Crossing the line: Estimations of line length in the Oppel-Kundt illusion

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In the Oppel-Kundt illusion, one of the oldest and least understood geometrical visual illusions, a line subdivided by a series of short orthogonal ticks appears longer than an identical line without these. Paradoxically, bisecting a long line with a single tick leads to perceived shortening of the line. We have systematically investigated the effects of adding 1 to 12 ticks on perceived line length and results suggest that at least three mechanisms must be at work: (a) bisection, which reduces perceived length; (b) a filled extent effect, which is also apparent in the von Helmholtz illusion, though no satisfactory explanation for it exists; and (c) a local contour repulsion effect of the penultimate tick upon the perceived position of the end tick, but this effect, though significant, is too small to explain the Oppel-Kundt illusion in its entirety.

Introduction

One of the earliest visual illusions to be investigated formally was the Oppel-Kundt illusion. In this illusion, a horizontal line with regularly spaced vertical line segments is perceived as larger than another one that is unfilled. Oppel (1855) was the first researcher to observe and report that dividing a stripe into its subparts affected its perceived size. Kundt (1863) investigated this effect further using the stimulus shown in Figure 1. The illusion was discussed by Helmholtz (1925), who concluded that filled spaces look bigger than unfilled spaces, giving us the Helmholtz squares illusion as further evidence of this general principle (Thompson & Mikellidou, 2011).

What is now referred to as the Oppel-Kundt illusion has also been found in dynamic touch for a haptically filled space (Sanders & Kappers, 2009) and in three-dimensional (3-D) space (Deregowski & McGeorge, 2006). Recently it has been established that distortions of space induced by Oppel-Kundt stimuli are not a consequence of a motor response bias but a perceptual illusion of length (Pia et al., 2012).

Several studies over the years have investigated how changing the number of dividing lines—or ticks—affects the size of the Oppel-Kundt illusion. Whereas Robinson (1972) suggested that the greater the number of dividing lines, the greater the size of the illusion, Coren and Girgus (1978) specified that this increase happens only up to a critical point; beyond that, the perceived size gradually decreases. Obonai (1933) suggested that the maximum effect is found with between 7 and 13 ticks, while Piaget and Osterrieth (1953) found that the maximum effect occurred when 9 to 14 ticks were present. Piaget and Osterrieth (1953) and Oyama (1960) have argued that both a very small and a very large number of dividing ticks moderate the effect, with seven to nine ticks increasing the illusory percept to its maximum.

More recently Craven and Watt (1989) proposed that the average contour density, determined by the number of zero-crossings in a range of spatial scales (Watt, 1990), is responsible for the phenomenon. Moreover, when the illusion was measured after adaptation of the subject to parallel lines, no after-effect was found, leading to the conclusion that the illusory percept is not a product of an uninterrupted spatial calibration mechanism (Craven, 1993).

In contrast to Helmholtz's (1925) filled spaced notion, it has been demonstrated that the addition of a single vertical tick induces a reduction in the perceived size of a horizontal line. Specifically, in their investigation of the vertical-horizontal illusion (Figure 2) Mamassian and de Montalembert (2010) revealed that two components contributed to the perceived shortening of the horizontal. The first component, anisotropy, reduces the perceived size of horizontal lines in comparison to vertical ones, and the second component, bisection, makes divided lines look *shorter* than undivided lines. This seems to conflict with Helm-

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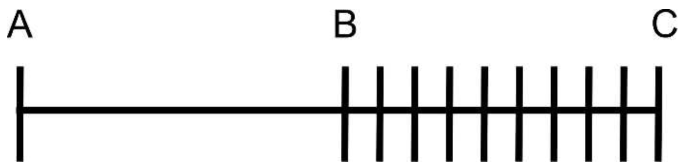

Figure 1. The stimulus used by Kundt (1863). Line segment AB looks shorter than segment BC.

holtz's filled space notion; if several ticks on the divided section of the Oppel-Kundt figure make that section look longer, why does a single tick make it look shorter?

Experiment 1

The aim of this experiment is to observe how the perceived size of a horizontal line can vary with the addition of regularly spaced ticks. We manipulated the number (0, 1, 5, 9) of ticks on a horizontal line of fixed length and each one of these was compared against a horizontal line without ticks of variable length.

Method

A single-interval, spatial two-alternative forced-choice method of constant stimuli was used to construct psychometric functions from which the point of subjective equality (PSE) was determined. Four conditions were interleaved; in the control condition (no vertical ticks) a standard horizontal line (6.1° long, 0.12° wide) with an end tick at each end was compared with one of seven comparator stimuli composed of a similar horizontal line, varying in size from slightly smaller to slightly longer than the standard. The deviations from the standard length were −0.9°, −0.6°, −0.3°, 0°, 0.3°, 0.6°, 0.9°. For the other three conditions, one, five, or nine vertical ticks crossed the standard horizontal line in a regular manner. The height of each vertical tick was 0.61° and the width was 0.12°. The size of the gap between the left and right stimulus varied between 5°–7°, depending on the size of the comparator stimulus and the amount of jittering introduced in every given trial. As in all subsequent experiments, no fixation point was used as we did not want to provide any means of reference to the participants, something that would allow them to use alternative strategies to carry out the task. Figure 3 illustrates the stimuli used in this experiment.

