1 **Induction of Kanizsa contours requires awareness of the inducing context**

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10

11 **Abstract**

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13 It remains unknown to what extent the human visual system interprets information

14 about complex scenes without conscious analysis. Here we used visual masking

15 techniques to assess whether illusory contours (Kanizsa shapes) are perceived when

16 the inducing context creating this illusion does not reach awareness. In the first

17 experiment we tested perception directly by having participants discriminate the

18 orientation of an illusory contour. In the second experiment, we exploited the fact

19 that the presence of an illusory contour enhances performance on a spatial

20 localization task. Moreover, in the latter experiment we also used a different

21 masking method to rule out the effect of stimulus duration. Our results suggest that

22 participants do not perceive illusory contours when they are unaware of the

23 inducing context. This is consistent with theories of a multistage, recurrent process

24 of perceptual integration. Our findings thus challenge some reports, including those

25 from neurophysiological experiments in anaesthetized animals. Furthermore, we

26 discuss the importance to test the presence of the phenomenal percept directly with

27 appropriate methods.

28

29 **Keywords**

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31 Illusory contours, Kanizsa, modal completion, awareness, masking

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34 **Introduction**

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36 What role does conscious processing of the environment fulfill and how much

37 processing occurs in the absence of awareness? It is self-evident that much of the

38 internal bodily functions and the learned motor behaviors, such as walking or

39 driving, operate mostly without awareness. But for processing through the classical

40 senses, like vision, there have been widely discrepant findings on how much stimulus

41 processing can occur and how it affects decision-making when the subject is

42 unaware of the stimulus. Moreover, the approach to be used when studying

43 unconscious stimulus processing has also been subject of controversy [1].

44

45 Several experiments suggest that the effect of contextual stimuli within a target,

46 such as the percept of visual illusions or adaptation effects, persists even when

47 participants are unaware of the presented contextual information [2–6]. The use of

48 continuous flash suppression (CFS), in which a dynamic, high-contrast stimulus is

49 presented to one eye to suppress the stimulus in the other eye from awareness, has

50 become a popular way to probe unconscious stimulus processing [7]. Using this

51 procedure it has been claimed that the perception of physical facial attributes [8],

52 the complex analysis of naturalistic scenes [9], and even linguistic processing and

53 arithmetic can be performed without awareness [10]. However, several of these

54 findings have recently failed to be replicated and were challenged on theoretical

55 grounds [11–13].

56

57 Neuroimaging experiments showed that while both simple and more complex

58 stimuli have a neural signature in the visual cortex under masking conditions [14–

59 16], the encoding of unconscious stimuli appears to be qualitatively different. Not

60 only is the overall response to unconscious visual stimuli weaker [15] but coupling

61 between different stages in the visual processing hierarchy is also reduced [17] and

62 the information content differs [16,18,19]. In particular, the response to these

63 stimuli is more variable [20], and also localized in more posterior regions than to

64 conscious stimuli [18]. . One reason for this variability could be that only simple

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65   positional or geometric information is processed in the absence of awareness, but

66   that more complex abstraction and perceptual integration requires consciousness

67   Under this hypothesis, the neural encoding of stimuli is noisy because local stimulus

68   interactions are preserved but abstract and therefore coherent representations are

69   disrupted. Specifically, we used shape stimuli that were either defined by the

70   position or the orientation of simple image elements. We demonstrated that when

71   such stimuli were rendered invisible using fast counter-phase flicker (at 120Hz) they

72   could speed up performance on a shape discrimination task of conscious stimuli [21].

73   Critically, this priming effect was only present for stimuli sharing the *same* positions,

74   or – if oriented elements were used for priming – the positions along the path

75   implied by the elements. We observed no priming by invisible primes if the test

76   stimulus was smaller than the prime stimulus. This suggests that invisible priming

77   operated locally, possibly in retinotopic space in early visual cortex, but no abstract

78   integration of individual elements into the concept of a shape occurred without

79   awareness.

80

81   We further tested whether two brightness illusions manifest when the inducing

82   context is rendered invisible by means of CFS [22]. We found that masking the

83   context (a smooth gradient in luminance) had little impact on simultaneous

84   brightness contrast of two targets that were unmasked. In a stark dissociation,

85   participants could not discriminate the orientation of an illusory contour, defined by

86   a Kanizsa triangle, when the inducing context (the 'Pacman' shapes whose open

87   segments define the corners of the triangle) were masked selectively by CFS. This

88   could indicate that the generation of the illusory contour percept occurs at a later

89   stage of visual processing than simultaneous brightness contrast, either in terms of

90   the visual hierarchy or in the latency of processing. These findings were also

91   consistent with previous reports that illusory contours are not perceived when the

92   inducers are suppressed from awareness during binocular rivalry [23].

93

94   These findings challenge some previous reports, using psychophysical tests in

95   healthy volunteers [24] and even neurophysiological experiments in anesthetized

96   animals [25] that suggested that illusory contours could be formed in the absence of

97   awareness. However, none of these previous studies specifically tested whether the

98   experimental participants actually *perceived* an illusory contour. Similarly,

99   neuropsychological studies in neglect patients [26–29] suggested that illusory

100   contour processing occurs when part of the inducing context is placed in the blind

101   hemifield. However, this also does not conclusively support the assertion that

102   contours are formed in the absence of any contextual awareness.

103

104   However, two issues burden the interpretation of previous experiments that show

105   no evidence of illusory contours when the inducers are masked. First, there is

106   evidence that illusory contours are processed by binocular neurons in early visual

107   cortex [30–33]. It does in fact seem unsurprising that the mechanisms inducing

108   illusory contours at least partially overlap with those for segmenting surfaces in

109   depth [34]. When retinal disparity implies that inducers are at different depths from

110   the background, the visual system not only produces the percept of illusory contours

111   but the surface bounded by illusory contours is also perceived in stereoscopic depth

112   [31]. Thus when binocular processing is disrupted or overwhelmed by a dichoptic

113   mask or binocular rivalry, the illusory contour percept is also broken. Another recent

114   study further complicated this situation by finding that Kanizsa shapes broke through

115   CFS faster than control stimuli [35]. Leaving aside conceptual issues with the time-to-

116   emergence paradigm, it is imperative that the dependence of illusory contours on

117   awareness must be confirmed using masking methods other than CFS.

118

119   A second confound with these previous studies [22,23] is that even if participants

120   perceived an illusory contour, this percept was far less salient than real luminance

121   contours, as it may have been obscured by the dominant masking stimulus. The

122   addition of a simple control condition could remedy this problem: One experimental

123   stimulus should be a *real contour* defined by a subtle luminance contrast that mimics

124   the illusory contour percept as closely as possible. If participants can detect and

125   discriminate this stimulus but are unable to do so for the illusory contour condition,

126   this indicates that the *illusory percept* is indeed disrupted specifically, rather than the

127   more general ability to detect subtle stimuli.

128

129 In the present paper, we carried out two experiments to address these confounds

130 and answer the question of whether Kanizsa contours are formed when inducers are

131 not consciously perceived. In experiment 1, we used a similar design as in our

132 previous study [22]. Here, participants were asked to discriminate the orientation of

133 a Kanizsa triangle. However, instead of CFS we employed a temporal masking

134 method to render the inducers invisible. Moreover, we included a control condition

135 in which a real, luminance-defined contour was present. Because this masking

136 method relies on very brief stimulus durations, in experiment 2 we presented long

137 (500ms) stimuli rendered invisible by means of fast counter-phase flicker [3,21]. This

138 is critical because the formation of illusory contours arise comparably slowly [36–38]

139 and thus may be disrupted by a fast temporal masking technique.. In addition to this,

140 previous research demonstrated that the presence of illusory contours boosts

141 participants' ability to discriminate the position of a tiny target [23,39], providing a

142 specific test of whether the participant in fact perceives an illusory contour or not.

143 We therefore measured the ability of a group of participants, who were well trained

144 at psychophysical tasks, to discriminate the position of a dot target for Kanizsa and

145 control stimuli presented with or without masking.

146

147 **Materials and Methods**

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149 Both experiments were carried out at the UCL Department of Experimental

150 Psychology. Procedures adhered to the Declaration of Helsinki. Ethical approval for

151 this study was obtained from the UCL Research Ethics Committee and all participants

152 gave written, informed consent.

153

154 Participants in experiments 1 were recruited among the UCL student population. In

155 experiment 2 we recruited participants who were familiar with psychophysical tasks.

156 All Participants had normal or corrected-to-normal visual acuity.

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158 All experiments were conducted in a dark, sound-attenuated room. For the duration

159 of the experimental sessions, participants were asked to stabilize their head on a

160   chin rest located at a fixed distance of 48cm from the stimulus presentation screen

161   where stimuli were presented to them binocularly.

162

163   Stimuli were generated by a computer and presented on a 22-inch Samsung

164   SM2233RZ LCD monitor at a resolution of 1680 x 1050 pixels. Screen refresh rate in

165   experiment 1 was set to 60Hz. In experiment 2 it was set to 120Hz. The experiment

166   was controlled and behavioral responses were recorded using MATLAB (The

167   Mathworks, Inc.) and Psychtoolbox 3 [40] using a standard keyboard.

168

169   Experiment 1

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171   The experiment comprised two tasks: the first, henceforth called 'Kanizsa' task,

172   investigated whether participants can perceive illusory contours without awareness

173   of their inducers. The second task, the 'Visibility' task, assessed the effectiveness of

174   the masking technique directly.

175

176   *Study design*

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178   Like our earlier experiment using continuous flash suppression, this experiment

179   aimed to measure the perception of illusory contours in a direct manner. We

180   implemented a 2x3 design with visibility (invisible, visible) and type of stimulus (real,

181   illusory, control) as within subject factors.

182

183   Every participant completed two different tasks. Each task comprised 25 blocks of

184   trials, where one block consisted of 24 trials in the Kanizsa task and 8 trials in the

185   visibility task. Across one task, each condition appeared 100 times. The visibility task

186   only comprised the visible and invisible control conditions.

187

188   Participants made behavioral responses in a forced-choice design by button press

189   (left or right arrow) on a standard computer keyboard. Each trial required either a

190   left or a right response and each response type appeared twice per block for each

6

191   condition. Conditions were selected pseudo-randomly for every trial but were
192   counterbalanced over each block.

193

194   *Participants*

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196   Seventeen (13 female; age range: 18-29, mean age: 23.8±2.5) normal, healthy
197   participants took part in the experiment. An additional two participants were tested
198   but they failed to discriminate the real luminance contour under masking conditions
199   and were therefore excluded from further analysis (see more details below). All
200   participants were unaware of the experimental hypothesis.

201

202   *Stimuli*

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204   Stimuli were created by placing four discs (inducer elements, diameter=2.2°) in the
205   configuration of a square (width=4.3°). The configuration of these discs was centered
206   on fixation. As both standard edge type and a number of line-end inducing elements
207   have comparable efficacy in the clarity with which illusory contours are perceived by
208   participants [41,42], here the discs were defined by partial concentric circles. Each of
209   the four lines forming the circles had a width of approximately 0.07° with a
210   luminance of 0.6 cd/m^2. The positioning of the gap within the circles gave rise to the
211   percept of a Kanizsa triangle (Figure 1A). Thus, a number of line-end inducing
212   elements gave rise to perception of illusory contours [43].

