

1 **The effect of pupil size and peripheral brightness on**
2 **detection and discrimination performance**

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14

Abstract

15 It is easier to read dark text on a bright background (positive polarity) than to read bright text on a dark
16 background (negative polarity). This positive-polarity advantage is often linked to pupil size: A bright
17 background induces small pupils, which in turn increases visual acuity. Here we report that pupil size, when
18 manipulated through peripheral brightness, has qualitatively different effects on discrimination of fine stimuli
19 in central vision and detection of faint stimuli in peripheral vision. Small pupils lead to improved
20 discrimination performance, consistent with the positive-polarity advantage, but only for very small stimuli
21 that are at the threshold of visual acuity. In contrast, large pupils lead to improved detection performance.
22 These results are likely due to two pupil-size related factors: Small pupils increase visual acuity, which
23 improves discrimination of fine stimuli; and large pupils increase light influx, which improves detection of
24 faint stimuli. Light scatter is likely also a contributing factor: When a display is bright, light scatter creates a
25 diffuse veil of retinal illumination that reduces image contrast, thus impairing detection performance. We
26 further found that pupil size was larger during the detection task than during the discrimination task, even
27 though both tasks were equally difficult and similar in visual input; this suggests that the pupil may
28 automatically assume an optimal size for the current task. Our results may explain why pupils dilate in
29 response to arousal: This may reflect an increased emphasis on detection of unpredictable danger, which is
30 crucially important in many situations that are characterized by high levels of arousal. Finally, we discuss the
31 implications of our results for the ergonomics of display design.

32 *Keywords: pupillometry, pupil size, pupil light response, display polarity, display design, ergonomics,*
33 *psychophysics*

34 **The Effect of Pupil Size and Peripheral Brightness on Detection and Discrimination** 35 **Performance**

36 You are probably reading this text as dark letters on a bright background. And if not, then you might consider
37 doing so, because it is easier to read dark letters on a bright background (positive polarity) than it is to read
38 bright letters on a dark background (negative polarity). This positive-polarity advantage has been well-
39 established in human-factors research (Buchner, Mayr, & Brandt, 2009; Dobres, Chahine, & Reimer, 2017;
40 Piepenbrock, Mayr, & Buchner, 2014b, 2014a; Taptagaporn & Saito, 1990), and is often studied using
41 proofreading experiments. For example, Piepenbrock et al. (2014b) asked participants to verbally report all
42 misspelled words in a short text. The authors found that participants read faster, and spotted more mistakes,
43 when the text was presented in a positive polarity, compared to a negative polarity. Findings such as these are
44 among the reasons that most websites and word-processing software use a positive polarity.

45 The positive-polarity advantage is likely related to pupil size. When the background of a display is bright, the
46 pupil constricts, compared to when the background is dark; this is the pupil light response (reviewed in Mathôt,
47 2018; Mathôt & Van der Stigchel, 2015). In terms of visual perception, there are three main consequences of a
48 bright background and the resulting pupil constriction. The first consequence is negative: A bright background,
49 as any source of brightness, results in light scatter; that is, some of the incoming light is not focused, but
50 instead spreads over a large part of the retina. This results in a diffuse veil of light that reduces image contrast.
51 The second consequence is also negative: Small pupils reduce the amount of light that falls on the retina, and
52 thus reduce the signal-to-noise ratio of the image. The third consequence is positive: Small pupils suffer less
53 from optical distortions that reduce image quality, and thus increase visual acuity (Campbell & Gregory, 1960;
54 Liang & Williams, 1997; M. Lombardo & Lombardo, 2010; Woodhouse, 1975); that is, small pupils see
55 sharper.

56 When reading text that is presented with sufficiently high contrast, as is typically the case in daily life, the
57 advantage of increased visual acuity seems to outweigh the disadvantages of reduced signal-to-noise ratio and
58 increased light scatter. Therefore, it is easier to read dark text on a bright background (when pupils are small),
59 especially when the text is written in a small font (Piepenbrock et al., 2014a).

