated increase in salience of visual context with body tilt. They did show, in experiment 2, that observers tilted 30° CCW set the dots 0.87° CW in the absence of the inducing grating, not significantly different from zero and opposite to the errors in their experiment 1, but in our view taking test minus pretest measures in the same experiment is a better design. One reason it is a better design is that there are large individual differences in the incidence and magnitude of A− and E− effects and in the angle of tilt at which they occur (Howard 1982). Hence, tilting observers' heads 30° either CW or CCW would be expected to induce large CW errors for some subjects and large CCW errors for other subjects, with a resulting large increase in variance but little or no change in constant error. This is what Prinzmetal and Beck found in their experiment 2. Only when each *individual* subject's own pretest setting with head tilted is subtracted from that subject's own test setting with head tilted can it be assumed that A− and E− effects contribute to both pretest and test measures. Only then can a pure TI be measured, uncontaminated by A− and E− effects, because each subject acts as his or her own control. It was additionally of some concern that several previous studies have cast doubt on dot alignment settings as an index of perceived orientation (Emerson et al 1975; Wenderoth 1978, 1980a; Wenderoth et al 1979). However, it should be stressed here that we never believed that Prinzmetal and Beck's results were either invalid or were entirely explicable in terms of dot attraction effects or A− and/or E− effects. We simply chose to use more conventional stimuli and a within-subjects design, the latter with the aim of *factoring out* any pretest differences and A− or E− effects, rather than merely randomising these potentially confounding effects.

Accordingly, we decided to partially repeat the Prinzmetal and Beck experiment, but to use more standard test and inducing stimuli to measure the TI: a sine-wave test grating surrounded by an abutting inducing grating, with the observers' task the conventional one of setting the test grating to perceived vertical (figure 2b). We also decided to run a more complete design with both CW and CCW head tilts, CW and CCW inducing gratings, and using inducing angles (15° and 75°) that usually induce maximum repulsion ('direct') and attraction ('indirect') TIs, respectively.

An important reason for testing the effect of head tilt on attraction effects as well as repulsion effects is that it had previously been suggested that repulsion effects in part, but attraction effects in toto, are products of orientation-constancy mechanisms (Wenderoth and Johnstone 1987, 1988) so that both might be expected to increase with head or body tilt. Specifically, Wenderoth and Johnstone postulated that repulsion effects are attributable to two processes: V1 lateral inhibition, as proposed by Carpenter and Blakemore (1973), but also an extrastriate constancy mechanism. Attraction effects, they claimed, derive from only the latter process. They based this conclusion on their experiments that showed that manipulations designed to remove the low-level (putatively V1) contribution to the repulsion effect only ever reduced it to roughly the magnitude of the attraction effect but never eradicated it entirely. Similar findings have been reported by Poom (2000). Thus, if body or head tilt does increase the component of illusions owing to orientation-constancy mechanisms, as Prinzmetal and Beck have claimed, then the Wenderoth and Johnstone hypothesis predicts that body/head tilt should increase both attraction and repulsion TI effects by roughly the same amount, if both possess equal-sized constancy-based components.

2 Experiment 1

2.1 *Method*

2.1.1 *Subjects.* Thirty-six subjects from an introductory Psychology course at Macquarie University volunteered in return for nominal course credit. All were emmetropic or had appropriately corrected vision.

2.1.2 *Apparatus and stimuli.* Displays were presented on a Sony Multiscan G520 20-inch monitor, connected to a G4 Macintosh computer. Subjects viewed the display from a chin-rest and through a circular viewing tube lined with black felt so that no extraneous contours other than the experimental display were visible. That is, no extraneous contours of either the display monitor or the laboratory were visible. Without access to a tilting chair, we tested subjects either with the head upright or with head tilted 30° CW or CCW, achieved by a tiltable padded head-rest.

The inducing and test grating stimuli were similar to those in figure 2b. All gratings had spatial frequencies of 1 cycle $\deg^{-1}$. The maximum and minimum luminances of the gratings were 61.6 cd m^{-2} and 0.42 cd m^{-2}, respectively, so that contrast, defined as $(L_{\max} - L_{\min})/(L_{\max} + L_{\min})$ was 0.98.