Each of eleven naive observers (age range 18–27) undertook 336 trials: eight pairs of stimuli (four configurations with the variable on both left and right; these conditions were subsequently collapsed) each presented six times for seven variable stimulus sizes. Participants were asked to indicate the longer horizontal line using a response box. Stimuli were positioned one next to the other and presented simultaneously for 1000 ms. The stimulus lines were black on a bright ground (20 cd/m^2). The timeline for the experiment is shown in Figure 4.

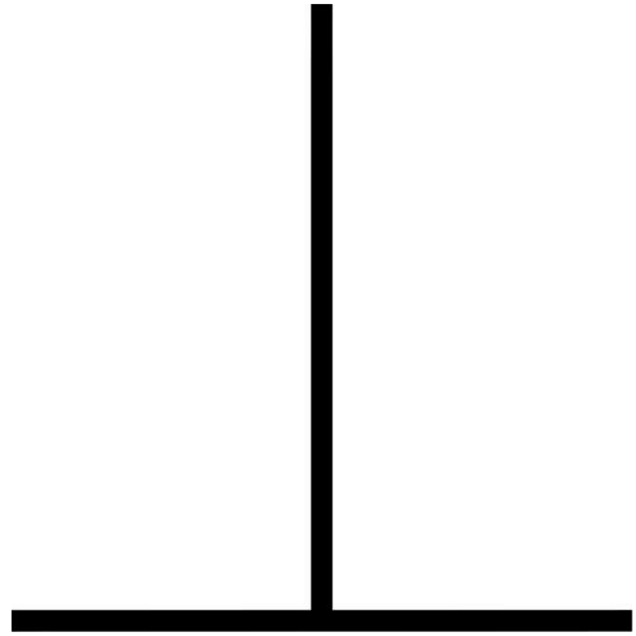

Figure 2. The vertical-horizontal illusion. Although of equal lengths, the vertical line looks longer.

Results

Comparisons between a horizontal line and the four conditions were made so that psychometric functions could be determined and PSEs calculated for 11 participants. Figure 5 illustrates the group results and the psychometric functions generated for a single participant for all four conditions.

Bisecting a line with a single tick results in the line being perceived shorter (by 6.8%) as has been found in the vertical-horizontal illusion. A line with nine ticks is overestimated in length (by 4.9%) in accord with the Oppel-Kundt illusion. When there are five ticks on the line there was no significant difference in its perceived length. The results show that the perceived length of the horizontal segment in our stimuli was significantly affected by the number of vertical lines crossing it, $V = 0.65$, $F(3, 30) = 10.23$, $p < 0.05$. A z test revealed a significant decrease in the perceived size of a horizontal line compared to the actual physical size of the stimulus, when a single tick was present ($p < 0.01$).

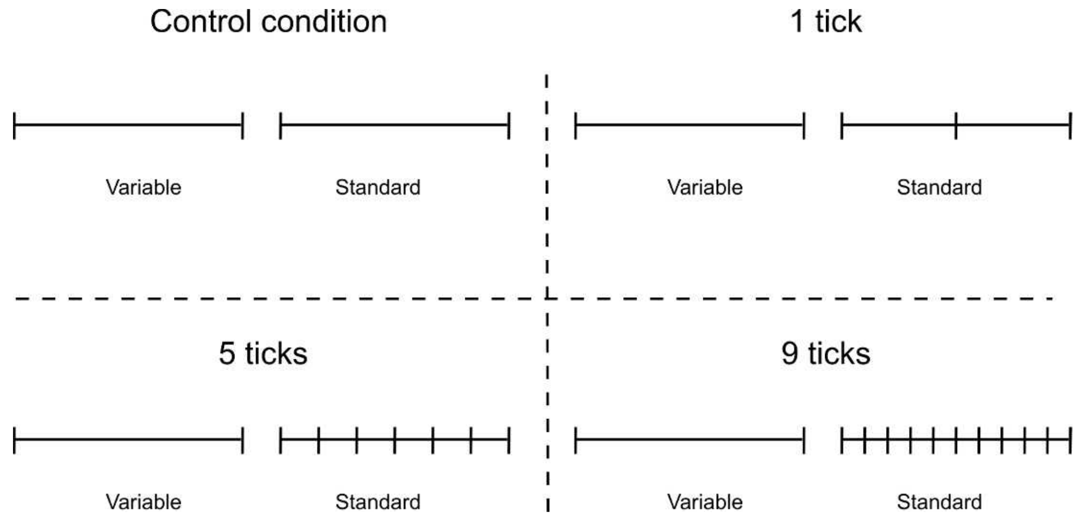

Figure 3. Stimuli used in Experiment 1. The variable stimulus was always a horizontal line with a tick at each end. Note that the number of tick marks on the standard stimulus excludes the end ticks in each case.

Another z test revealed a significant increase in the perceived size of a horizontal line compared to the actual physical size of the stimulus when nine ticks were present ($p < 0.01$).