60 There is also some neurophysiological evidence that small pupils increase visual acuity. For example,
61 Bombeke and colleagues (2016) manipulated pupil size by having participants covertly attend to either a bright

62 or a dark disk, which respectively constricts or dilates the pupils, without changing eye position or visual input
63 (cf. Binda, Pereverzeva, & Murray, 2013; Mathôt, van der Linden, Grainger, & Vitu, 2013). They then briefly
64 presented a task-irrelevant but salient line-grating stimulus in peripheral vision, and measured the C1, an
65 event-related potential (ERP) component that is associated with activity in primary visual cortex. The
66 amplitude of the C1 was larger when participants attended the bright disk, compared to when they attended the
67 dark disk. According to the authors, this result was due to the fact that small pupils improved the resolution of
68 the C1-eliciting stimulus, in turn leading to a stronger neural response in primary visual cortex.

69 However, behavioral evidence for a link between pupil size and visual acuity is mixed. In a recent study by
70 Ajasse, Benosman, and Lorenceau (2018), participants made a sequence of eye movements toward a
71 configuration of disks; each disk had a different brightness, and the size of the pupil was therefore different
72 depending on which disk the participant was fixating. While participants were fixating a disk, two gabor
73 patches were briefly and sequentially presented in their visual periphery. The spatial frequency of the gabor
74 patches differed, and participants indicated which of the two had the highest spatial frequency. The authors
75 predicted that performance on this task should increase with decreasing pupil size (and thus with increasing
76 brightness of the fixated disk). However, they found no such relationship; that is, performance did *not* depend
77 on pupil size.

78 The results of Ajasse and colleagues (2018) show that small pupils do not lead to improved discrimination
79 performance in every situation. Specifically, in their experiment, stimuli were presented in peripheral vision,
80 where acuity is mostly limited by the reduced density of cone photoreceptors; therefore, in peripheral vision,
81 optical blur due to large pupils likely has at most a very small effect on stimulus discrimination. However, the
82 results of Bombeke and colleagues (2016), who also used a peripherally presented stimulus, suggest that under
83 specific conditions a small-pupil advantage can also be found in peripheral vision.

84 In yet other situations, small pupils may even *impair* visual performance (reviewed in Mathôt, 2018; Mathôt &
85 Van der Stigchel, 2015). Specifically, detecting faint stimuli in peripheral vision requires a high signal-to-noise
86 ratio of the image, and visual acuity is only of secondary importance. In this case, large pupils may improve
87 the signal-to-noise ratio of vision by increasing overall light influx. Therefore, stimulus detection in the visual
88 periphery should benefit from large pupils. When large pupils are associated with a dark environment, as is
89 typically the case in real life, this benefit should be even stronger, because the increased signal-to-noise ratio
90 due to large pupils is accompanied by reduced light scatter due to the dark environment.

91 However, a study by Thigpen, Bradley, and Keil (2018) suggests that large pupils may not necessarily ‘boost’
92 neural responses to visual input. In their study, they presented a rapidly flickering stimulus, and measured so-
93 called Steady-State Visually Evoked Potentials (ssVEPs): neural oscillations in visual cortex with the same
94 frequency as the inducing stimulus. ssVEP power is believed to reflect the level of neural activity. Crucially,
95 the authors found no relationship between ssVEP power and pupil size, and they interpreted this result as
96 evidence for divisive normalization (Carandini & Heeger, 2012); that is, they suggested that visual responses,
97 even in early visual cortex, are invariant to overall light influx and thus unaffected by pupil size.

98 Taken together, previous research has provided compelling evidence for an advantage of small pupils (and a
99 bright background) for text reading (Buchner et al., 2009; Dobres et al., 2017; Piepenbrock et al., 2014b,
100 2014a; Taptagaporn & Saito, 1990). There is also some neurophysiological evidence for a small-pupil benefit
101 for visual acuity (Bombeke et al., 2016; but see Ajasse et al., 2018). In contrast, there is no evidence for a
102 large-pupil advantage for stimulus detection (e.g. Thigpen et al., 2018). Nevertheless, a large-pupil advantage
103 for detection is clearly predicted based on the optical properties of the eye (see Mathôt, 2018; Mathôt & Van
104 der Stigchel, 2015).

105 The aim of the current study is to demonstrate both a small-pupil advantage for discrimination of stimuli in
106 central vision, and a large-pupil advantage for detection of stimuli in peripheral vision. We will manipulate
107 pupil size by manipulating the brightness of the visual periphery, while presenting all task-relevant stimuli on a
108 central gray disk of constant brightness.