2.1.3 *Experimental design.* A three-factor design was employed. One factor was between subjects (direction of head tilt, CW or CCW), with eighteen of the thirty-six subjects assigned to each direction of head-tilt condition. There were two within-subjects factors: head position (upright versus tilted), and inducing grating orientation (+15°, +75°, −15°, and −75°), where '+' means CW and '−' means CCW.

2.1.4 *Procedure.* Rather than using adjustment to vertical, we used a double randomly interleaved staircase method to estimate the point of subjective verticality (PSV). Each staircase ran for 12 reversals with step sizes of 9° up to the first two reversals, then 3° for the next two reversals, and 0.5° step sizes after that. Only the last 8 reversals were used to estimate the PSV in each staircase. Pretest and test displays were always flashed for 500 ms. Each trial ceased when the subject responded "left" or "right" with the arrow keys and the next trial commenced 500 ms after the previous response.

2.2 *Results*

Overall mean TIs, defined as test minus pretest PSVs, are shown as a function of inducer orientation in table 1, together with standard errors. Two-tailed *t*-tests, also shown in table 1, indicated that all four TIs were significantly different from zero. Figure 3 shows the interaction between head position (tilted versus upright) and inducer tilt.

Table 1. Means and standard errors of tilt illusions, as a function of inducer orientation, together with *t*-tests for single means, experiment 1.

	Inducer orientation/°			
	+15	−15	+75	−75
Mean TI	+5.24	−6.81	−1.58	+1.49
SE	0.45	0.46	0.45	0.44
$t_{1,35}$	11.64	−14.80	−3.51	3.39
p	<0.0001	<0.001	<0.01	<0.01

Clearly, obtained TIs with head tilted (open symbols) were in every case larger than TIs obtained with head upright (solid symbols). For CW inducing gratings (circle symbols in figure 3) obtained repulsion TIs were larger with head tilted (+6.10°) than with head upright (+4.37°), as were attraction effects (−1.91° versus −1.25°, respectively). Similarly, for CCW inducing gratings (square symbols in figure 3) obtained

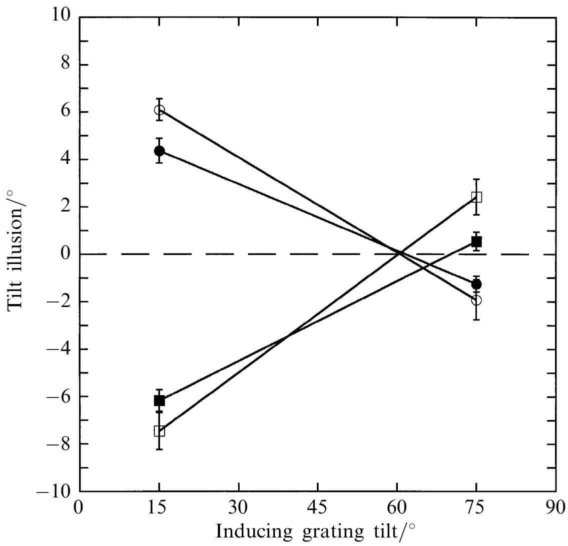


Figure 3. Tilt illusions and standard errors as a function of inducing grating tilt, experiment 1. Inducer tilts were either clockwise (circles) or counterclockwise (squares) and the head was either upright (solid symbols) or tilted 30° clockwise or counterclockwise (open symbols).

repulsion TIs were larger with head tilted (−7.45°) than with head upright (−6.17°), as were attraction effects (+2.43° and +0.45°, respectively).

A repeated-measures analysis of variance with one between-subjects factor (head tilt direction—CW or CCW) and two within-subjects factors (inducer tilt and head position—upright or tilted) indicated two significant effects: the main effect of inducer orientation ($F_{3,\,102} = 134.43$, $p < 0.0001$); and the interaction between head position and inducer orientation ($F_{3,\,102} = 8.43$, $p < 0.0001$). Two planned contrasts were carried out to test this interaction separately for repulsion and attraction effects and in both cases the interaction was significant ($F_{1,\,102} = 14.42$, $p < 0.0005$ and $F_{1,\,102} = 10.40$, $p < 0.005$, respectively).