213

214   We also included a real luminance condition. Here, the stimuli did not contain any
215   discs but instead there was a triangle defined by a real but subtle luminance contrast
216   at the exact location where the Kanizsa triangle would be perceived in the illusory
217   condition (Figure 1B). We reasoned that if participants were unable to discriminate
218   the orientation of this subtle luminance edge when the inducers were masked, this
219   implied that they would be unable to detect any illusory contour that could have
220   formed without awareness of the inducers. Therefore, we removed two participants
221   whose discrimination performance for this condition was at chance levels from any
222   further analyses.

223

224   Control stimuli did not form any triangle and were created by altering the

225   orientations of the inducers by a systematic rotation of 180º (Figure 1C). This

226   condition was somewhat unnecessary because the dependent variable, accuracy for

227   discriminating the orientation of the triangle, was orthogonal to the condition and

228   for these control stimuli there was no strictly correct answer in this discrimination

229   task. The "correct" responses in this condition were dummy coded so that the

230   stimulus-response mapping matched that for the equivalent illusory triangle stimuli

231   before rotating the inducers. We included this condition as catch trials – participants

232   should be guessing here because there was no triangle to discriminate. Thus it

233   provided information on whether participants could indeed perceive the triangle

234   contours or whether they adopted a strategy of matching the inducer orientation to

235   feedback.

236

237   The background had a luminance of 76.6 cd/m^2 and real triangles were defined by a

238   subtly greater luminance of 86.9 cd/m^2. The mask was only used in the invisible

239   conditions and was designed as a square configuration of four black discs (0.6

240   cd/m^2), each containing four white concentric circles (230 cd/m^2). It was wide

241   enough to cover all four Pacmen in the illusory and control conditions (Figure 1D).

242   The masking technique consisted of a sequence of three frames which was repeated

243   three consecutive times: At first the mask appeared on the screen, followed by the

244   appearance of the stimulus and a final blank screen. In the visible conditions, a blank

245   grey screen replaced the mask frame.

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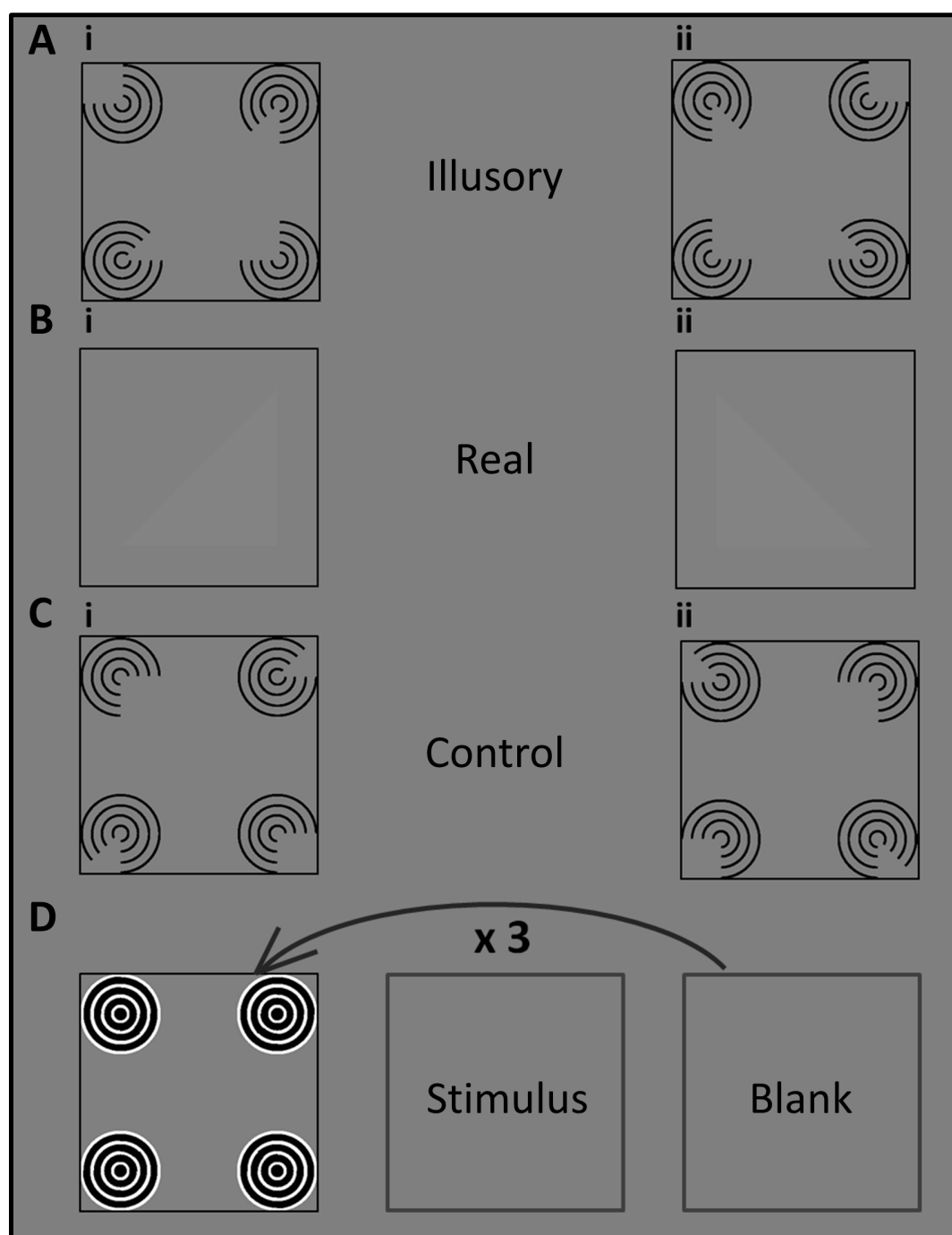
Figure 1. Illustration of the stimuli. A) (i) Kanizsa triangle pointing right (ii) Kanizsa triangle pointing left. B) (i) Real triangle pointing right (ii) Real triangle pointing left. C) Control stimuli were created by a systematic 180° rotation of the individual Pacmen. D) Illustration of the masking procedure in the invisible conditions: A mask-stimulus-blank screen frame sequence was repeated three times. In the visible conditions a blank screen replaced the mask.

256   *Procedure*

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258   *Kanizsa task:* At first, participants were instructed that they would see a triangle

259   appear on the screen. They were asked to judge whether its hypotenuse was tilted

260   clockwise or counter-clockwise from vertical by pressing the corresponding response

261   key. We explained this task to them as a decision whether the right angle of the

262   triangle was pointing to the left or to the right but they were told explicitly to *judge*

263   *the contours of the triangle*, in particular the long hypotenuse extending through the

264   center of the stimulus display. Because we wished to keep the contrast between real

265   triangle and the background as low as possible, we trained participants on the visible

266   and invisible real triangle condition until they were able to detect them correctly.

267

268   Participants were instructed to fixate a small black dot (0.2° wide) that was present

269   in the center of the screen throughout the experiment. On each trial, the fixation dot

270   was displayed alone for 500ms. This was followed by a sequence of three frames

271   that defined whether the condition was a visible or an invisible one. In the invisible

272   condition a 300ms mask followed the fixation period. Subsequently, the stimulus

273   appeared on the screen for one frame of approx. 16.7 milliseconds (ms),

274   immediately followed by a blank screen that was shown for one frame as well. This

275   mask-stimulus-blank sequence was repeated three times before a second and final

276   post-stimulus blank screen was presented until participants gave their response.

277   Figure 2A shows the general paradigm for the experimental procedure.

278

279   *Visibility task:* We further tested whether participants indeed did not consciously

280   perceive any contextual information of the stimuli in the invisible condition. For this

281   purpose, the visibility task assessed the effectiveness of the masking technique by

282   measuring whether participants could consciously discriminate the inducer

283   elements. Participants were asked to judge whether a right angle was presented in

284   the left or right bottom inducer. The timing of the trial sequence in this task was

285   identical to the Kanizsa task, with one exception: only control stimuli were used

286   (Figure 2B).

287
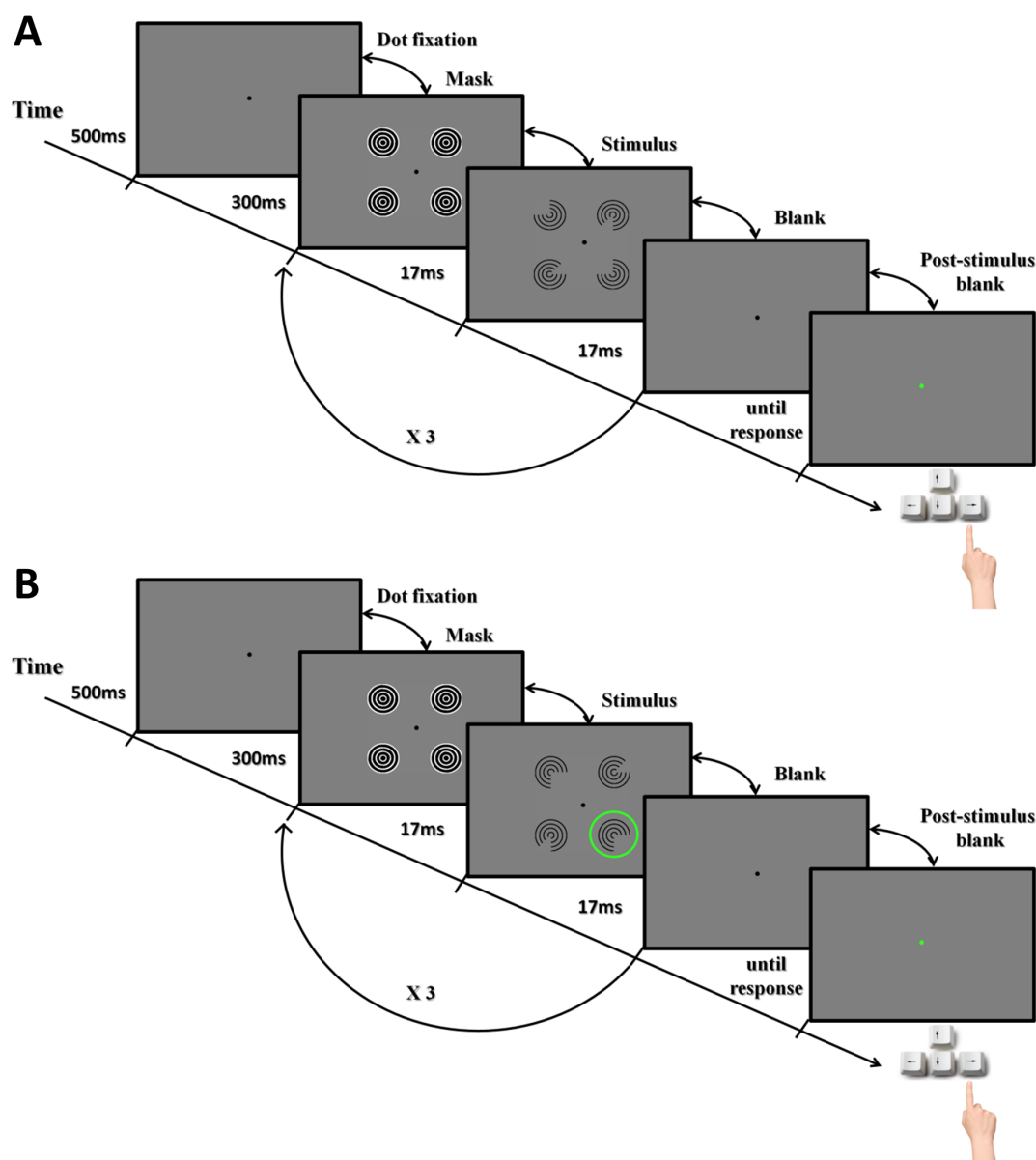
Figure 2. Illustration of the trial sequence in experiment 1. A) Kanizsa task: Each trial was composed of five frames: fixation dot, mask, stimulus, blank, and post-stimulus blank. After the participant's response, the fixation point provided feedback for 100ms (green: correct; red: incorrect). The duration of each frame is shown on the time-line. Note that in the visible conditions, a blank screen replaced the mask. B) Visibility task: Trials proceeded in the same way as in the Kanizsa task except that only control stimuli were being shown and participants judged whether the right-angle gap was in the bottom left or right inducer (indicated by the green circle, which was not present in the actual stimuli).