109 **Experiments 1 and 2**

110 The goal of Experiments 1 and 2 was to investigate whether pupil size, when manipulated through peripheral
111 brightness, differentially affects performance on detection and discrimination tasks. In Experiment 1,
112 participants detected, or discriminated the orientation of, a tilted Gabor patch. In Experiment 2, participants
113 detected, or discriminated the lexicality of, a single word.

114 **Methods**

115 **Experiment 1**

116 **Participants, Ethics, and Apparatus** Nine naive observers participated in the experiment, after providing
117 informed consent. The experiment was approved by the local ethics committee of Groningen University

118 (16163-SP-NE and 16349-S-NE). Pupil size was recorded with an EyeLink 1000 (SR Research). Stimuli were
119 presented with OpenSesame 3.1 (Mathôt, Schreij, & Theeuwes, 2012) on a 27" flat screen monitor with a
120 resolution of 1920 x 1080 px.

121 **Pupil-size manipulation** Pupil size was manipulated by varying the brightness of the visual periphery (low:
122 0.16 cd/m², medium: 8.30 cd/m², high: 52.26 cd/m²; see [Figure 1](#)), which corresponded to the full display
123 (49.22° × 27.70°) except for a central gray disk. All task-relevant stimuli were presented on the central gray
124 disk (2.84 cd/m²; diameter: 25.65°) that was kept constant throughout the experiment.



125 **Figure 1.** *The luminance of the visual periphery was varied to manipulate pupil size. All task-relevant stimuli*
126 *appeared on a central gray disk that was kept constant throughout the experiment.*

127 **Design** The experimental task (Discrimination or Detection) was varied between sessions. One experimental
128 session consisted of five blocks.

129 The first two blocks of each session served to calibrate a Quest adaptive procedure, which varied the properties
130 of the Target stimulus (see below) such that accuracy was kept at 75%. During these calibration blocks,
131 peripheral brightness was set to 2.84 cd/m². After these two blocks, the Quest procedure was stopped, and the
132 Target was kept constant throughout the remainder of the session. Next, participants performed three blocks of
133 50 trials. Peripheral Brightness was varied between blocks ([Figure 1](#)).

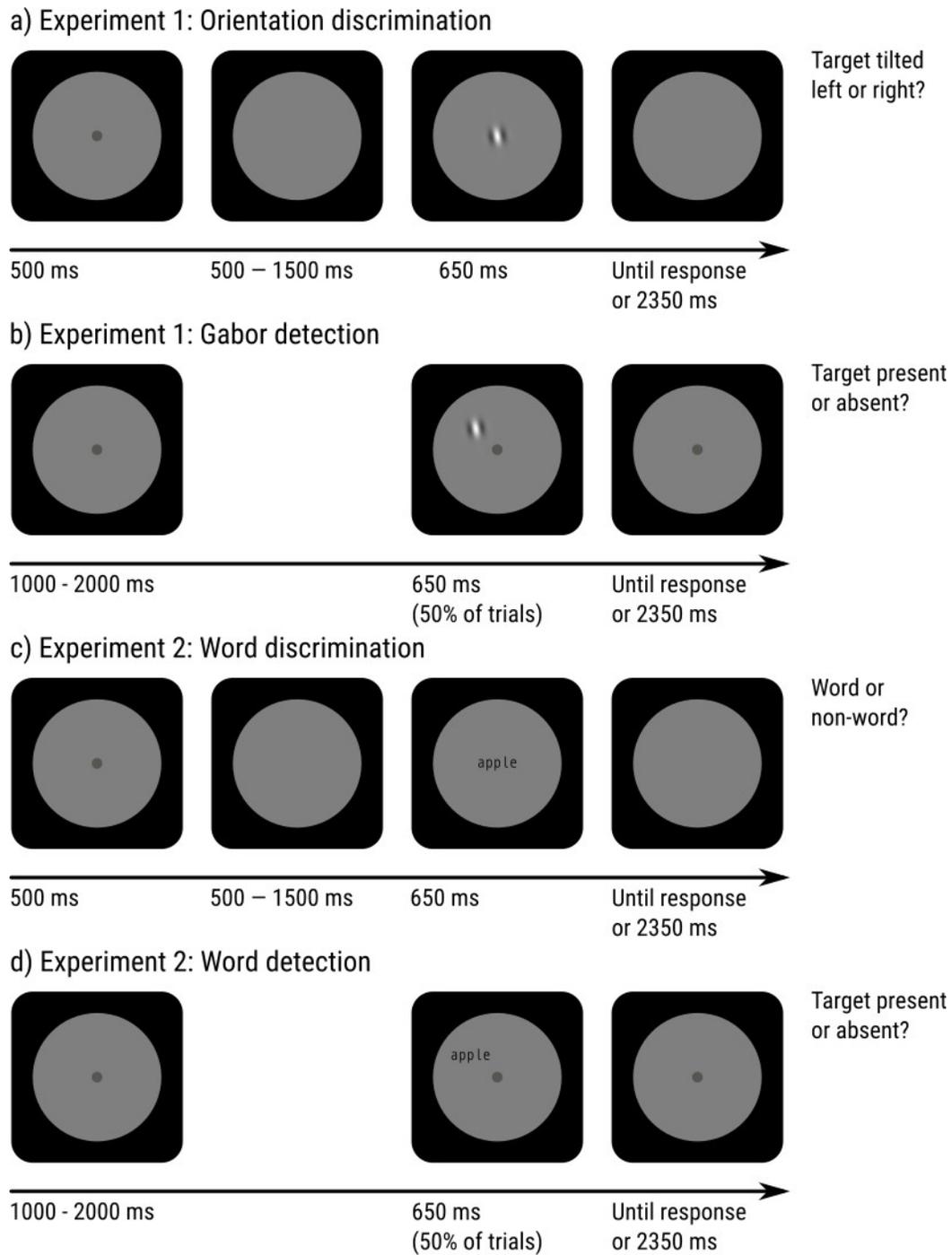
134 Block order was fully counterbalanced, such that each possible order occurred once for each participant and
135 task. Half the participants started on the first day with a Discrimination session followed by a Detection
136 session, vice versa on the second day, etc. The other half of the participants started with a Detection session on
137 the first day. In some cases, participants did more than two sessions per day. In total, participants performed
138 3,000 trials across 12 sessions in approximately six hours.