Finally, the means and standard errors of pretest PSVs for the group tested with CW head tilts were 0.01° (0.31°) when the head was upright and 0.43° (1.21°) when it was tilted. The corresponding pretests for the CCW head tilt group were −0.53° (0.45°) and −0.07° (1.32°). Repeated-measures analyses of variance showed that in neither case was there a difference between the upright and tilted PSVs ($F_{1,\,17} = 0.13$ and 0.14, respectively, and $p > 0.7$ in both cases): head tilt increased the standard error by a factor of 3–4 but did not change the constant error.

2.3 *Discussion*

The results of experiment 1 confirmed the finding of Prinzmetal and Beck (2001) that TIs were significantly larger when observers' heads were tilted 30° than when the heads were upright. Our experiment extended the previous result in several ways. First, experiment 1 showed that the increase occurred not only in the case of repulsion effects, induced by gratings tilted ±15°, but also in the case of attraction effects, induced by gratings tilted ±75°. Second, it showed that the increased TIs were obtained with a stimulus display most commonly used in studies of the TI, namely a test grating surrounded by an abutting inducing grating (figure 2b), rather than the more unusual display used by Prinzmetal and Beck (figure 2a). Third, in the present experiment we measured TIs as test minus pretest effects rather than just as test measures, in case constant pretest errors differed significantly between head-upright and head-tilted conditions, although such a difference was not obtained: head tilt increased only the variance of PSVs, consistent with previous findings of large individual differences in the incidence and magnitude of A− and E− effects (Howard 1982).

Nevertheless, two aspects of our results suggested that it would be of interest to attempt more closely to repeat the Prinzmetal and Beck experiment using stimuli more similar to theirs. First, whereas Prinzmetal and Beck reported that head and body tilt of 30° increased TIs from 2.4° to 9.4°, a relatively large increase of 7°, the effects we obtained were increased by head tilt by no more than 1°–2°. Second, careful inspection of our data revealed a suggestion that the increase in the repulsion TI with head tilt tended to be slightly larger when the directions of head tilt and inducer tilt were the same than when they were opposite. Thus, when head and inducer tilts were both CW or CCW, the increases in TIs were +2.35° and −1.45°, respectively. When head tilts were CW and CCW but inducer tilts were in the opposite direction, TIs increased by −1.10° and +1.11° respectively. Since these were between-subjects effects, it was not surprising that the interaction of head direction by inducing grating direction was not significant ($F_{1,102} = 1.01$, $p > 0.3$).

However, given that Prinzmetal and Beck used only CCW inducer and body tilts, we were interested in examining whether effects might differ between same and opposite head and inducer tilts in a fully repeated-measures design. The tilt-constancy theory put forward by Prinzmetal and Beck states that the sole effect of body and/or head tilt is to increase the observer's reliance on visual context. Accordingly, the theory would seem to predict no difference between TI increases with same and opposite head and inducer tilts, with the sole effect of head tilt being to increase the effectiveness of any equally tilted inducing stimulus, whatever its direction of tilt. To test this prediction was one aim of experiment 2. The second aim was to use methods more similar to those of Prinzmetal and Beck to see whether we could obtain illusion increases due to head tilt as large as those that Prinzmetal and Beck reported.

3 Experiment 2

Because we had no access to a tilting chair, we were not able to attempt to replicate the Prinzmetal and Beck TI experiment. However, the stimuli and the procedures we used in experiment 2 much more closely resembled those of Prinzmetal and Beck than did our methods in experiment 1.

3.1 *Method*

3.1.1 *Subjects.* Twenty-three subjects were all emmetropic or had appropriately corrected vision. Sixteen of the subjects were from an introductory Psychology course at Macquarie University and volunteered in return for nominal course credit. An additional seven subjects were members of an advanced undergraduate Perception class.

3.1.2 *Apparatus and stimuli.* The apparatus was as in experiment 1. The white-on-black inducing grating had a duty cycle of 0.05 and closely resembled that used by Prinzmetal and Beck (2001). The maximum and minimum luminances of the grating were 61.6 cd m^{-2} and 0.42 cd m^{-2}, respectively, so that contrast, defined as $(L_{max} - L_{min})/(L_{max} + L_{min})$ was 0.98. The two test dots were 0.15 deg in diameter and were separated vertically by 3.6 deg. Starting positions were randomly 2.84 deg left or right of vertical alignment and each arrow key-press moved the upper dot 0.14 deg to the left or right. The grey background screen had a luminance of 14.6 cd m^{-2}.