Experiment 2

Piaget and Osterrieth (1953) demonstrated that the Oppel-Kundt illusion is maximal when 9 to 14 tick lines are present, whereas Obonai (1933) suggested that the maximum effect is found between 7 and 13 lines. The aim of this experiment is to observe how the magnitude of the Oppel-Kundt illusion is affected around and beyond nine ticks. As in Experiment 1, we manipulated the number of vertical lines regularly spaced on the standard component of the stimulus with 0, 1, 8, 10, and 12 vertical ticks, and each one of these was compared against the variable component of the stimulus.

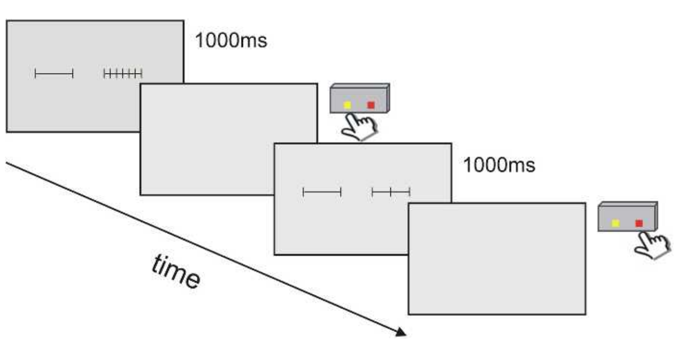

Figure 4. Timeline of Experiment 1 showing two trials. Order of stimuli was random throughout.

Method

The experimental details are identical to Experiment 1 with three modifications. Firstly the stimuli were presented in the more familiar configuration of the Oppel-Kundt illusion, i.e., as a single horizontal line with one half filled with ticks and the other without any ticks. Five conditions were interleaved: 0, 1, 8, 10, and 12 ticks were positioned on the standard horizontal line in a regular manner.

Secondly, the range of the variable component values was wider. This was done in order to capture both ends for the psychometric function for all types of stimuli and generate a more accurate mean PSE for each individual case. Deviations from the standard width were –1.4°, –0.9°, –0.5°, 0°, 0.5°, 0.9°, and 1.4°, with the length of the variable stimulus ranging between 4.7° and 7.5°. Figure 6 illustrates the stimuli used in this experiment.

Thirdly, the presentation time of the stimuli is reduced from 1000 to 750 ms, a duration which was found not only to be sufficient for participants to make their judgments, but it also allowed for more repetitions to be carried out within the same amount of time. Each of eight naive observers (four females; age range 18–27) undertook 1,750 trials; 10 pairs of stimuli each presented 25 times for seven variable stimulus lengths. Participants were asked to indicate the longer horizontal component using a response box and the control condition was used to evaluate whether or not they were able to carry out the task. The luminance of the stimuli was approximately 20 cd/m^2, whereas the background luminance approached 0 cd/m^2, so the contrast is approaching 1.00. This reversal of contrast polarity compared to Experiment 1 was carried out to

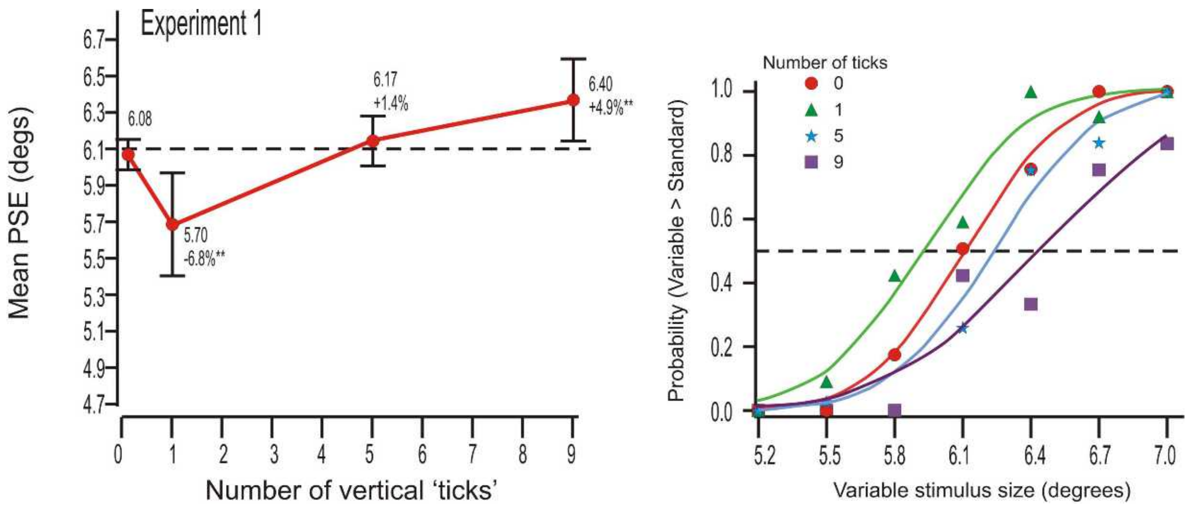

Figure 5. (Left) Results from Experiment 1, showing a significant underestimation of the perceived size of a horizontal line with a single tick by 6.8% and a significant overestimation of the perceived size of a horizontal line with nine ticks by 4.9% ($N = 11$). (Right) Psychometric functions for a single participant from Experiment 1.

determine whether this is a determining factor of either of the two illusions.