139 **Discrimination Task** In the Discrimination task (see [Figure 2a](#)), each trial started with a central fixation dot (a
140 uniform patch with a gaussian envelope with a standard deviation of 0.51° [20 px] and a peak brightness of
141 4.41 cd/m^2) that was removed after 500 ms. After a random interval between 500 and 1,500 ms, drawn from a
142 uniform distribution, a central Target Stimulus smoothly faded in and out over a period of 650 ms. The Target
143 was a centrally presented sinusoidal grating with a gaussian envelope (a Gabor patch) with a standard
144 deviation of 0.51° (20 px). To maintain accuracy at 75%, the spatial frequency, contrast, and orientation of the
145 Target was varied with a Quest adaptive procedure during calibration blocks as described above.

146 At any point during the trial, participants pressed the left arrow key if the Target was tilted counterclockwise
147 from a vertical orientation, and the right arrow key if it was tilted clockwise. The trial ended 3 s after the onset
148 of the Target.

149 **Detection Task** In the Detection task (see [Figure 2b](#)), each trial started with a central fixation dot (4.41 cd/m^2)
150 that remained visible throughout the trial. On 50% of trials, after a random period drawn from a flat
151 distribution between 1 and 2 s, a Target Stimulus was smoothly faded in and out over a period of 650 ms. The
152 Target was identical to that of the Discrimination task, except that its standard deviation was 1.02° (40 px; i.e.
153 twice as big), and that it was presented at a random point on an imaginary circle around the fixation dot with a
154 radius of 7.70° (300 px).

155 At any point during the trial, participants pressed the space bar when they detected a Target, and did not press
156 any key when they did not detect a Target. The trial ended 3 s after the onset of a Target (when present), or
157 after a random interval between 4 and 5 s, drawn from a uniform distribution.



158 **Figure 2.** Schematic paradigm of Experiments 1 and 2. a) Orientation-discrimination task for Experiment 1.
159 b) Orientation-detection task for Experiment 1. c) Word-discrimination (lexical decision) task for Experiment
160 2. d) Word-detection task for Experiment 2.

161 **Experiment 2**

162 Experiment 2 was in most ways identical to Experiment 1, and only the differences are described below.

163 **Participants, Ethics, and Apparatus** Nine naive observers, most of whom had not participated in Experiment
164 1, participated in the experiment after providing informed consent. All participants were native Dutch
165 speakers.