3.1.3 *Procedure.* Each trial began with a homogeneous grey screen. A tone prompted the subject to press the space-bar to begin a trial. When the stimulus appeared, subjects used the same adjustment method as that used by Prinzmetal and Beck to set the upper dot to vertical alignment. When satisfied with the adjustment, the subject pressed the space-bar to record the setting and present the next trial.

3.1.4 *Experimental design.* All subjects were tested under 4 repeated-measures conditions, 2 head tilts (upright and tilted CW 30°) × 2 inducing tilts [+(CW)18° and −(CCW)18°], the same extents of head and inducer tilts used by Prinzmetal and Beck. However, unlike Prinzmetal and Beck, we also obtained pretest settings with a blank black surround and measured illusions as test minus pretest settings. Each subject completed 10 replications under each of the experimental conditions and these were averaged for the purpose of analysis.

3.2 *Results*

Mean TIs, defined as test minus pretest vertical settings, are shown as a function of inducer orientation in table 2, together with standard errors. Two-tailed *t*-tests, also shown in table 2, indicated that three of the four TIs were significantly different from zero.

Table 2. Means and standard errors of tilt illusions, as a function of inducer and head orientation, together with *t*-tests for single means, experiment 2.

	Inducer/Head orientation/°			
	+18/upright	−18/upright	+18/tilted	−18/tilted
Mean TI	+1.04	−1.05	+2.53	−0.74
SE	0.22	0.24	0.60	0.60
$t_{1,22}$	4.73	−4.38	4.22	−1.23
p	< 0.001	< 0.001	<0.001	>0.9

Figure 4 shows the interaction between head position (tilted versus upright) and inducer tilt. In accordance with the tendency noted in experiment 1, the increase in the TI with head tilt appears larger when both head and inducer were tilted CW than when the head was tilted CW and the inducer was tilted CCW. It can also be noted from both figure 4 and table 2 that with head upright, the −18° and +18° inducing gratings resulted in equal but opposite TIs.

A subjects by treatments repeated-measures analysis of variance showed that the main effect of head tilt was significant ($F_{1,22} = 6.58$, $p < 0.02$). The main effect of inducer tilt was also significant ($F_{1,22} = 23.60$, $p < 0.0001$). The interaction between head tilt and inducer tilt was not significant ($F_{1,22} = 1.17$, $p > 0.2$).

The means and standard errors of pretest settings for the group tested with +18° inducing grating tilts were −0.37° (0.25°) when the head was upright and −1.25° (1.21°)

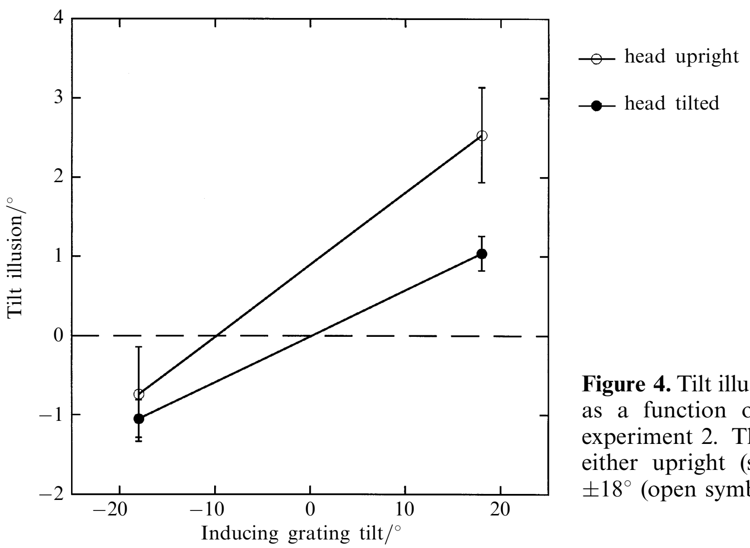


Figure 4. Tilt illusions and standard errors as a function of inducing grating tilt, experiment 2. The observer's head was either upright (solid symbols) or tilted ±18° (open symbols).

when it was tilted. The corresponding pretests for the $-18°$ inducer tilt group were 0.03° (0.32°) and $-0.97°$ (1.05°). Repeated-measures analyses of variance showed that in both cases there was a difference between the head-upright and head-tilted vertical settings ($F_{1,22} = 6.49$ and 8.29, and $p < 0.02$ and < 0.01, respectively).