300   *Data analysis*

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302   Performance in both tasks was defined in terms of mean proportion of accurate

303   responses in each condition. Initially, we conducted binomial tests at the individual

304   level to quantify how many participants performed significantly above chance. A

305   condition for any participant's data to be considered in the group analysis of this

306   experiment was that their performance to the invisible real stimulus condition was

307   significantly above chance (0.5). This is because the features necessary to distinguish

308   the contours of the real triangle were not masked and if a participant could not

309   perform the task for this particular stimulus, any test of the perception of illusory

310   contours would be redundant.

311

312   One-sample t-tests were carried out at the group level for each condition individually

313   to assess whether the participants' level of performance was significantly above

314   chance (>0.5). In addition to traditional frequentist statistical tests, we also

315   quantified the evidence for or against the hypothesis that participants could

316   discriminate the stimuli by calculating a Bayes Factor using a default Cauchy prior

317   with scaling factor 0.707 for the alternative hypothesis [44]. For conditions with

318   performance near chance levels, this enabled us to also quantify how strongly the

319   evidence supported the null hypothesis that participants were actually guessing.

320

321

322   Experiment 2

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324   This experiment only comprised one task that tested the percept of illusory contours

325   by measuring participants' threshold on a spatial localization task. Such a

326   manipulation has been used successfully in previous experiments [23,39]. While it is

327   an indirect test, the contour aids performance on the spatial localization task. This

328   provides independent evidence about whether participants perceived any illusory

329   contours and therefore helps to address confounds with measuring the percept

330   directly as we did in experiment 1. Pilot experiments using a task in which we

331   directly measured the illusory percept (the same task as experiment 1 but with the

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332   long-lasting masking technique employed in experiment 2) could encourage

333   participants to pay close attention to the masked context and thus reduce the

334   effectiveness of the masking procedure. This would mean that participants use

335   residual awareness of the inducers to perform the task instead of actually making a

336   perceptual judgment of the illusory contour.

337

338   Moreover, because the masking procedure in experiment 1 used very brief

339   presentations of the invisible Kanizsa stimuli (16.7ms) while these were much longer

340   (300ms) for the visible ones, in experiment 2 we used a different masking procedure:

341   stimuli were defined by sinusoidal gratings which reversed contrast polarity at

342   120Hz. This method can effectively render stimuli invisible for prolonged periods so

343   that participants only perceive a grey screen. Previous research suggests that stimuli

344   masked in this way are processed in early visual cortex [3]. Moreover, we showed

345   that stimuli rendered invisible by this method could induce local priming effects on a

346   shape discrimination task [21].

347

348   *Participants*

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350   Five normal, healthy participants (3 female; age range: 24-37; mean age: 30.2)

351   completed this experiment, including one of the authors (DSS). All participants were

352   experienced with psychophysical experiments. While the results from a larger

353   subject base might generalize more to a broad population, we reasoned that only

354   precise measurements of participants' visual performance would afford

355   interpretable data. Unlike in the first experiment, in experiment 2 we measured how

356   position discrimination thresholds changed between experimental conditions. Naïve,

357   untrained participants from the general population would be more likely to

358   contribute noisy data and this might obscure potential subtle perception of illusory

359   contours in the masked condition.

360

361   *Stimuli*

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363   We generated a Kanizsa shape by presenting four Gabor patches (sinusoidal gratings

364   with wavelength 0.33° visual angle convolved with a Gaussian with standard

365   deviation 0.8° at 30% contrast) in the locations of the four corners of a square with a

366   side-length of 8.2°. We turned these patches into Pacmen by setting a right-angled

367   region of each patch to zero contrast (uniform background grey). This stimulus thus

368   described an illusory square (Figure 3A). In the control conditions, the Pacmen were

369   rotated by 180° so that the corners faced outward breaking the illusory percept

370   (Figure 3B). In the real luminance control, we did not present any Gabor patches but

371   instead a square region with a subtle luminance contrast (54 cd/m^2) relative to the

372   background (Figure 3C). The orientation and phase of each Gabor patch was

373   randomized in each trial. Finally, we created a mask stimulus by overlaying 24 Gabor

374   patches in the four locations. These patches were presented at 5% contrast and

375   covered the full range of orientations in equal steps of 15° but their phases were

376   randomized. This resulted in a patchy pattern without any obvious orientation cue

377   (Figure 3D). The mask pattern was also generated anew in every trial.

378

379   These stimuli were presented in the center of the screen. The target stimulus was a

380   tiny dark grey dot (diameter: ~0.1°) which could appear somewhere along the

381   horizontal meridian, either near the right or the left vertical boundary of the square.

382

383   The square stimuli were either invisible or visible. In the invisible condition, the

384   gratings reversed contrast polarity at 120Hz. In the visible conditions and the real

385   luminance control, every even-numbered frame was uniform grey (except for the

386   fixation dot).

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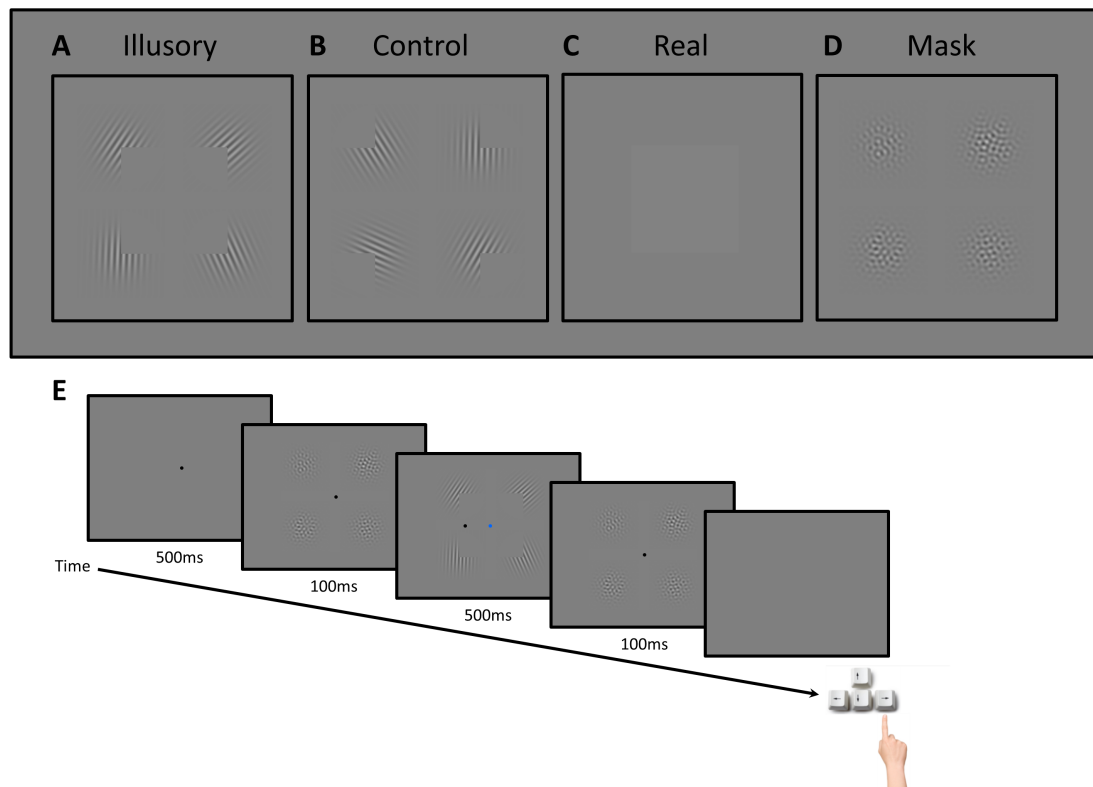
Figure 3. Stimuli (A-D) and trial sequence (E) in experiment 2. During the stimulus interval either an illusory Kanizsa square (A), a control stimulus with rotated inducers (B), or a real luminance square without any inducers (C) was presented. In visible trials every odd-numbered video frame at 120Hz contained the stimulus while every even-numbered frame contained only a blank screen with the blue fixation dot. In invisible trials, both frames contained the Gabor patches for A and B but their contrast polarity alternated between frames. For real luminance stimuli the even-numbered frames always contained a blank screen. D) A mask stimulus preceded and followed each stimulus interval. E) Each trial started with 500ms of fixation, followed by a 100ms mask, the 500ms stimulus interval, another 100ms mask, and finally a blank screen without a fixation dot that remained until participants gave their response. Their task was to locate the small target dot in the stimulus display and decide whether it appeared to the left or the right of the vertical boundary of the square (here, the correct response is right).

402

403

Procedure

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Figure 3E depicts the sequence of an invisible Kanizsa trial in experiment 2. Each trial started with 500ms of a blank grey screen that only contained a black fixation dot

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408   (diameter 0.26°). This was followed by a 100ms presentation of the mask and then

409   500ms of the stimulus, after which another 100ms mask interval was presented.

410   Then the screen turned grey and the fixation dot was removed, indicating that

411   participants could give their behavioral response.

412

413   During the stimulus interval the fixation dot was blue instead of black to denote that

414   this was the task-relevant interval. As described above, the stimuli in this interval

415   either reversed in contrast polarity at 120Hz (invisible Kanizsa and control

416   conditions) or the frames were interleaved with blank frames (visible Kanizsa, real

417   luminance stimuli and control). During the stimulus presentation the small dark

418   target dot also appeared at some location along the horizontal meridian. Its position

419   was randomized to be either near the left or the right vertical boundary of the

420   square region. The dot could either appear inside or outside the square region.

421

422   The dependent variable in this experiment was the distance between the target dot

423   and the boundary of the square region and it was controlled by a 2-down, 1-up

424   staircase procedure that converged on the threshold distance in each of the five

425   experimental conditions at which performance was approximately 70.7% correct.

426   That is, after every consecutive two correct trials the distance would decrease by

427   one pixel (~0.03°) while after every incorrect trial it increased by one pixel. All five

428   staircases started at a distance of 15 pixels (0.49°). The minimum and maximum that

429   they could reach were one pixel and 25 pixels (0.82°), respectively.