Results

Comparisons between the simple horizontal component of the stimulus and the five conditions were made so that psychometric functions could be determined and PSEs for eight participants. The mean PSEs for the eight subjects are shown in Figure 7 along with the psychometric functions generated for a single participant for all five conditions.

These results show that participants could match the size of the two simple horizontal components in the control condition. Additionally, the perceived length of a bisected horizontal line was found to be approximately 13% smaller than that of an unbisected line of the same size, an effect even larger than that found in Experiment 1, but with considerable variance between participants. When 8, 10, or 12 ticks were equally spaced along the length of a horizontal, there was a 4.8%, 5.2%, and 5.1% increase in its perceived size, respectively. This suggests that the magnitude of the effect saturates once about eight tick lines are present.

Mauchly's test indicated that the assumption of sphericity had been violated, $\chi^2(9) = 57.591$, $p < 0.05$; therefore multivariate tests are reported $\varepsilon = 0.28$. A repeated-measures ANOVA revealed that the perceived size of the divided part of the stimulus was significantly affected by the number of vertical lines crossing it, $V = 0.87$, $F(1.11, 7.80) = 14.7$, $p < 0.05$. A z test revealed a significant decrease compared to the actual physical

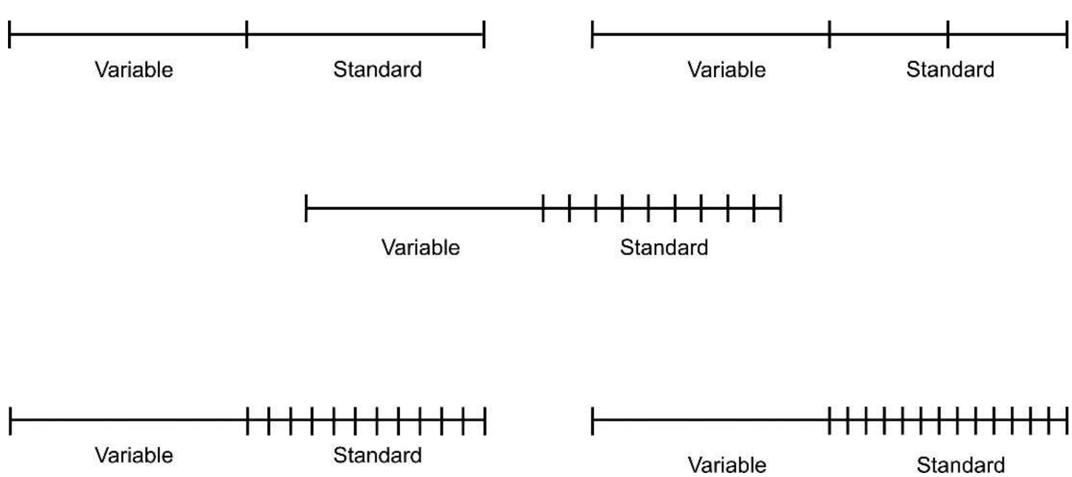

Figure 6. Stimuli used in Experiment 2, with 0, 1, 8, 10, and 12 ticks. The variable part of each stimulus (which could occur either on the left or right side of the stimulus) contained no vertical ticks.