3.3 *Discussion*

The results of experiment 2 confirm those of experiment 1 in demonstrating that a head tilt of 30° increases TIs but this time with stimuli and methods much more similar to those employed by Prinzmetal and Beck. However, we again obtained a maximum increase with head tilt of only $1°-2°$ or less, much smaller than the 7° they obtained, and then only when head and inducer were tilted in the same direction.

Consistent with Prinzmetal and Beck's (2001) second experiment in which they obtained a positive (CW) vertical setting when subjects were tilted CCW 30°, we found that our CW head tilt resulted in pretest vertical settings that were significantly more CCW than those obtained with head upright. Prinzmetal and Beck did not measure a pretest with body upright but the vertical setting error they obtained with 30° CCW body tilt was very small, $+0.87°$, and not different from zero. Our pretest vertical settings with head upright and tilted CW were, respectively, $-0.17°$ (0.20°) and $-1.11°$ (0.66°), both slightly CCW of true vertical.

The tilt-constancy theory of visual illusions postulates that head tilt increases TIs simply because it increases reliance on visual context cues. If that were the case, then the CW head tilt would have been expected to increase the almost identical but directionally opposite TIs obtained with the $+18°$ and $-18°$ inducing gratings by equal but opposite amounts. That, in turn, would have led to a prediction of no main effect of head tilt but a significant head-tilt by inducer-tilt interaction. Instead, the main effect of head tilt was significant but the interaction was not, indicating that the CW head tilt resulted in the overall TI becoming more positive, regardless of the inducer tilt direction. A possible reason for the ineffectiveness of the CCW inducing grating relative to the CW inducing grating with CW head tilt is as follows. When head and grating are tilted 30° CW and 18° CW, respectively, the inducing grating is tilted only 18° from gravitational vertical and 12° (not considering torsion) from retinal vertical. However, an inducing grating tilted 18° CCW is still tilted 18° from gravitational vertical but 48° from retinal vertical, possibly too far away in orientation to act as a frame of reference for vertical judgments.

4 General discussion

The tilt-constancy theory of visual illusions put forward by Prinzmetal and Beck (2001) originally seems to have emerged from earlier studies of the 'Mystery Spot', a Californian roadside attraction where various illusions can be experienced, such as balls appearing to roll uphill, and the relative heights of people appearing to change as they change position in front of a shed on a hillside tilted 18° CW of horizontal (Shimamura and Prinzmetal 1999). It is instructive to consider this report because it includes what is essentially an earlier version of the tilt-constancy theory and also explains the choice of stimulus parameters in some of the later Prinzmetal and Beck (2001) experiments.

Shimamura and Prinzmetal had two subjects perform two tasks at the Mystery Spot in front of the shed. First, they adjusted one marker on a pole on their right to be at the same apparent height as a left-hand marker. Because the shed, tilted down on the right, made the right-hand marker appear too high when it was physically at the same height as the left-hand marker, subjects set it too low to make the heights appear the same. Second, the subjects told the experimenters when the orientation of a rod presented in front of the shed appeared horizontal. The shed tilting down at the right made a truly horizontal rod appear tilted CCW of horizontal so that it had to be set down at the right to appear horizontal. When the errors in the marker's height judgment were converted to angular errors (3.5°), this angular error was virtually identical to that measured by the tilting rod (3.4°). In simple terms, the 18° CW tilted shed made both the virtual line joining a pair of truly horizontal markers and the truly horizontal rod appear tilted CCW by about the same amount. Shimamura and Prinzmetal (1999) replicated the Mystery Spot height illusion in the laboratory. They presented two horizontally aligned dots superimposed on an 18° CCW tilted real-world campus scene and found that the right-hand dot appeared too high. In our view, this is simply a TI with the virtual line defined by the dots undergoing an orientation repulsion effect. Indeed, long before this Shimamura and Prinzmetal experiment, it was shown that such real-world scenes not only induced tilt illusions but that they induced both repulsion and attraction effects (Purcell et al 1978).

Shimamura and Prinzmetal then offered the 'Orientation Framing Theory', clearly a precursor to the tilt-constancy theory of visual illusions of Prinzmetal and Beck (2001), and they concluded, inter alia, that:

> "Misperceptions of the true gravitational axes distort many aspects of perceptual processing, including object orientation, object location, line length, and angles .... In sum, we explain the properties of the height illusion at The Mystery Spot in terms of a tilt-induced effect. This illusion is thus closely related to the rod–frame and other tilt-induced illusions. These findings extend tilt-induced illusions to include distortions of height and spatial location."