430

431   Before the actual experiment we showed participants static examples of the Kanizsa

432   and the control stimuli. Participants were instructed to judge whether the target dot

433   was left or right of the (imaginary) vertical boundary of the square region. While

434   showing them still images of the stimuli, we specifically explained to them that this

435   boundary was defined by the exact center of the Gabor patches (i.e. the corner of

436   the Pacman's mouth) and that this was identical in both the Kanizsa and the control

437   conditions. We further informed them that there would be a third condition in which

438   they should only see a subtly lighter grey square against the background but no

439   Gabor patches. In order to become acquainted with the task, they then performed 1-

16

440   2 blocks of the experiment with only the visible Kanizsa, the control and the real

441   luminance condition. Finally, the actual experiment would commence. Participants

442   were informed that the task was largely always the same as the familiarization run,

443   although during this experiment there would be many more trials in which they

444   either only see a light grey square but no Gabor patches or that they might even only

445   see a grey blank screen. Except for the author, all participants were unaware of the

446   experimental hypothesis. In debriefing none of the participants reported seeing any

447   Gabor patches during the invisible condition.

448

449   Participants performed two consecutive runs comprising 500 trials each. These runs

450   were further subdivided into 25 blocks. In every block each of the five conditions

451   appeared 4 times in a pseudo-randomly interleaved order. Blocks were initiated by

452   button-press. During block breaks a message on the screen reminded the participant

453   of the task instructions and of the number of blocks they had already completed.

454

455   *Data analysis*

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457   We determined the threshold distance in each of the five experimental conditions by

458   calculating the mean distance across the final 15 reversals in the staircase

459   procedure. Then we conducted a group level analysis in which we compared the

460   average thresholds for conditions across participants. For this we used a two-way

461   repeated-measures ANOVA with the factors visibility (visible vs invisible) and

462   stimulus type (illusory vs control stimulus). As there was only one condition with a

463   real luminance contour, the thresholds for this condition were not included in the

464   ANOVA. However, we used paired t-tests to compare results for the illusory and

465   control stimuli directly to the real luminance condition.

466

467

468   **Results**

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470   <u>Experiment 1</u>

471

472   In this experiment, 17 participants judged the orientation (left vs right) of a triangle

473   that was either defined by an illusory contour or a subtle real luminance edge. In a

474   third control condition the Pacmen stimuli inducing illusory contours were rotated so

475   that no triangle shape could be perceived.

476

477   *Kanizsa Task*

478

479   Accuracy across participants for discriminating the orientation of the triangle for the

480   six conditions is displayed in Figure 4. We tested whether discrimination

481   performance in each condition was above chance at the group level.

482

483   In the visible condition, the mean proportion of correct responses for the group was

484   close to ceiling and clearly better than chance both for the real (M=0.97, t(16)=83.5,

485   p< 0.001, BF_{10}>9.8*10^{18}) and the illusory condition (M=0.99, t(16)=120.8, p<0.0001,

486   BF_{10}>2.4*10^{21}). In the control condition, however, the group performed significantly

487   below chance level (M=0.30, t(16)=-3.87, p=0.001, BF_{10}=29.3). There was

488   considerable variability in performance for this condition ranging from 0 to 0.74.

489

490   In the invisible condition, only performance on the real triangle condition was

491   significantly above chance level (M=0.71, t(16)=6.4, p<0.001, BF_{10}=2608.7).

492   Performance on both the illusory triangle condition (M=0.51, t(16)=1, p=0.332,

493   BF_{10}=0.385) and the control condition (M=0.50, t(16)=0.2, p=0.859, BF_{10}=0.253) were

494   at chance level. Importantly, performance on the real triangle condition was also

495   significantly greater than for either the illusory contour (t(16)=6.1, p<0.0001,

496   BF_{10}=1475.4) or the control condition (t(16)=5.6, p<0.0001, BF_{10}=688). In contrast,

497   performance for the illusory contour did not differ from the control condition

498   (t(16)=0.7, p=0.525, BF_{10}=0.3).

499

500   *Visibility Task*

501

502   In a supplementary control task we asked participants to make a decision directly

503   based on the inducers by reporting which one of the two bottom inducers contained

18

504 the right angle. This assessed any residual perception of the inducer shapes under

505 masking conditions. In the visible condition, the mean proportion of correct

506 responses across participants was again close to ceiling and far above chance level

507 ($M=0.96$, $t(16)=22.2$, $p<0.001$, $BF_{10}>2.9*10^{10}$). In contrast, participants' mean

508 performance in the invisible condition did not significantly differ from chance level

509 ($M=0.48$, $t(16)=-1.3$, $p=0.227$, $BF_{10}=0.489$), suggesting that participants could

510 generally not perceive the inducers under masking conditions. Note, however, that

511 there was only anecdotal support for the null hypothesis ($BF_{10}>1/3$).

512

513 The first experiment thus suggested that if participants were unaware of the

514 inducers because they had been masked, they were unable to judge the orientation

515 of the Kanizsa triangle. This supports the interpretation that illusory contours are not

516 formed under these conditions.

517

518
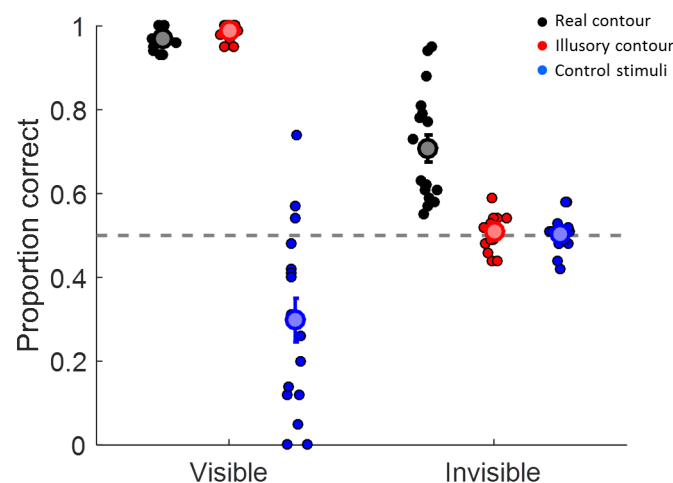
519 **Figure 4. Results of experiment 1.** Accuracy for discriminating the orientation of a triangle

520 stimulus in visible or invisible (masked) trials. Each dot represents the performance of an

521 individual participant in each of the conditions. The large symbols and error bars denote the

522 mean ±1 standard error for each condition. Black: real luminance contour. Red: illusory

523 (Kanizsa) contour. Blue: control stimuli.

524

525 <u>Experiment 2</u>

526

527   In experiment 2 we changed the approach in a number of ways. First, instead of the
528   brief stimulus presentations used in the first experiment we used counter-phase
529   flicker to render stimuli invisible for prolonged periods. Moreover, we used an
530   indirect measure of illusory contour processing: we took advantage of previous
531   reports that the presence of an illusory contour stimulus enhanced participants'
532   thresholds at discriminating the position of a small dot [23,39]. Here we tested
533   whether this also occurred when the inducers generating the illusory contour were
534   invisible. Because this task was more challenging than those in previous
535   experiments, and to rule out that our previous results might have been due to
536   insufficient practice or familiarity with psychophysical experiments, in this
537   experiment we only tested a small group of well-trained psychophysics participants.

538

539   Figure 5 plots position discrimination thresholds in the different conditions for all
540   individual participants and the group averages. Overall, thresholds measured while a
541   Kanizsa stimulus was presented were significantly lower than those measured for
542   control stimuli (F(1,4)=34.6, p=0.004). There was also a non-significant trend of
543   lower thresholds during visible than invisible trials (F(1,4)=7.5, p=0.052). Importantly,
544   there was a significant interaction between visibility and stimulus type (F(1,4)=15.9,
545   p=0.016). In the visible condition thresholds measured while an illusory Kanizsa
546   contour was present were significantly lower (M=0.08°, t(4)=-5.27, p=0.006,
547   BF_{10}=9.95) compared to the control condition without a contour (M=0.21**°**). In
548   contrast, in the invisible condition the difference in thresholds for illusory contours
549   (M=0.20**°**) was not significantly different from that for the control stimulus (M=0.21°,
550   t(4)=-0.16, p=0.882, BF_{10}= 0.4).

551

552   Thresholds measured for the real luminance contour were of a similar magnitude as
553   those measured for the visible illusory contour (M=0.10°, t(4)=-0.92, p=0.409,
554   BF_{10}=0.55). In contrast, thresholds for the real luminance contour were significantly
555   lower than for invisible Kanizsa stimuli (t(4)=3.84, p=0.019, BF_{10}=4.53). Thresholds
556   for the real luminance contour were also significantly lower than for either control
557   stimulus (visible: t(4)=4.4, p=0.012, BF_{10}=6.19; invisible: t(4)=5.3, p=0.006, BF_{10}=9.9).

558
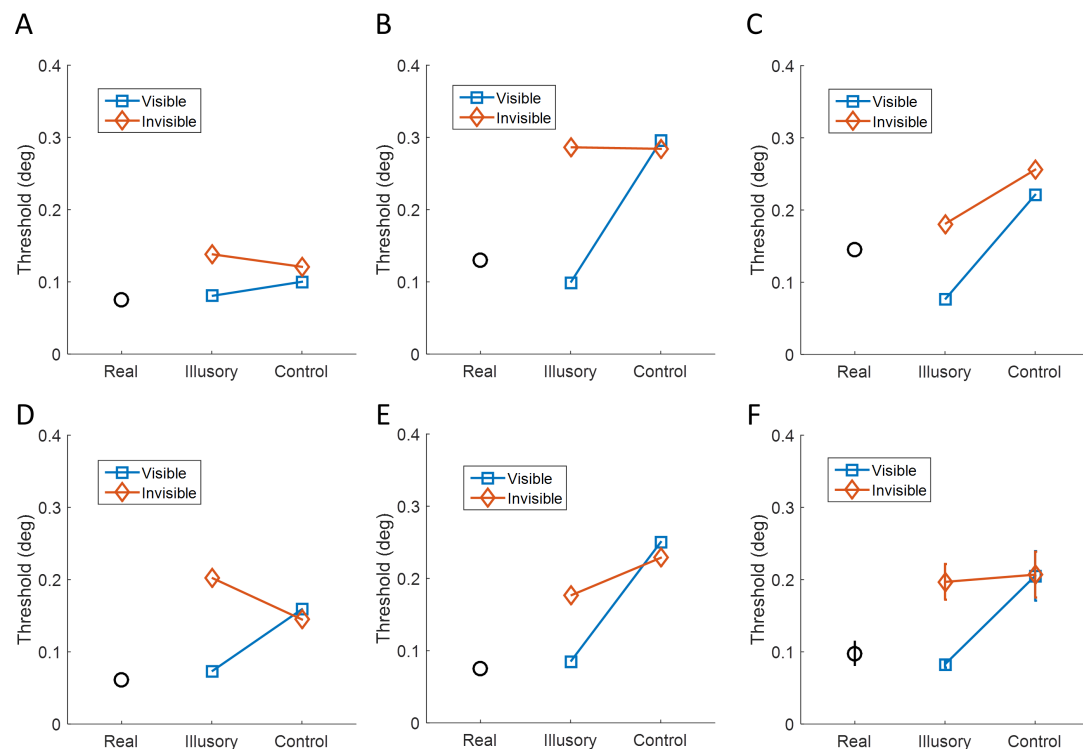
Figure 5. Results of experiment 2. Spatial discrimination thresholds per condition (real luminance vs illusory vs control) on a dot localization task while participants were presented with visible (blue squares), invisible (orange diamonds), or real luminance stimuli (black circles). A-E) Plots for the five individual participants. F) Thresholds averaged across participants ±1 standard error of the mean.