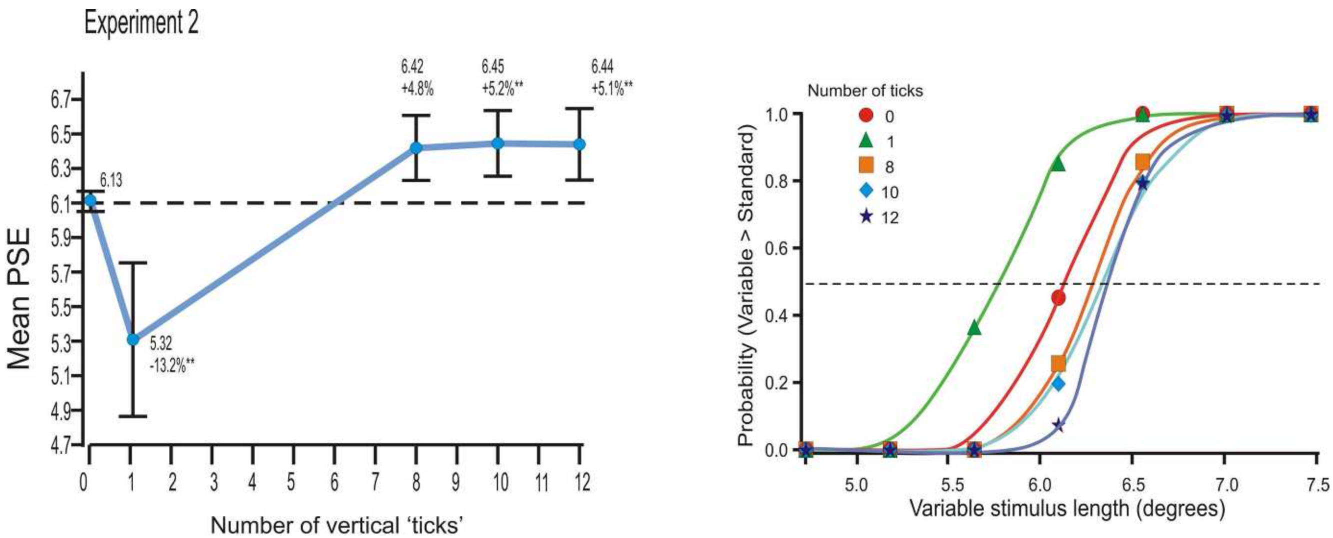

Figure 7. (Left) Results from Experiment 2, showing a significant underestimation of the perceived size of a horizontal line with a single tick by ~13% and a significant overestimation of the perceived size of a horizontal line with 8, 10, and 12 ticks by ~5% ($N = 8$). Error bars show 95% CI. (Right) Psychometric functions for a single participant from Experiment 2.

size of the stimulus in the perceived size of a horizontal line when a single tick was present ($p < 0.01$). Three more z tests revealed a significant increase compared to the actual physical size of the stimulus in the perceived size of a horizontal line when 8, 10, or 12 ticks were present ($p < 0.01$).

Discussion

The main purpose of Experiment 2 was to observe changes, if any, in the size of the Oppel-Kundt illusion when 8, 10, or 12 vertical ticks were added on a horizontal line. Results from the current experiment confirmed those of Experiment 1, albeit with a larger effect of a single tick (~13%). This result was surprising, not only in comparison with Experiment 1, but also with our previous reports on the effects of bisection (Mikellidou & Thompson, 2013), both showing the effect of a single tick was to reduce perceived length by 7%. This difference could be explained by the large error bars for this condition in Experiment 1, which show 95% confidence intervals. When 8, 10, or 12 ticks were present, the Oppel-Kundt illusion was approximately 5% with no significant differences between the three conditions. Additionally, taking into account results from Experiment 1, it appears that the size of the Oppel-Kundt illusion is relatively constant from 8 to 12 vertical ticks, inducing a 5% increase in the perceived size of the horizontal line. Due to a plateau in the results between 8 to 12 ticks, we are unable to determine at which point exactly the maximum effect would occur. However, any function fitted to these data would reveal a peak at no less than 10 vertical ticks, and this is in accordance with results from Spiegel (1937, as cited in Wackermann & Kastner, 2009) and Wackermann and Kastner (2009), which showed a maximal Oppel-Kundt illusion at 17 and 16 lines, respectively. Please note that although the contrast polarity (stimulus luminance 20 cd/m^2; background luminance approaching 0 cd/m^2) was reversed in comparison with Experiment 1, no differences were observed in the pattern of results.

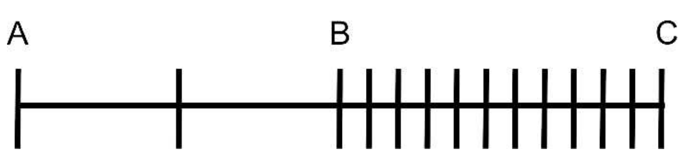

Figure 8. The best Oppel-Kundt illusion? The length of AB is shortened by the single tick while the length of BC is made longer by the 10 ticks.

Experiment 3

We predict that the greatest illusory percept should be generated by the stimulus illustrated in Figure 8 as the bisected left side will be underestimated by at least 7% and the right side will be overestimated by approximately 5%.

Method

The experiment was similar in most respects to Experiment 2. Ten vertical lines were positioned within

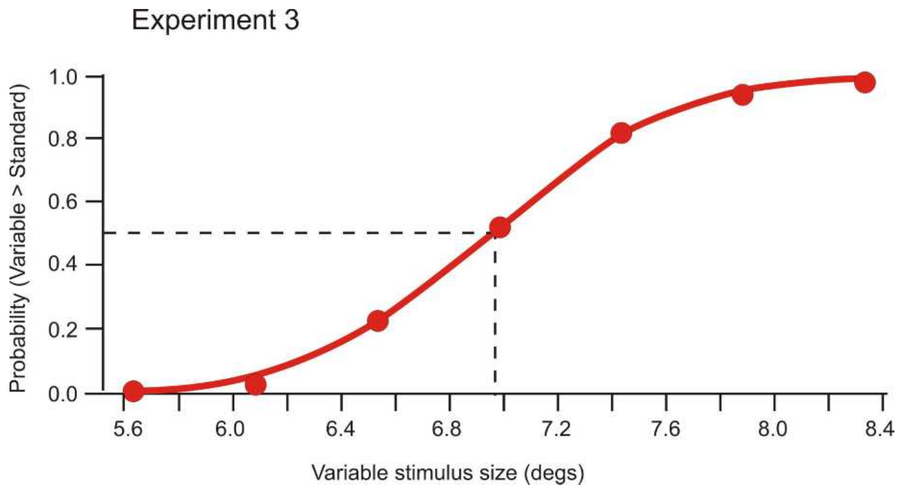

Figure 9. Psychometric function for a single participant from Experiment 3. This participant has a PSE where a bisected line of 6.1° is matched in length by a line of 6.97°.

the standard horizontal line BC in a regular manner. As in the previous experiments this standard was 6.1° in length. This standard part of the stimulus was compared with one of seven comparator stimuli composed of a bisected horizontal line AB, varying in size from 5.6° to 8.3° in steps of 0.45°; a range that encompassed the psychometric function. The size of the comparator part of the stimulus was varied in such a way so that the single vertical tick in the middle was always bisecting it.