166 **Stimulus selection** We selected the 750 most highly frequent words between four and six characters from the
167 Dutch Lexicon Project (Keuleers, Diependaele, & Brysbaert, 2010), after manually (and based on our
168 subjective impression) excluding overly offensive words. For each word, a matching pseudoword was
169 generated with Wuggy (Keuleers & Brysbaert, 2010).

170 **Design** Participants performed 1,500 trials across six sessions in approximately three hours. All participants
171 saw all words and pseudowords once in a random order.

172 **Task** Targets were (pseudo)words presented in a monospace font. In the Discrimination task, Targets were
173 centrally presented, and participants pressed the left arrow key if the Target was a pseudoword and the right
174 arrow key if it was a word (i.e. a lexical-decision task). In the Detection task, Targets were peripherally
175 presented on 50% of trials, and participants pressed the space bar if they detected a target, and did not press
176 any key otherwise. To maintain accuracy at 75%, the font size and contrast of the Target was varied.

177 **Results**

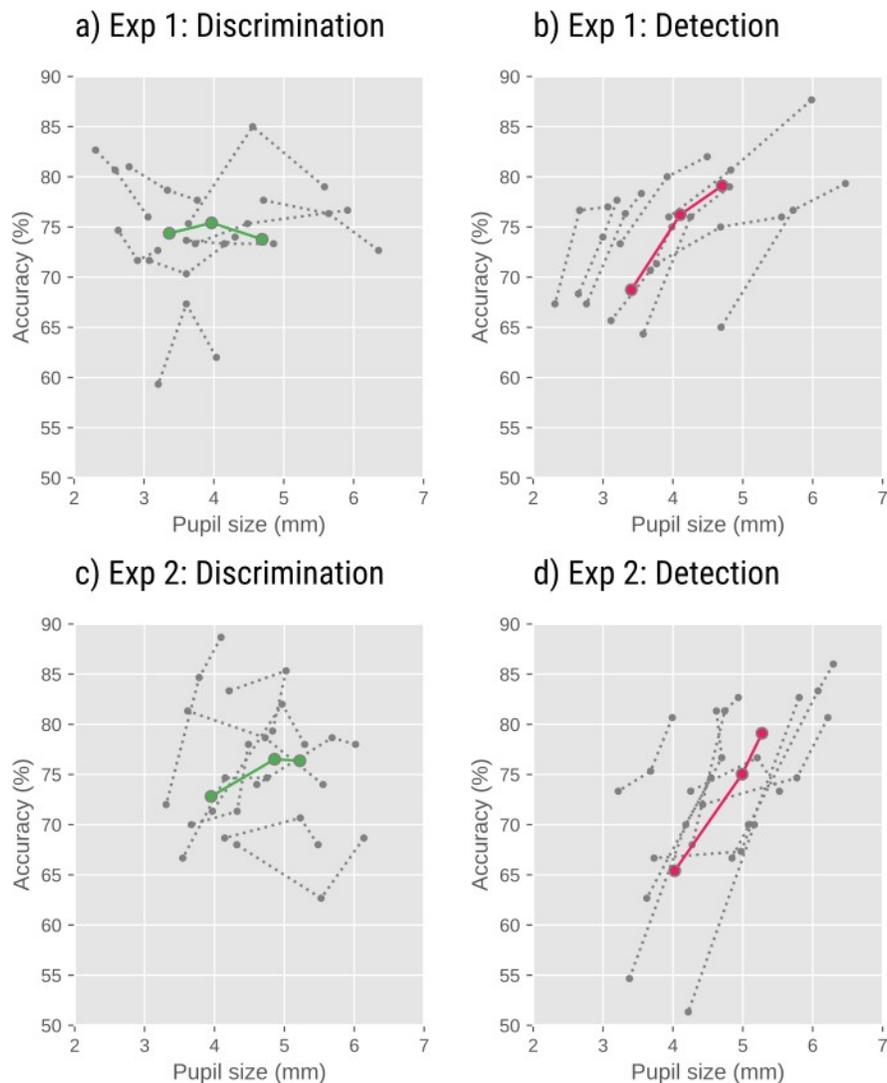
178 We performed the same set of analyses on both experiments. The results from both experiments were very
179 similar.