Discussion

In two psychophysical experiments we tested whether the visual system forms illusory (Kanizsa) contours in the absence of awareness of the inducing context. Taken together, with previous experiments using dichoptic stimulation [22,23] all the findings suggest that illusory contours are not perceived when the inducers are masked.

In our first experiment, we directly measured illusory contour perception by asking participants to discriminate the orientation of a Kanizsa triangle. This procedure was akin to our earlier experiments [22] that showed no evidence either that illusory contours are formed when inducers are suppressed from awareness. In those

21

579   experiments we employed CFS in which a dynamic, high-contrast mask presented to

580   one eye suppresses awareness of a stimulus viewed by the fellow eye. Similarly,

581   previous studies showed that illusory contours are not formed when the inducers

582   are suppressed from awareness during binocular rivalry [23]. However, because

583   previous reports indicate that illusory contours are processed by binocular neurons

584   [30–33] the use of dichoptic stimuli may simply disrupt their processing.

585

586   Therefore here we used normal binocular viewing conditions and a different method

587   to render the inducers invisible. In addition, we included a real luminance contour

588   condition as a baseline check. This helped to rule out another trivial explanation for

589   our earlier findings: The presence of the bright masks could possibly have obscured

590   the detection of the subtle illusory boundary. Our real luminance contour was never

591   masked because the masks only overlapped with the corners of the triangle;

592   therefore, if participants were able to discriminate the subtle real luminance contour

593   they should also be able to do so if an illusory contour were indeed formed. We only

594   included participants for whom discrimination of this real luminance contour was

595   significantly above chance levels. Nonetheless, participants were unable to

596   discriminate the orientation of the illusory contour when inducers were masked. The

597   phenomenological experience of the real luminance and the illusory contour is not

598   perfectly identical (and it obviously is not for the visible conditions). However, the

599   real luminance conditions were very faint while illusory contours tend to be

600   subjectively quite salient. Thus it seems unlikely that participants should be able to

601   detect only the real luminance contour but not the illusory contour.

602

603   Experiment 1 also contained control conditions in which the individual inducers had

604   been rotated by 180° and thus no illusory triangle should be formed. These were

605   essentially catch trials because participants should have been guessing, as there was

606   no actual triangle to discriminate. This was clearly the case for control stimuli when

607   inducers were invisible. However, for visible control stimuli discrimination

608   performance varied widely from 0-0.74 proportion correct responses and was even

609   significantly below chance level. The "correct" responses in this condition were

610   dummy coded so that the stimulus-response mapping matched that for the

611   equivalent illusory triangle stimuli before rotating the inducers. Therefore one

612   inducer in the top row had a right-angled cutout that pointed inwards (Figure 1) and

613   this would be consistent with the presence of a triangle oriented in the opposite

614   direction (even though no actual triangle should be perceived). Some participants

615   may have adopted this stimulus response mapping while others did not. It would

616   therefore have been better to have all inducers point outwards in this control and

617   randomize their locations. However, our actual results serendipitously support the

618   fact that masking was effective in this experiment: The fact that participants

619   performed at chance level when the control stimuli were masked rules out that they

620   had any residual awareness of the inducers. The results of our explicit Visibility task

621   after the main experiment also corroborated this conclusion.

622

623   The results of experiment 1 contradict previous claims that a "ghostly triangle" could

624   be perceived when the inducers of a Kanizsa triangle were masked [24]. However,

625   follow-up experiments failed to replicate these experiments but instead suggested

626   that conscious processing of the inducers precedes awareness of the illusory

627   contours and that these earlier results were in fact due to residual awareness of the

628   inducers [45]. Another critical issue with these experiments is that the perception of

629   illusory contours is based on a Yes or No judgment of whether a triangle shape was

630   present. Such a task could theoretically be performed based on any residual

631   awareness of the corners in the inducers. Our task required an explicit orientation

632   discrimination of the illusory contour. If participants had been able to perform this

633   task in spite of being unable to perceive the inducers, this would have been more

634   conclusive evidence that illusory contours are indeed formed when inducers are

635   masked.

636

637   Naturally, our design that split the main task from a test of awareness did not allow

638   us to measure the awareness on each actual trial of the main experiment – only a

639   dual-task design in which visibility is probed directly in the main experiment would

640   permit this. However, a dual-task design cannot classify the awareness of individual

641   trials perfectly as the participant's judgment of their own awareness is subject to

642   variability. Dual-tasks also entail a division of attentional resources across the

23

643 different task components. It could be argued that the Visibility task was more

644 difficult than the Kanizsa task because the former required the judgment of one a

645 small, peripheral feature of the stimulus. This may complicate the interpretation of

646 chance performance on this task.

647

648 Experiment 1 also used very brief stimulus presentations and powerful, high-contrast

649 masks to render stimuli invisible. Rather than the absence of awareness, the reason

650 why invisible contours were not formed could be the brevity of the stimuli or

651 because the mask fundamentally disrupted stimulus processing. This is certainly a

652 possibility because previous research indicated that the processing of illusory

653 contours occurs relatively slowly [36–38]. Therefore, in our second experiment, we

654 used counter-phase flicker to mask the inducers instead of the masking methods

655 employed in the earlier experiments. This allowed us to present stimuli for

656 prolonged periods. While this is also a temporal masking procedure, the stimulus

657 energy is constant during the entire presentation because only the polarity changes

658 between frames. Furthermore, we exploited the fact that the presence of an illusory

659 contour enhances performance on a dot localization task because it provides a visual

660 aid for determining its spatial location [23,39]. We confirmed this advantage when

661 inducers were not masked and performance was comparable to when we presented

662 real luminance contours only. However, when inducers were rendered invisible this

663 advantage for illusory contours disappeared. This task may actually be an even more

664 appropriate test of the induction of illusory contours than testing discrimination of

665 the contour itself as in experiment 1. For that experiment, the interpretation is

666 unproblematic because we found no evidence of discrimination when inducers were

667 masked. However, if we had found above chance performance for masked stimuli, it

668 would have been impossible to conclude that this was not due to discrimination of

669 the inducers. Pilot experiments for experiment 2 suggested that with the long-lasting

670 counter-phase flicker masking, participants might in occasional trials have had some

671 residual awareness of the corners in the inducers. Thus they might still have

672 performed above chance at a shape/orientation discrimination on the purported

673 illusory contour even though they did not in fact perceive any illusory contour. This

674 problem also plagues many previous experiments that directly tested the presence

675   of an illusory shape [36,37]. Therefore, only a task that exploits the presence of the

676   illusory contour to modulate performance on an orthogonal task, like the dot

677   localization task we used, can provide conclusive evidence that an illusory contour

678   was in fact perceived. An alternative possibility could be a task that relies on a fine

679   discrimination of a feature of the illusory contour such as its curvature [38] but even

680   such discriminations may be confounded (with?) discrimination of the inducers

681   [46,47].

682

683   In all tests of performance against chance levels we used Bayesian hypothesis tests

684   that can quantify the strength of evidence for the null hypothesis indicating that

685   participants were guessing [44]. None of these tests revealed *strong* evidence for the

686   null hypothesis as typical Bayes Factors fell between 0.3-0.5. To establish more

687   compelling support for the null hypothesis in those cases much larger samples would

688   be required. Crucially, the Bayes Factor indicates by how much the observed

689   evidence should update one's prior belief in the null or alternative hypothesis. Even

690   if the evidence is relatively weak, any Bayes Factor below 1 is evidence *in favor of*

691   the null and not for the alternative hypothesis. Unless one starts with a prior belief

692   that people are clearly able to discriminate masked stimuli, even these modest Bayes

693   Factors suggest that participants were probably guessing.

694

695   Several previous studies used stimulus manipulations that seek to disentangle the

696   factors associated with Kanizsa-type illusory contours [39,48,49]. Rounding the

697   corners of the Pacman inducers results in a notable reduction in the illusory contour

698   percept and abolishes the concordant improvement on a spatial localization task.

699   However, stimuli like this nonetheless activated higher extrastriate cortex to a

700   similar degree as Kanizsa stimuli [39]. This is consistent with the theory that later

701   stages of visual processing, presumably mediated by higher visual areas, segment

702   surfaces and assign boundaries to objects. These segmentations are then fed back to

703   early visual cortex to generate signals that are interpreted as illusory contours [48].

704   Practical support for this idea comes from transcranial magnetic stimulation

705   experiments that disrupted neural processing either in object-sensitive lateral

706   occipital (LO) cortex or in early visual areas V1 and V2 [50]. Critically, the disruption

707   of LO cortex only abolished the illusory contour percept early after stimulus onset

708   while disruption of early visual areas only did so at a later stage – presumably

709   affecting feed-back signals rather than the early feed-forward response.

710

711   Additional stimulus processing that is unrelated to the actual formation of illusory

712   contours could also explain previous reports that Kanizsa stimuli are faster to break

713   through CFS masking than control stimuli [35]. The collinearity of edges and the

714   thereby inferred surface may be processed even while the stimulus is suppressed

715   from awareness – this may in turn produce an attentional signal that causes the

716   stimulus to break suppression. Recent experiments that tested a range of visual

717   control stimuli under CFS suggest that low-level properties of the stimulus determine

718   the time it takes to break suppression [51]. Such stimulus-dependent effects are also

719   plausible because attentional processing can occur without awareness of the

720   stimulus [52–54]. However, this does not prove that any percept of an illusory

721   contour was actually formed. This process may also explain why crowding interferes

722   with discrimination of the inducer orientation but not with illusory contour

723   formation [55].

724

725   While we did not manipulate the presence of illusory contours in this way in our

726   experiments, we nonetheless controlled this factor by including real luminance

727   contour conditions. In experiment 2 the presence of a contour should afford an

728   improvement on an orthogonal spatial localization task. Such an improvement in

729   localization thresholds only occurred for the real luminance contour or when Kanizsa

730   inducers were visible. Improvements like this are not observed for stimuli that match

731   the global characteristics but which do not produce illusory contours [39]. Therefore

732   our results from this experiment strongly support the conclusion that illusory

733   contours were simply not formed when inducers were masked.

734

735   Our results also agree with previous findings that only local processing occurs in the

736   absence of awareness but that more complex analysis of scene geometry requires

737   conscious processing [21]. This would also explain why the nature of stimulus

738   representations in higher visual areas differs depending on awareness.

26

739

740   However, our findings do not accord with a number of other studies that suggest

741   that illusory contours are processed unconsciously. Experiments on a patient with

742   extinction due to a parietal lesion suggest that perception of a Kanizsa shape occurs

743   even when some inducers are placed into parts of the visual field where the patient's

744   conscious perception is impaired [26–29]. These findings indicate that visual

745   processing operates at the surface- or object-based level. Segmenting and grouping

746   the local features of an image into a coherent, global shape may only require

747   awareness of some component features but it then spreads to the whole object.