It is instructive to consider these origins of the tilt-constancy theory because they seem to account for the choice by Prinzmetal and Beck of an inducing tilt of 18° (the same as the shed tilt at the Mystery Spot) and a pair of dots for the measurement of perceived cardinal axes (dots resembling the height markers used at the Mystery Spot). It is also of interest to note that, whereas Shimamura and Prinzmetal, in the above quote, wish to equate illusions of tilt, height, and spatial location, it has been strongly argued elsewhere by others, and with relevant data, that it is *not always* possible to equate judgments in the orientation and position domains (Wenderoth 1978, 1980a, 1983; Wenderoth and O'Connor 1987).

On the basis of previous findings (Asch and Witkin 1948; DiLorenzo and Rock 1982; Witkin and Asch 1948), Prinzmetal and Beck (2001) predicted that the TI and related illusions would increase when the observers' head or head and body were tilted, and obtained that result with the TI as well as the Zöllner, the Poggendorff, and the Ponzo illusions. Prinzmetal and Beck claimed that this increase in errors occurred because a tilted observer is forced to place increased reliance on visual context cues in judging vertical or horizontal, at the expense of gravity-based information that otherwise mitigates the effect of the tilted visual context when the observer is upright. The experiments that we have reported here have confirmed that tilting the observer's head 30° does increase the TI, as reported by Prinzmetal and Beck. Experiment 1 showed that this occurs with a test grating surrounded by an abutting inducing grating (figure 2b), a more standard display than that used by Prinzmetal and Beck (figure 2a). Whereas Prinzmetal and Beck tested only repulsion effects with inducers tilted 18°, we additionally showed that both repulsion and attraction effects increased when the inducer was tilted 15° or 75°, respectively. However, the TI increases we obtained were of the order of 1°–2°, unlike the 7° increase reported by Prinzmetal and Beck. It is possible that this difference in the magnitude of the effects obtained results from Prinzmetal and Beck's use of whole-of-body tilt compared to our use of head tilt only, so that the neck joint signals could have reduced errors in our experiments. This possible explanation of our smaller effects needs to be tested.

There was a suggestion in experiment 1 that larger increases in the TI occurred when the inducer and the head were tilted in the same rather than opposite directions. This was confirmed in experiment 2 and it was argued that this result is not predicted by the tilt-constancy theory. Interestingly, DiLorenzo and Rock (1982) measured the rod-and-frame illusion both with head upright and head tilted 45° CW. They too predicted and found that the illusion increased with head tilt owing, they argued, to a "weakening [of the] efficacy of available gravity cues" (page 540). Note, however, that they also obtained a significant increase in illusion with head tilt *only when the head and frame tilts were in the same direction*, yet they failed to discuss that result further.

Apart from the data we have obtained in experiment 2 which are difficult to explain by the tilt-constancy theory, there are also reasons to doubt the claim by Prinzmetal and Beck that the reason that the Poggendorff illusion increased when their observers' bodies were tilted was because the illusion is essentially one of misperceived orientation (figure 1c). It is extremely important to consider the previous literature that casts doubt upon the claim that the Poggendorff effect arises from orientation processing mechanisms, because if this is not the basis of the illusion then why does it increase with body tilt; and might that reason, whatever it is, also account for the increases in the Zöllner and Ponzo effects? So: what are the data that strongly suggest that the Poggendorff effect is not one deriving from orientation constancy mechanisms?