180 **Task performance**

181 To be able to directly compare performance in the Detection and Discrimination tasks, we used accuracy as
182 our dependent measure. However, the results for the Detection task are similar when using d' (a measure of
183 sensitivity that is based on signal-detection theory). Mean accuracy on the Detection task was 74.7% (Exp 1)
184 and 73.2% (Exp 2). Mean accuracy on the Discrimination task was 74.5% (Exp 1) and 75.2% (Exp 2).

185 To test whether pupil size (as manipulated through peripheral brightness) affects performance (see [Figure 3](#)),
186 and does so differently for the Discrimination and Detection tasks, we conducted a generalized linear mixed

187 effects model (GLM) with Correct as dependent variable (binomial), Brightness (Low [reference], Medium,
188 High), Condition (Detection [reference], Discrimination), and the Brightness \times Condition interaction as fixed
189 effects. We included only by-participant random intercepts, because more complex models failed to converge.
190 (However, the results do not crucially depend on the exact model structure.) All mixed-effects analyses were
191 conducted with the R package lme4 (Douglas et al., 2015).



192 **Figure 3.** Detection accuracy increased with decreasing peripheral brightness, and thus increasing pupil size
193 (b, d). However, there was no effect of peripheral brightness on discrimination performance (a, c). Gray
194 dotted lines indicate individual participants. Colored solid lines indicate grand averages.

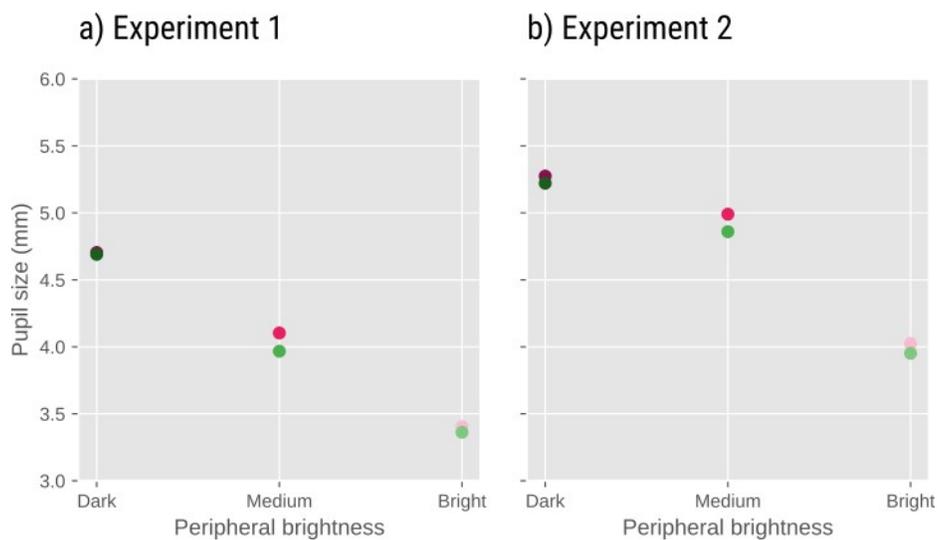
195 There was an effect of Brightness (Exp 1: $Z = -8.754$, $p < .001$; Exp 2: $Z = -8.005$, $p < .001$), indicating that for
196 the Detection (reference) Condition, accuracy decreased with increasing Brightness. There was an effect of
197 Condition (Exp 1: $Z = -5.343$, $p < .001$; Exp 2: $Z = -2.001$, $p = .045$) indicating that for the Low (reference)
198 Brightness, accuracy was lower for the Discrimination than Detection condition. Crucially, there was also a
199 Brightness \times Condition interaction (Exp 1: $Z = 6.586$, $p < .001$; Exp 2: $Z = 4.114$, $p < .001$), indicating that the
200 effect of Brightness was driven by the Detection Condition, and not present in the Discrimination Condition.

201 To confirm this, we also analyzed the Discrimination Condition separately, in a model with only Brightness as
202 fixed effect. Here we found no effect of Brightness in Exp 1 ($Z = 0.503$, $p = .615$), and only a weak effect of
203 brightness in Exp 2 ($Z = -2.153$, $p = 0.031$).

204 Pupil size

205 The EyeLink provides pupil size in arbitrary units. To convert these units to millimeters of diameter, we first
206 recorded artificial pupils (black circles printed on white paper) of different sizes, and then determined a
207 function to convert EyeLink pupil units to pupil diameter (mm).