748   However, this is not sufficient evidence to demonstrate that these processes would

749   occur when the participant is unaware of all components. More importantly, it also

750   does not demonstrate that the percept of illusory contours was actually formed

751   under these conditions but only that some processing of the features producing

752   illusory contours under normal viewing conditions still occurred.

753

754   Another study used functional magnetic resonance imaging (fMRI) and an

755   inattentional blindness paradigm to study illusory contours processing [49].

756   Participants were presented with a sequence of images, some of which contained

757   Kanizsa shapes whilst others were various types of control stimuli. Simultaneously,

758   participants were engaged in a demanding attentional task at fixation. A sub-group

759   of participants subsequently reported not to have seen any Kanizsa stimuli. These

760   participants nonetheless showed stronger fMRI responses to Kanizsa than control

761   stimuli. Multivariate classification methods further demonstrated that the activation

762   patterns produced by unseen Kanizsa stimuli were more reliable than those

763   produced by control stimuli. The authors suggested that the neural signature of

764   illusory contours differs from that of other, carefully matched stimuli and thus

765   argued that illusory contours are processed even without awareness of the stimuli.

766

767   This finding is interesting because it tests the consequences of awareness without

768   any experimental manipulation of the stimuli. The distinction of what is or is not

769   processed without awareness only depends on the contents of the participant's

770   consciousness. However, this also makes it difficult to interpret these results. First, it

771   is unclear whether participants apparently oblivious to the presence of the stimuli

772   really did not perceive any illusory shapes. Due to the design of the experiment,

773   awareness could only be assessed after the main fMRI experiment rather than on a

774   trial-by-trial basis (but see above our discussion why such trial-by-trial judgments of

775   awareness are complicated). Only participants who reported having seen the actual

776   Kanizsa stimulus during the experiment were classified as having had awareness of

777   the stimuli. However, many of the candidate stimuli were similar Kanizsa shapes.

778   Therefore it is possible that participants had some awareness of the stimuli, even if

779   an imprecise one.

780

781   Second, while the control stimuli in the main fMRI experiment were very carefully

782   matched to rule out the influence of global characteristics this can by definition only

783   be an approximation: if conditions were perfectly matched, the stimulus would be

784   identical and thus an illusory contour would be perceived. It is possible that the

785   conditions resulting in an illusory contour percept are also particularly effective in

786   producing discriminable activation patterns in visual cortex. For instance, the

787   contrast energy along the mouths of the Pacmen inducers differed considerably

788   between the Kanizsa and the global control stimuli. Thus, surface segmentation or

789   collinear interactions may have also differed between these conditions.

790

791   All these issues again highlight an important point: The only way one can truly infer

792   that illusory contours are formed is by using a measure that is specific to the

793   presence of an illusory contour. This is indeed what we did in our previous CFS

794   experiment [22], our present experiment 1, or what was done in several other

795   previous experiments [23,34,50,55], by asking participants to directly report a

796   feature of the contour. Another useful manipulation is the spatial localization task

797   used by other studies [23,39] as well as our experiment 2. This is because the

798   performance enhancement only occurs in the presence of an actual contour helping

799   the participant to localize the target. Many previous studies suggesting that illusory

800   contours are processed without awareness of the inducers are confronted with this

801   problem. In the appendix we included another experiment in which we tested

802   whether Kanizsa shapes masked from awareness could nevertheless provide an

803   attentional cue for a subsequent visual search task. Even if a robust priming effect

804   were found in such an experiment, this design simply cannot rule out alternative

805   explanations. It only tests the consequences of the stimuli that may in fact not be

806   specific to illusory contours.

807

808   In the same vein, neurophysiological and neuroimaging experiments have shown

809   that illusory contours are encoded by neurons even in the early visual cortex

810   [25,33,56–67]. The overwhelming majority of these experiments were conducted on

811   awake participants. However, some neurophysiological studies reported neuronal

812   tuning to illusory contours even in anesthetized animals [25,58,67]. Such findings

813   seem to superficially contradict our conclusion that awareness of the inducing

814   stimuli is necessary for the formation of illusory contours. However, these

815   experiments are in fact a perfect illustration of the importance to distinguish

816   between *perceptual experience* and correlated processing. Because animals are

817   anesthetized in these experiments and thus by definition unaware of the stimuli, it is

818   impossible to determine whether illusory contours were formed. The neural

819   correlates of these stimuli could be related to the contextual processing of the

820   inducing stimuli, such as the discontinuities detected by "end-stopped cells" or the

821   detection of collinearity in the image. Such processing may indeed occur in the

822   absence of awareness as is supported by our finding of collinear priming [21] and the

823   induction of contextual visual illusions under masking conditions [2,3] or inattention

824   [6]. Furthermore, it is quite likely that such stimulus processing is a necessary

825   prerequisite for the formation of illusory contours. However, they do not

826   conclusively prove that illusory contours are formed under anesthesia.

827

828   A related issue is that all of these studies use illusory contours induced by abutting

829   lines (offset gratings) rather than Kanizsa shapes. While the two share a similar

830   phenomenology, contours induced by abutting lines are arguably simpler and may

831   be based mostly on local processing while Kanizsa shapes are likely to involve more

832   complex inferences of surface depth and boundary ownership. Our experiments did

833   not explicitly test illusory contours generated with abutting lines and therefore do

834   not speak to the question whether such simpler illusory contours are in fact

835   perceived when the inducers are masked.

836

837   We conclude that there is little evidence that Kanizsa-type illusory contours are

838   processed when participants are not aware of the inducing context. This appears to

839   be the case for a range of different methods to render the inducers invisible.

840   However, all of these experiments employed physical stimulus manipulations, while

841   it is likely that an experimental design that allows the use of the participant's own

842   report to determine awareness on a trial-by-trial basis whilst also testing directly

843   whether an illusory contour was in fact formed can answer this question

844   conclusively.

845

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856   **Data and Materials**

857

858   All stimulus code and data for this study are available for download at:

859   https://dx.doi.org/10.6084/m9.figshare.2009952.

860

861

862   **References**

863

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1064

1065

1066 **Appendix**

1067

1068 *Priming experiment*

1069

1070 Previous experiments used illusory contours to capture attention in a visual search

1071 task [68] or for priming [69,70]. In our priming experiment, we therefore tested if

1072 Kanizsa triangles rendered invisible using a similar masking procedure could be used

1073 as primes in a visual search task on a subsequent, visible stimulus array. Like

1074 experiment 1, this experiment comprised two consecutive tasks. The first, again

1075 called 'Kanizsa' task, was an indirect test that investigated whether priming with a

1076 Kanizsa triangle in the location of the target improves detection of the target. A

1077 second task consisted of a 'Visibility' task that directly tested the effectiveness of the

1078 masking technique.

1079

1080 *Study design*

1081

1082 In the context of this experiment, priming refers to the attentional cue provided by

1083 the prime shape about the location of the subsequently presented target in one of

1084   four possible locations that in turn affords a boost in behavioral performance on an

1085   orthogonal discrimination task. In the primed conditions the location of the target

1086   was always identical with the location of the prime, whereas in the unprimed

1087   conditions the prime shape was replaced by a control stimulus, which looked exactly

1088   like the distractors in the other three locations. Therefore, the unprimed condition

1089   provided a baseline that allowed the assessment of whether the triangle prime

1090   boosted the participants' performance by capturing their attention.

1091

1092   We tested priming with a 2x2x2 design with attentional priming (primed vs.

1093   unprimed), the type of priming triangle (real vs. illusory), and prime visibility

1094   (invisible vs. visible) as within subject factors. There were two different prime

1095   shapes: a real triangle defined by a strong luminance contrast or an illusory (Kanizsa)

1096   one. The visibility of the cue was manipulated by varying presentation times of the

1097   priming array that followed the mask. A short presentation time of 16.7ms was

1098   selected for the invisible conditions to render the prime invisible. In the visible

1099   conditions, however, the priming array was presented for 300ms, which left enough

1100   time for the prime to enter awareness.

1101

1102   Every participant completed two different tasks. Each task comprised 20 blocks of

1103   trials, where one block consisted of 32 trials. Across one task, the unprimed visible

1104   and invisible conditions appeared for a total of 160 times each, whereas the four

1105   primed conditions (real vs illusory and visible vs invisible) occurred 80 times each.

1106   Thus, half the block consisted of unprimed trials and the other half of primed ones.

1107

1108   Behavioral responses were given on a forced-choice discrimination task by button

1109   press (left or right arrow) on a standard computer keyboard. Each trial required

1110   either a left or a right response (see experimental procedure) and each response

1111   type appeared twice per block for each condition, except for the unprimed ones

1112   where it appeared four times per block. Conditions were selected pseudo-randomly

1113   for every trial but were counterbalanced within each block.

1114

1115   *Participants*

1116

1117   Participants in this experiment were recruited among the UCL student population.

1118   Seventeen (13 female, age range: 21-32 years, mean age 24.7±2.5 years) normal,

1119   healthy participants took part in the experiment, including the two authors. All other

1120   participants were unaware of the experimental hypothesis.

1121

1122   *Stimuli*

1123

1124   In half the trials, participants were cued with one of four possible cues. We created

1125   shape stimuli by placing four black discs (inducer elements, diameter=1.96°) in the

1126   configuration of a square (width=2.8°). In order to produce the illusory shape of a

1127   right isosceles triangle sitting on top of the square, a wedge was removed from each

1128   inducer element (Pacman). Wedges started at the center of their respective discs

1129   and extended to their edges. One wedge measured 90° and was always positioned

1130   either in the bottom left or bottom right inducer. The two wedges that formed the

1131   apexes of the triangle measured 45°. Finally, the wedge of the fourth inducer

1132   element measured 90°. This Pacman did not form part of the triangle and was

1133   positioned opposite the hypotenuse of the right isosceles triangle. It always faced

1134   the outside of the disc configuration. When the inducers were oriented with the

1135   gaps forming the three corners of a triangle, an illusory light grey Kanizsa triangle

1136   was visible on top of the black discs (Figure S1A, i and ii).

1137

1138   Real triangles were identical to the corresponding illusory shapes except that their

1139   contour was defined by a luminance contrast with a black line connecting the

1140   corners of the triangle (Figure S1A, iii and iv).

1141

1142   The control stimuli were created by altering the orientations of the three Pacmen by

1143   a systematic rotation of 180º. This modification broke the link between these

1144   inducers and thus no illusory triangle was perceived (Figure S1B). Control stimuli

1145   could also be horizontal mirror images of the illustrated examples.

1146

1147   Stimuli in the search array were right isosceles triangles with a contour defined by

1148   luminance (Figure S1C, i and ii). Target stimuli were triangles with the right angle

1149   pointing down, either to the left or to the right, while in distractors the right angle

1150   pointed up (Figure S1C, iii and iv). Participants were asked to detect the target and

1151   respond via button press whether its right angle was pointing to the left or to the

1152   right.

1153

1154   The mask consisted of a square of black lines connecting four discs, one at each

1155   corner. It was wide enough to cover all four Pacmen, as well as the location of the

1156   triangle within them (Figure S1D, i). In the 'Visibility' task, there was no search array.