Each of five naive observers (two female) undertook 350 trials; two pairs of stimuli each presented 25 times for seven variable stimulus sizes. Participants were asked to indicate the longer horizontal line using a response box and the control condition was used to evaluate whether or not participants were able to carry out the task. Stimuli were positioned one next to the other and presented simultaneously for 750 ms. The luminance of the stimuli approached 0 cd/m^2 whereas the background luminance was 20 cd/m^2, so the contrast is approaching 1.00.

Results

Figure 9 depicts the psychometric function generated for a single participant. Overall the average match for the five participants was 6.95° (95% CI = ±0.50°), an effect size of 14%.

As predicted this is a large illusion brought about by opposite effects affecting the two halves of the display, a reduction in perceived length of the bisected half and an increase in the length of the half filled with 10 ticks. Unfortunately the error bars are sufficiently large to prevent us from determining whether these two effects are additive.

Experiment 4a

The aim of this experiment is to investigate whether the Oppel-Kundt illusion arises due to the repulsion of the end ticks by the adjacent ticks. Such a mechanism was put forward by Ganz (1966), who proposed that shifts in the apparent position of contours arise when visual stimuli are located close to one another, as in the case of the figural aftereffect of Kohler and Wallach (1944). A similar hypothesis, proposing angle expansion of acute angles due to lateral inhibition between orientation channels, was put forward by Blakemore, Carpenter, and Georgeson (1970). Subsequently physiological measurements made in the visual cortex of the cat by Blakemore and Tobin (1972) provided support for this hypothesis. Such mechanisms could provide an explanation of the Oppel-Kundt figure (see Figure 10), and a direct test of this hypothesis was carried out by Rentschler, Hilz, and Grimm (1975). The perceived position of a vertical test line was measured by subjects aligning a small dot below the line to be collinear with it. A second vertical line, the inducing line, was added to the display at a range of distances from the test line. The expectation was that the introduction of the inducing line would repel the test line in a manner analogous to Blakemore et al.'s (1970) acute angle expansion. Surprisingly, no repulsive effects were observed by Rentschler et al. (1975); indeed the only condition that produced any perceived shift in the test line was when a high-contrast inducing line was positioned close to a low-contrast test line. In this case an attraction of the test line towards the inducing line was observed.

In the present experiment we have used the same alignment task employed by Rentschler et al. (1975) to investigate if any contour-shift of the end ticks of the

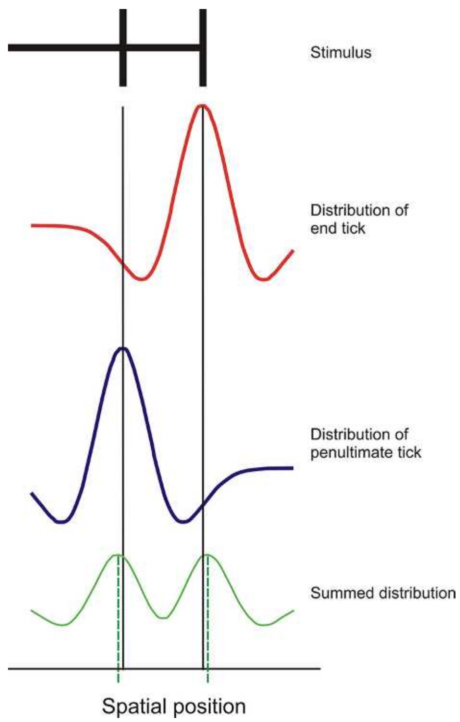

Figure 10. Contour repulsion from lateral inhibition. Analogous to the Blakemore et al. (1970) angle expansion model, adjacent lines are mutually repelled by lateral inhibitory processes.

Oppel-Kundt illusion occurs. We manipulated the number of vertical ticks regularly spaced on the standard stimulus with 0, 1, and 9 ticks, and participants were asked to indicate the position of a small tick located under one of these relative to one of their end ticks (i.e., left or right). This is a vernier acuity task at which we expect participants to be extremely good.

Method

Three conditions were interleaved; in the control condition (no vertical ticks) the position of either the left or the right final tick of the stimulus was compared to one of seven comparator ticks (height 0.61°, width 0.12°), varying in position from slightly outwards to slightly inwards. The tick was placed approximately 0.50° below the stimulus and deviations from the standard end tick position were −0.16°, −0.11°, −0.05°, 0°, 0.05°, 0.11°, and 0.16°. Negative values refer to positions towards the center of the figure, positive values away from the center. For the conditions A, B, and C, zero, one, or nine vertical ticks, respectively, were crossing the standard horizontal line in a regular manner as in previous experiments. Figure 11 illustrates the stimuli used in this experiment.