208 Mean pupil size during the Detection task was 4.1 mm (Exp 1) and 4.8 mm (Exp 2). Mean pupil size on the
209 Discrimination task was 4.0 mm (Exp 1) and 4.7 mm (Exp 2).



210 **Figure 4.** In both experiments, pupil size decreased with decreasing peripheral brightness. In addition, pupil
211 size was slightly larger in the Detection than in the Discrimination condition.

212 Our brightness manipulation should have a large effect on pupil size. It is also possible that the task affects
213 pupil size, despite the fact that the two tasks were equally difficult. To test this, we conducted a linear mixed-
214 effects analysis (LMER) with Pupil Size as dependent measure and Brightness, Condition, and a Brightness \times
215 Condition interaction as fixed effects. Again, we included only by-participant random intercepts, because more
216 complex models failed to converge.

217 There was an effect of Brightness (Exp 1: $t = -87.405$; $p < .001$ Exp 2: $t = -58.165$, $p < .001$), reflecting that
218 pupil size decreased with increasing brightness. There was also an effect of Condition (Exp 1: $t = -3.849$, p
219 $< .001$; Exp. 2: $t = -4.340$, $p < .001$), reflecting that pupil size was larger in the Detection than in the
220 Discrimination condition. There was no notable Brightness \times Condition interaction (Exp 1: $t = -0.930$, $p =$
221 0.352 ; Exp 2: $t = -0.216$, $p = 0.829$).

222 Discussion

223 In summary, we found that detection performance was better with large pupils (and a dark periphery) than with
224 small pupils (and a bright periphery). This effect was large, robust, and in the direction that we predicted.
225 However, and unlike we predicted, we did not find that discrimination performance increased with decreasing
226 pupil size (and thus increasing peripheral brightness); in fact, there was a slight effect in the opposite direction
227 for Exp. 2.

228 In addition, we found that pupil size was larger in the Detection than in the Discrimination condition, even
229 though both tasks were equally difficult.

230 A limitation of our setup for measuring discrimination performance was that we could not present very small
231 stimuli: When presented at full contrast, even the finest possible grating (i.e. 2 px/cycle) or the smallest
232 possible letter (5×5 pixels) could be discriminated without too much trouble by someone with normal vision.
233 Therefore, to increase the difficulty of the discrimination task, we also reduced the contrast of the target
234 stimulus, and our discrimination task was therefore not a pure measure of discrimination performance (a
235 limitation that we addressed in Experiment 3).

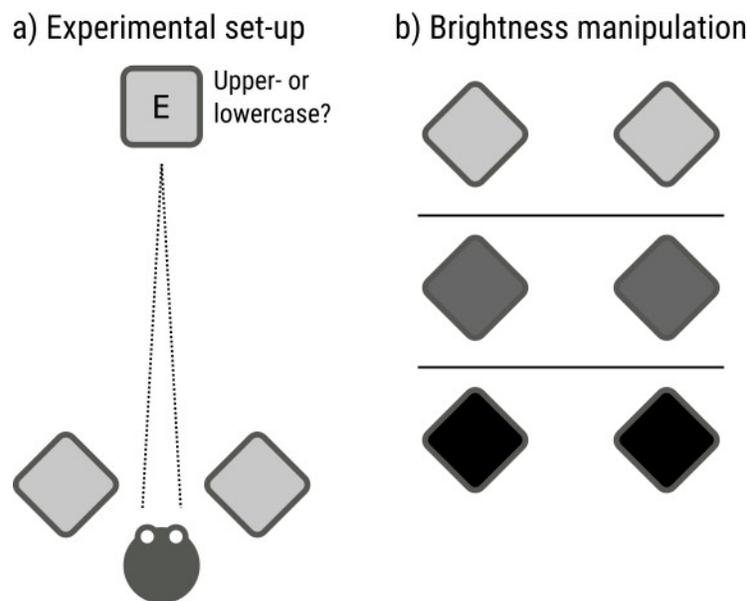
236

Experiment 3

237 In Experiment 3, we used a setup that allowed us to present very small letters. The aim of this experiment was
238 to investigate whether we could observe an advantage of small pupils (and increased peripheral brightness) on
239 discrimination performance in a task that tested the limits of visual acuity. If so, this would suggest that the
240 absence of a small-pupil benefit in Experiments 1 and 2 was due to the fact that, in these experiments, our
241 stimuli were not sufficiently fine to test the limits of visual acuity.