1157   Instead, the stimulus array following the prime was a square containing a cross that

1158   gave no clue about the location and orientation of the target triangle (Figure S1D, ii).

1159

1160   The luminance of the background was 156 cd/m^2. The luminance of inducer

1161   elements, the contour of the real triangle and the black of the mask was 2 cd/m^2.

1162   Finally, the grey of the mask in the first task was 58.2 cd/m^2.

1163

1164   Note that although there were differences between stimuli, the individual inducers

1165   remained the same and there was no change in the local image properties (i.e.

1166   square configuration of the four Pacmen and their position among the other 3

1167   configurations). This enabled an assessment of the different effects of priming with

1168   the Kanizsa shape, as compared to the corresponding real triangle and ungrouped

1169   Pacmen or distractors in the unprimed conditions.

1170

1171
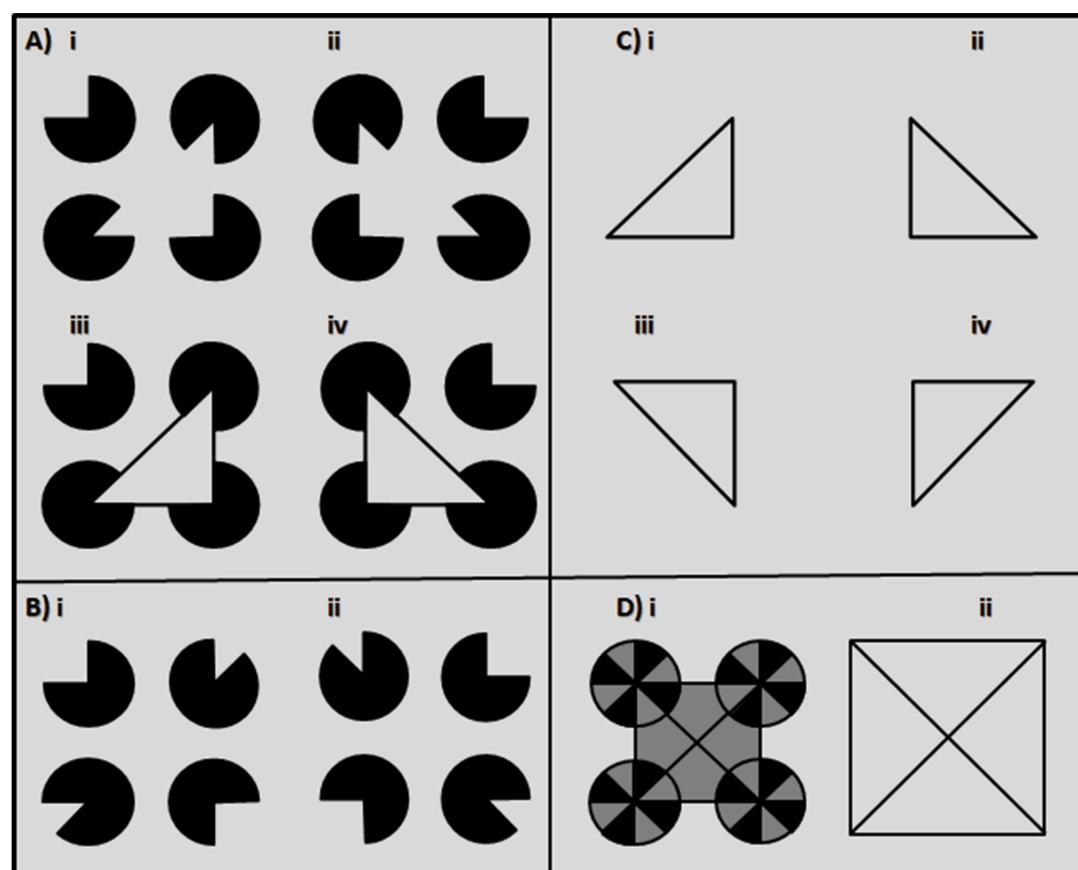
1172 **Figure S1. Illustration of the stimuli in the priming experiment.** A) The four primes were

1173 formed of four inducer elements, of which three created either a real triangle or the illusory

1174 impression of a triangle. In half the trials, participants were cued with one of the four

1175 possible cues: (i) Kanizsa triangle pointing right, (ii) Kanizsa triangle pointing left, (iii) Real

1176 triangle pointing right, (iv)Real triangle pointing left. B) Examples of control stimuli used

1177 during cue presentation. Control stimuli were created by a systematic 180° rotation of the

1178 individual Pacmen, so that all gaps within the black discs pointed to the outside of the

1179 formation. Control stimuli could also be the horizontal mirror image of the presented

1180 examples. C) The two possible targets in the search task were right isosceles triangles with

1181 their right angle pointing down, either to the right (i) or to the left (ii). Distractor stimuli in

1182 the search array always pointed up, but varied between pointing left and right. D) (i) The

1183 mask used to render the prime invisible. (ii) The uninformative post-stimulus mask replacing

1184 the target array in the 'Visibility' task.

1185

1186

1187

1188

1189   *Procedure*

1190

1191   *Kanizsa task, indirect test assessing priming:*

1192   At first, participants were instructed that they would see an array of four triangles of

1193   which only one, the target, had a right angle pointing down and were asked to

1194   decide whether this angle was pointing to the left or to the right by pressing the

1195   respective response keys.

1196

1197   The 20 experimental blocks were preceded by as many practice blocks as needed in

1198   order to fully familiarize the participants with the task requirements. Participants

1199   could initiate a new block by pressing any button on the keyboard and, if needed,

1200   take small breaks between blocks.

1201

1202   Participants were instructed to fixate a small black dot (0.2° wide) that was present

1203   in the center of the screen throughout the experiment. On each trial, the fixation dot

1204   was displayed alone for 500ms. Subsequently, a mask array was displayed for 100ms

1205   and was immediately followed by one of the priming arrays (see conditions in study

1206   design), which was presented for either 16.7ms or 300ms. This array could contain

1207   one of the two possible prime shapes (real or illusory triangle) or a simple control

1208   stimulus among the other three control stimuli. Immediately after this, a target array

1209   containing one target among three distractors was displayed and remained on the

1210   screen until the participant's response.

1211

1212   The response was self-paced; however, participants were instructed to respond as

1213   quickly as possible. Responses were made with the index (for left) and the middle or

1214   ring finger (for right), depending on how participants felt comfortable. For every

1215   response, the fixation dot provided feedback (100ms) by changing its color (green:

1216   correct; red: incorrect). Then, the next trial started without any delay. Figure S2A

1217   shows the general paradigm for the experimental procedure.

1218

1219   *Visibility task, direct test assessing prime discrimination:*

1220   The second task assessed the effectiveness of the mask by measuring the conscious

1221   discriminability of the primes in a direct manner. For this purpose, participants were

1222   asked to make the same decision as in the previous task, but this time with respect

1223   to the prime. Thus, instead of discriminating whether the right angle of the target

1224   was pointing to the left or to the right, participants discriminated this aspect of the

1225   prime shape.

1226

1227   Procedure, stimuli and timing of the trial sequence in this task were kept identical to

1228   the previous indirect test, with a single exception: Instead of a target array, an array

1229   comprising new identical mask shapes covered the four stimuli locations (Figure

1230   S2B).

1231

1232
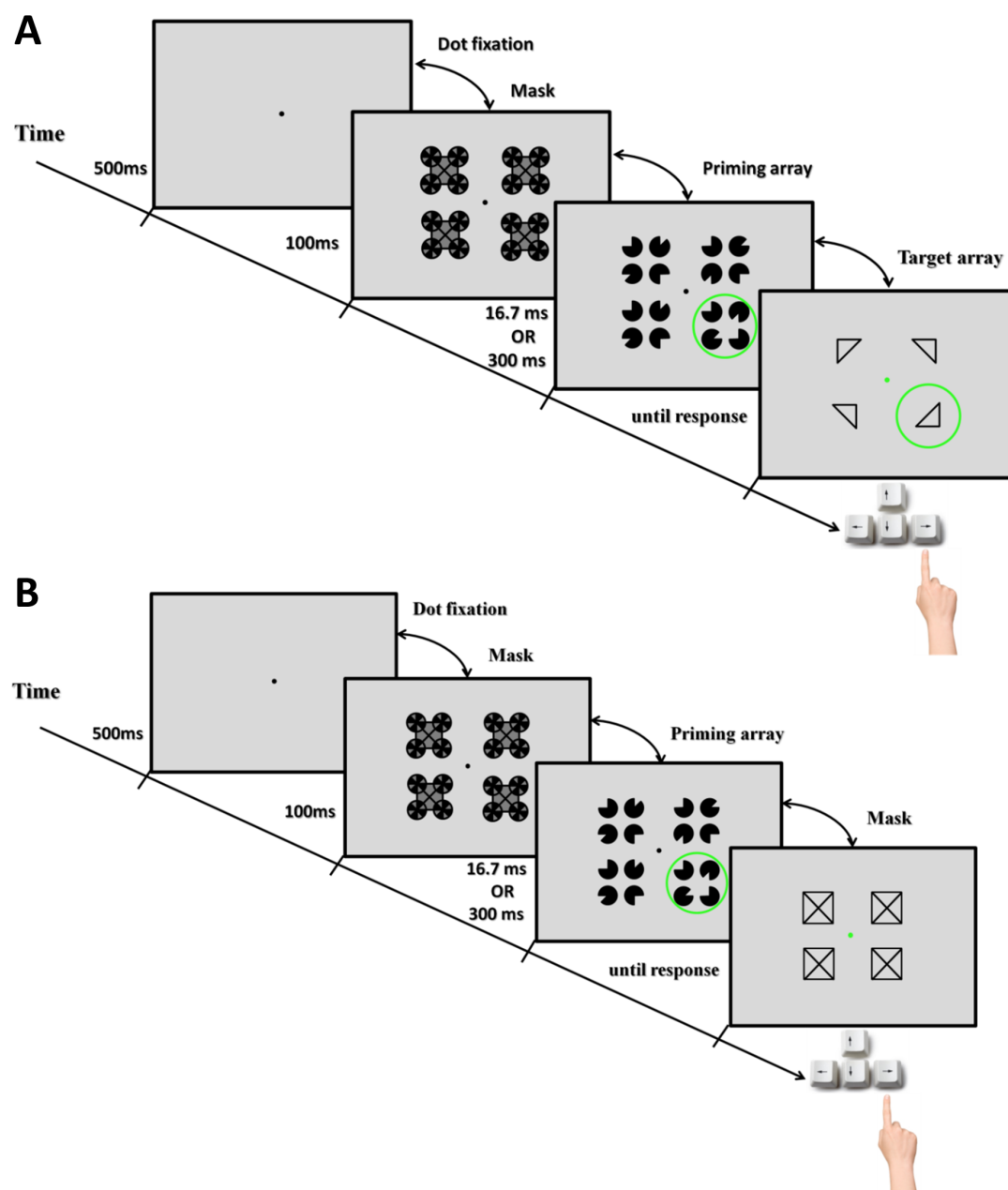
1233 **Figure S2. Illustration of an example trial sequence in the priming experiment.** A) Kanizsa

1234 task: Each trial was composed of four frames: fixation period, mask, cueing array and target

1235 array. After the participant's response, the fixation point provided feedback for 100ms

1236 (green: correct; red: incorrect). The duration of each frame is shown on the time-line. The

1237 duration of the cueing array was varied between conditions: 16.7ms in the invisible

1238 conditions and 300ms in the visible ones. Note that in the unprimed conditions, the cueing

1239 array did not contain any prime shape and was composed exclusively of control stimuli. B)

1240 Visibility task: Trial procedure was identical to the one in the Kanizsa task except for the

1241 fourth frame in which the search array was replaced by an array of four identical mask

1242 shapes.