Each of seven naive observers (five female; age range 18–27) undertook 1,050 trials; three types of stimuli

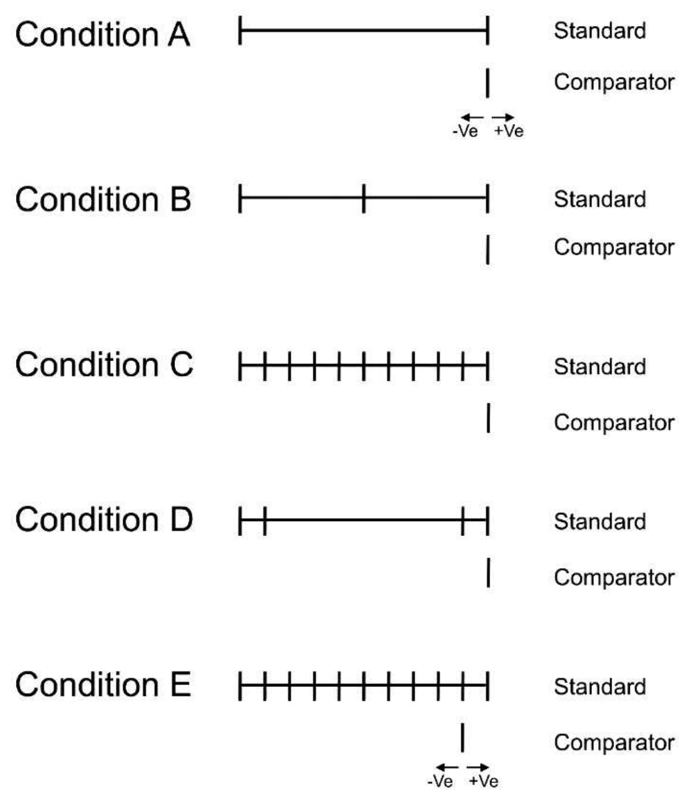

Figure 11. Stimuli used in Experiment 4. Participants were asked to indicate the position (i.e., left or right) of the small comparator tick relative to the position of the end or penultimate tick on the standard stimulus. Conditions A, B, and C were used in Experiment 4a and conditions C, D, and E in Experiment 4b. Other details in text.

were presented 25 times each for seven comparator stimulus positions positioned under either the left or right end tick. Participants were asked to indicate the position (i.e., left or right) of a small tick relative to the position of the end tick on the figure right above it using a response box. Stimuli were presented simultaneously for 750 ms. The stimulus lines were black against a bright (20 cd/m^2) background.

Results

Comparisons between the position of a small tick and the end ticks in three conditions were made so that psychometric functions could be determined and PSEs calculated for seven participants. Data for the right and left end ticks were collapsed. The results are shown in Table 1, and psychometric functions for conditions A, B, and C are shown in Figure 12.

Although in the nine-tick condition the end tick shows a significant perceptual displacement ($p < 0.05$), the magnitude of the effect (0.87 min) is too small to account for the effects of the illusion seen in Experiment 1, in which a perceived increase in length of

	Condition A (0 ticks)	Condition B (1 tick)	Condition C (9 ticks)
Mean bias in PSE (min arc)	0.16	0.28	0.87
95% CI	0.43	0.38	0.52

Table 1. The perceived shifts (in minutes of arc) of the end tick of an Oppel-Kundt figure. *Note*: In no case does the effect reach even one minute of arc, and thus contour repulsion cannot be put forward as a mechanism for the illusion.

19.2 min was seen. We would have expected to find shifts of around 10 min (allowing for equal expansion at each end of the figure). It would appear, therefore, that the Oppel-Kundt illusion cannot result for a simple contour repulsion effect as postulated by Ganz (1966). In this we are in agreement with the findings of Rentschler et al. (1975).

Experiment 4b

Method

Following from the previous experiment, the aim of Experiment 4b was to investigate whether the apparent displacement of the end ticks in the predicted direction is a local effect. We manipulated the number of vertical ticks regularly spaced on the standard stimulus, as well as the position of the comparison tick, and participants were again asked to compare the position of the latter to either the ultimate or penultimate tick in three conditions. The three conditions C, D, and E illustrated in Figure 11 were identical in procedure to the

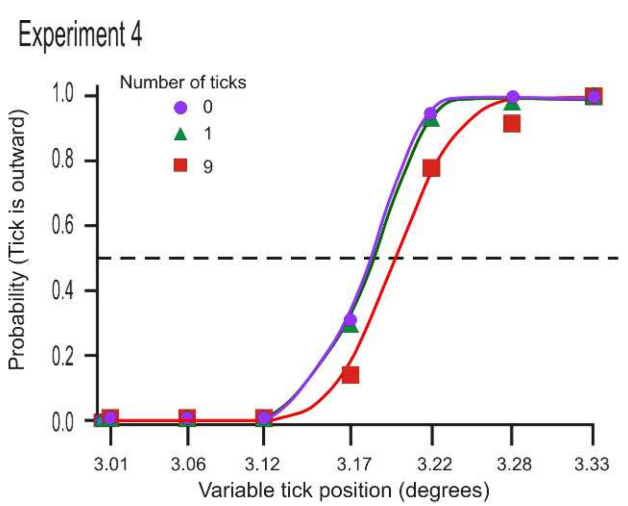

Figure 12. Psychometric functions for a single participant from Experiment 4a showing a significant perceptual in the nine-tick condition by displacement.