First, there are several studies that manipulate perceived spatial layout and these manipulations affect the size of the illusion considerably but should be inconsequential for orientation illusion effects (Gillam 1998; Spehar and Gillam 2002). Second, it has been shown that when an oblique transversal abuts a vertical inducer and subjects are instructed to set dots to the virtual continuation of the transversal, errors are much larger at the abutting end of the transversal than at the free end (Wenderoth et al 1978). A simple misperception of the orientation of the entire transversal predicts equal errors at both ends. Third, it has been shown that Poggendorff illusions are largest when the transversal exactly abuts the vertical inducer but are markedly reduced if the transversal either falls short of the inducer or passes through it (Tong and Weintraub 1974). The TI would be expected to be equally large (at least) when inducing and test lines intersect compared to when they merely abut. Fourth, if the Poggendorff effect were explicable simply in terms of misperceived transversal orientation (figure 1c) then the illusion should be identical whether subjects are instructed perceptually to align the abutting end of the upper transversal segment to the apparent extension of the lower transversal or to align the non-abutting, distal tip of the upper transversal. Contrary to this prediction, errors are much larger with the former instruction (Wenderoth 1980b, 1981). Fifth, Prinzmetal and colleagues claim that the TI, Ponzo, Zöllner, and Poggendorff illusions all peak in magnitude when the angle between the test and inducing segments is of the order of 10° – 15°, thus allegedly implicating a common mechanism (Prinzmetal et al 2001; Shimamura and Prinzmetal 1999). If the Poggendorff illusion is measured in millimetres by which the upper right transversal is set too low, then it is true that the Poggendorff effect is larger when the abutting angle is of the order of 15° rather than 40° – 50° (Weintraub and Krantz 1971). However, when such errors are converted to angular errors, the appropriate comparison with the TI, then the peak effect no longer occurs with the smaller angle (see Robinson 1972, page 78). For example, Weintraub and Krantz obtained vertical errors of about 30 mm and 9 mm for transversal angles of 16.7° and 50°, respectively, when the inducing parallels were 60 mm apart but an arctan transformation produces angular errors of 2.74° and 5.43°, respectively. However, the TI is negligible with a test-inducing angular separation of 50°.

Taken together, we believe that the data reported here, plus the additional issues discussed above, cast considerable doubt upon the veracity of the very simple tilt-constancy theory espoused by Prinzmetal and colleagues. That theory attempts to explain a subset of visual illusions entirely in terms of tilt-constancy mechanisms. To question this, as we are doing, is not to deny that some proportion of some visual illusions is explicable in terms of orientation-constancy mechanisms. Prinzmetal and Beck (2001, page 207) refer to Wenderoth and Johnstone (1988) as measuring a rod-and-frame effect but they did not; rather they used a square frame not to induce a tilt effect but rather to eradicate an attraction ('indirect') TI, by providing the observer with visual cues to the cardinal axes of space. Wenderoth and Johnstone (1988, pages 310 – 311) stated:

> "In this context, the indirect tilt illusion could be seen as arising from such global mechanisms involved in orientation constancy. Under normal circumstances, a rich collection of cues to vertical and horizontal ... is available in the visual field so that orientation coding errors are minimised. However, under impoverished conditions in the laboratory, when the inducing stimulus is the sole reference orientation, errors occur. This could explain why the surrounding frame in our Experiments 4, 5, and 6 removed indirect effects by providing the global orientation mechanisms with additional orientation data.
>
> If this hypothesis is plausible, then the direct TI might also be expected to have a small component that derives from the same global mechanism and it is consistent with this expectation that the manipulations which we performed to reduce inhibition attenuated but never *eradicated* direct effects."

Thus, Wenderoth and Johnstone preceded Prinzmetal and Beck in implicating tilt-constancy mechanisms as *partial* determinants of repulsion TIs and *complete* determinants of attraction TIs. We believe that this is consistent with our finding, in experiment 1, that tilting the observer's head increased both repulsion and attraction effects by the same, but relatively small, amount. It remains to be determined what is the extent to which tilt-constancy mechanisms contribute to the magnitudes of the Zöllner, Poggendorff, and Ponzo illusions. In addition if, as we have argued, the Poggendorff illusion is not essentially one that derives from orientation-constancy mechanisms, there is a need to investigate further why it increases with body tilt.

Finally, it is of interest to note that if the Ponzo illusion were partially determined by TI mechanisms, then, if the angle between the inducing lines were increased to 150°, each of those lines would be at an angle of 75° to gravitational vertical and so should induce an attraction rather than a repulsion effect. This, in turn, would result in apparent contraction of the space at the top of the Ponzo figure resulting in the perceptual *contraction* of the upper horizontal test line, a reversal of the usual Ponzo effect. Interestingly, and this time consistent with Prinzmetal and Beck's ideas, Pressey et al (1971) have reported precisely that result. Clearly, further research is required to determine the number and the nature of the mechanisms underlying the subset of illusions that Prinzmetal and Beck have shown to increase with body tilt.

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