1243

1244

1245   *Data analysis*

1246

1247   Response times (in milliseconds) and performance accuracy (in proportion correct)

1248   were measured for each of the six conditions. To analyze priming effects, response

1249   times were calculated on correct trials only.

1250

1251   For the Kanizsa task, accuracy of responses was less informative, as the target array

1252   was present until the participant's response. We reasoned that priming in the

1253   indirect Kanizsa task would be reflected by faster mean response times to primed

1254   than unprimed conditions. Therefore the priming effect was calculated by

1255   subtracting response times under priming from those without priming for correct

1256   responses.

1257

1258   Priming effects from all participants for all conditions were entered into a two-way

1259   repeated-measures analysis of variance (ANOVA) with prime visibility (visible vs

1260   invisible) and prime stimulus (real vs illusory triangle) as within subject factors. In

1261   addition to this, further comparisons between experimental conditions (visible or

1262   invisible/real or illusory) and control conditions (unprimed) were assessed with

1263   paired t-tests. We also determined the significance of the priming effect by

1264   comparing it against zero with one-sample t-tests.

1265

1266   In the visibility task, the variable of interest was the accuracy of responses as this

1267   allowed us to test whether participants could discriminate the orientation of the

1268   primes. One-sample t-tests were carried out at the group level for each condition

1269   individually in order to assess whether the participants' level of performance was

1270   significantly above chance (>0.5) and paired-tests were used to compare

1271   performance in different experimental conditions. As in experiment 1, for all t-tests

1272   we also calculated the default Bayes Factor in addition to frequentist statistics.

1273

1274

1275 *Results*

1276

1277 In the priming experiment we asked whether masked Kanizsa shapes could afford an

1278 attentional priming effect. We tested whether a Kanizsa stimulus presented as part

1279 of an array of four stimuli could prime participants to the location of a target in a

1280 visual search array presented subsequently. The prime could either be a Kanizsa

1281 triangle or a triangle defined by a real luminance contour. In the unprimed condition

1282 all four stimuli in the priming array were control stimuli without a triangle shape.

1283

1284 *Kanizsa Task*

1285

1286 Overall participants made very few errors in determining whether the target pointed

1287 to the left or to the right. Indeed, the mean accuracy in all conditions was above

1288 0.94. Therefore, for each experimental condition we quantified the effect of priming

1289 by the difference in response time with priming subtracted from that without

1290 priming on correctly answered trials (Figure S3A).

1291

1292
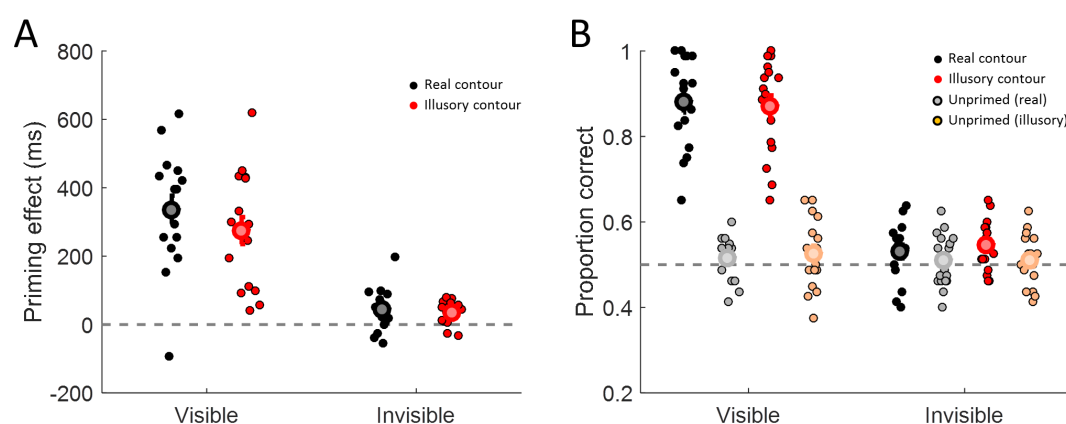
1293 **Figure S3. Results of experiment 2.** Priming effect (response time for unprimed trials minus

1294 primed trials) on the Kanizsa task (A) and accuracy for discriminating the inducer location in

1295 the Visibility task (B) for visible or invisible (masked) trials. Each dot represents the mean

1296 performance of an individual participant in each of the conditions. The large symbols and

1297 error bars denote the mean ±1 standard error for each condition. Black: real luminance

1298 contour. Red: illusory (Kanizsa) contour. In B) Grey: unprimed trials dummy coded for real

1299 contour prime. Orange: unprimed trials dummy coded for illusory contour prime.

1300

1301   We conducted a two-way repeated-measures analysis of variance, with visibility

1302   (visible vs invisible) and stimulus (illusory vs real triangle) as within subject factors, to

1303   compare the priming effects (response time on unprimed minus primed trials)

1304   between conditions. There was a significant main effect of visibility of the prime

1305   ($F(1,16)=60.06$, $p<0.001$), and a significant main effect of stimulus type

1306   ($F(1,16)=13.82$, $p=0.002$). The interaction between visibility and the stimulus type

1307   was not significant ($F(1,16=3.52$, $p=0.079$).

1308

1309   There was a clear difference in the strength of priming between the visible and

1310   invisible condition. However, the critical test is whether the priming effect was

1311   significant, that is, if it differed from zero (i.e. a paired t-test between primed and

1312   unprimed response times). Unsurprisingly, the very pronounced priming effect for

1313   visible trials was extremely significant for both conditions (real: $M=336ms$, $t(16)=8.2$,

1314 $p<0.001$, $BF_{10}>4.1*10^4$; illusory: $M=275ms$, $t(16)=6.9$, $p<0.001$, $BF_{10}>5.8*10^3$). There

1315   was also a much more modest but nonetheless very significant priming effect for

1316   both stimulus types in the invisible condition when inducers were masked (real:

1317 $M=43ms$, $t(16)=3$, $p=0.01$, $BF_{10}=5.6$; illusory: $M=36ms$, $t(16)=4.4$, $p<0.001$,

1318 $BF_{10}=80.8$).

1319

1320   *Visibility Task*

1321

1322   As in experiment 1 we used a direct Visibility test to assess whether participants

1323   might have had residual awareness of the priming stimuli under masking. The task

1324   procedure was the same as in the Kanizsa task except that the search array was

1325   replaced with a foil in which all four stimuli were identical and non-informative

1326   about the correct answer. We quantified the accuracy (proportion correct) with

1327   which participants could discriminate the orientation of the priming triangle (Figure

1328   S3B).

1329

1330   Unsurprisingly, in the visible condition performance for discriminating the

1331   orientation of a real ($M=0.88$, $t(16)=14.9$, $p<0.001$, $BF_{10}=9.5*10^7$) and an illusory

1332   triangle (M=0.87, t(16)=14, p<0.001, BF_{10}=4.0*10^7) was significantly above chance.

1333   Conversely, performance for the unprimed conditions, that is, stimulus arrays that

1334   contained no triangle shape, performance was consistently at chance ("real":

1335 M=0.52, t(16)=1.3, p=0.21, BF_{10}=0.52; "illusory": M=0.53, t(16)=1.3, p=0.219,

1336 BF_{10}=0.5; but note that these two conditions were dummy coded in this case as they

1337   contained the same stimuli).

1338

1339   Critically, performance in the invisible condition showed that discrimination in the

1340   primed with an illusory triangle condition was also significantly above chance (M=

1341   0.55, t(16)=3.24, p=0.005, BF_{10}=9.4), and discrimination of a real triangle showed a

1342   similar result even though it did not reach significance (M=0.53, t(16)=1.9, p=0.075,

1343 BF_{10}=1.1). Performance for the two invisible triangles also did not differ significantly

1344   (t(16)=-0.9, p=0.385, BF_{10}=0.35). Again, as expected both of the unprimed conditions

1345   were at chance level ("real": M=0.51, t(16)=0.6, p=0.534, BF_{10}=0.3; "illusory":

1346 M=0.51, t(16)=0.7, p=0.494, BF_{10}=0.31).

1347

1348

1349   *Discussion*

1350

1351   Taken together, the results of the priming experiment contradict those of

1352   experiment 1 and 2 , as they suggest that Kanizsa triangles rendered invisible by

1353   masking could afford an attentional priming effect in a subsequent visual search

1354   task. However, a control experiment testing participants' ability to discriminate the

1355   prime shape orientation directly suggested that this small priming effect for invisible

1356   trials could have been due to some residual awareness of the masked triangle

1357   stimuli. When conducting such tests of awareness, it is of paramount importance to

1358   ensure that trials with masked and unmasked conditions are interspersed. When

1359   only masked conditions are tested for awareness, it is possible that the participant's

1360   performance is at chance even though there is in fact residual awareness in the main

1361   task due to what has been referred to as "priming of awareness" [71]. Conversely,

1362   the ability to correctly identify purportedly subliminal prime stimuli (as in our

1363   priming experiment) may have been enhanced by the inclusion of trials with clearly

1364   visible primes [72]. Either way, because we controlled for this possibility our visibility

1365   test should have provided a robust test of awareness. Therefore, the most

1366   parsimonious interpretation of the priming results is that participants had some

1367   residual awareness of the primes and that Kanizsa contours were probably not

1368   processed when inducers were masked. Using a different masking technique, for

1369   example the fast counter-phase flicker used in experiment 2 could be more effective

1370   and provide a better test of whether unconscious Kanizsa stimuli can act as

1371   attentional cues.

1372

1373   Critically, however, because priming experiments like this are only an indirect test of

1374   an effect that is not specific to illusory contour formation, this would not be

1375   informative. Even if we interpret the somewhat inconclusive results of this

1376   experiment as showing that masked triangles produced priming effects, this does

1377   not provide direct evidence that this advantage is actually caused by the presence of

1378   illusory contours. A Kanizsa triangle can clearly provide a salient attentional cue but

1379   this may be due to shared features, such as the collinearity of the edges in the

1380   inducers or the implication of a surface. This is also consistent with previous reports

1381   that priming of a shape discrimination task by subliminal stimuli depends on the

1382   strength of the salient region [73] and that salient regions of such stimuli are

1383   detected efficiently regardless of whether they are bounded by illusory contours

1384   [39,74]. Finding a priming effect thus only suggests that attentional cuing can occur

1385   without awareness but it does not rule out that other factors produced this

1386   attentional capture. Conversely, the absence of a priming effect would only confirm

1387   that whatever acts as attentional cue is disrupted. Therefore, the only meaningful

1388   test that illusory contours are indeed formed is via a measure that is *specific* to this

1389   percept.

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