	Condition C (9 ticks)	Condition D (2 ticks)	Condition E (9 ticks)
Mean bias in PSE (min arc)	1.01	0.59	0.35
95% CI	0.71	0.56	0.55

Table 2. The perceived shifts (in minutes of arc) for conditions C, D, and E. In Conditions C and D, perceived shifts of the end tick are reported. In Condition E perceived shifts of the penultimate tick are reported. *Notes*: In each case the effect is much too small to account for the Oppel-Kundt illusion.

conditions in Experiment 4A. Condition C was repeated; in condition D only the ultimate and penultimate ticks on either end of the horizontal line were present in order to establish how much of the illusion results from the penultimate ticks. If some lateral inhibitory mechanism was responsible for the shift seen in Experiment 4A condition C, then we would expect it to be a very local effect, perhaps depending only on the penultimate ticks. In condition E, nine vertical ticks were crossing the standard horizontal line in a regular manner, as in condition C, but now the perceived position of the penultimate tick is measured. Again if a local inhibitory mechanism was responsible, the position of the penultimate tick should be influenced solely by its immediately adjacent neighbor on each side and therefore perceived veridically.

Each of nine naive observers (eight female; age range 18–27) undertook 1,050 trials; three types of stimuli each presented 25 times for seven comparator stimulus positions. In conditions C and D participants indicated the perceived position of the ultimate tick, whereas in condition E, they indicated the perceived position of the penultimate tick. Stimuli, black lines on a bright (20 cd/m^2) background, were presented for 750 ms.

Results

As in Experiment 4a, psychometric functions were determined and PSEs calculated for nine participants. Results are shown in Table 2. Condition C is again significant ($p < 0.05$), as is condition D. However, the size of these effects is again far too small to explain the Oppel-Kundt illusion.

Discussion

The main aim of Experiment 4 was to determine whether the introduction of ticks along a line distorts the perceived position of the endpoints. Condition A demonstrated that subjects can accurately locate the endpoints of a horizontal line in the absence of vertical ticks, while condition B showed that bisection of a line that leads to a reduction of perceived length does not affect the perceived location of the end points. Condition C, the standard Oppel-Kundt figure, reveals a significant, but small shift in the perceived position of the end points. A spatial repulsion effect, analogous to the angle expansion effect of Blakemore et al. (1970) could be responsible for this effect. Conditions D and E lend support to this idea, with the repulsion effect being a local effect, but the magnitude of this effect is too small to account fully for the Oppel-Kundt illusion. The possibility remains, however, that when attending to one end of the stimulus to complete the task in Experiment 4, distortions of space occur in the opposite end ∼6° from fixation. If this is true, the Oppel-Kundt illusion should be more prominent in peripheral vision.

General discussion

The Oppel-Kundt illusion is one of the best known and least well understood of geometrical visual illusions. Whereas bisecting a horizontal line with a vertical tick decreases its perceived length, the addition of more ticks progressively increases the perceived extent of the line. Perhaps the most parsimonious explanation would appeal to two underlying mechanisms. It is well known that bisection reduces the perceived extent of a line (Mamassian & de Montalembert, 2010; Mikellidou & Thompson, 2011, 2013) while Helmholtz (1867/1925) reported several effects in which filled space caused an expansion of perceived size (Thompson & Mikellidou, 2011). This latter effect might plausibly be understood as an effect analogous to the angle expansion effect reported by Blakemore et al. (1970), resulting from inhibition between neighboring orientation channels (Blakemore & Tobin, 1972). However, although there is evidence for contour displacement in the Oppel-Kundt illusion, the size of this component is insufficient to account for the magnitude of the illusion.

Why a single central tick should lead to the underestimation of line length, as seen here and in the classical vertical-horizontal illusion (Mamassian & de Montalembert, 2010), clearly cannot be explained in terms of local inhibitory processes. The answer may lie at a higher level in the visual system, for example in patterns of eye-movements that have been shown to cause a decrement of the Oppel-Kundt illusion compared to steady fixation viewing (Coren & Hoenig, 1972) and have been implicated in other illusions of this kind, such as the Muller-Lyer illusion (Burnham, 1968).

As with many other illusions, the Oppel-Kundt almost certainly involves a number of components. We have shown for the first time that there is a contour repulsion component that operates on the perceived position of the end ticks in the figure. However, the mechanism behind what Helmholtz (1867/1925) calls the illusion of "filled extent" apparent in the Helmholtz and the Oppel-Kundt illusions remains as mysterious as ever.

Keywords: Oppel-Kundt, illusion, lateral inhibition, bisection, line length

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