242

Methods



243 **Figure 5.** Schematic set-up and paradigm of Experiment 3. a) Participants indicated whether a target letter
244 was uppercase or lowercase. b) Pupil size was manipulated by varying the brightness of two displays that
245 were positioned near the participant, and flanked the target display.

246 **Participants, Ethics, and Apparatus** 20 naive observers participated in the experiment, after providing
247 informed consent. The experiment was approved by the local ethics committee of Groningen University
248 (16163-SP-NE and 16349-S-NE). Pupil size was recorded with an EyeLink 1000 (SR Research). Stimuli were
249 presented with OpenSesame 3.1 (Mathôt et al., 2012) on three separate 7" tablets (Samsung Galaxy Tab 7),
250 each with a resolution of 1280 × 800 px. Two tablets were presented nearby, on both sides, of the participant's

251 head, and served as light sources. One tablet was placed in front of the participant, at a distance of 5.5 m, and
252 served as the target display.

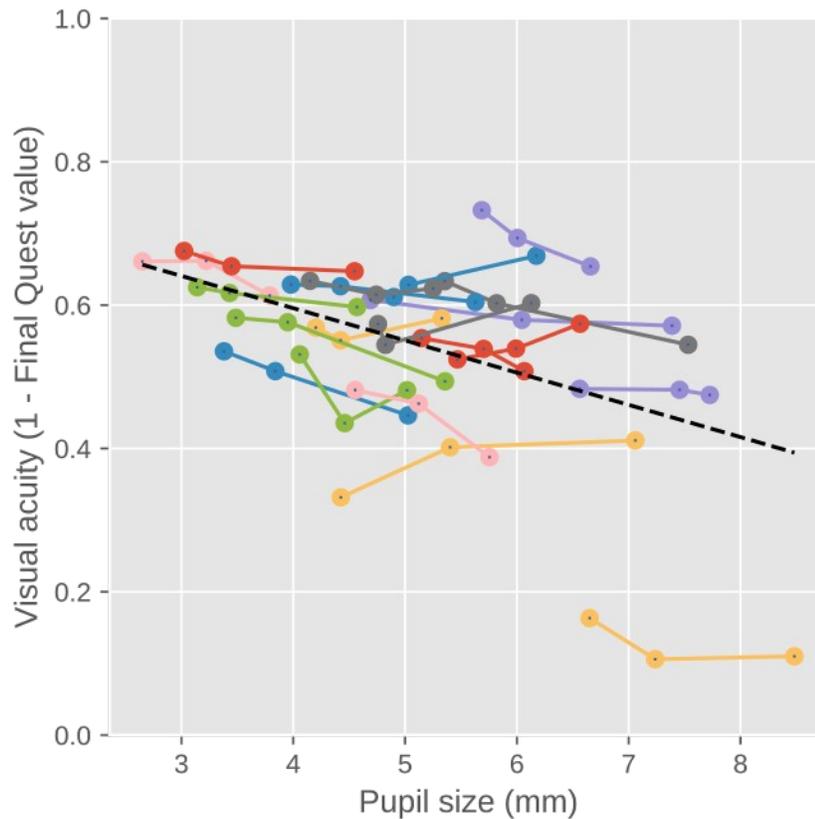
253 **Task and Design** Each trial started with the presentation of a black central fixation dot ($R=0.11^\circ$ [90 px]) for
254 500 ms on the target display. Next, a lowercase or uppercase letter ('a', 'b', 'd', 'e', 'g', 'h', 'l', 'm', 'n', 'q',
255 'r', or 't') was presented for 2.5 s. Letters were presented centrally in black monospace font. The size of the
256 letters was varied with a Quest adaptive procedure to converge on 75% accuracy. Participants pressed the 'z'
257 key to indicate that the letter was lowercase, and the '/' key to indicate that the letter was uppercase.

258 The experiment started with a practice block of 75 trials during which the background of all tablets was gray
259 (72.15 cd/m^2 for target display; $69.01, 64.70 \text{ cd/m}^2$ for peripheral displays). This practice block also served to
260 determine an appropriate font size to start with during the experimental blocks. Next, participants performed
261 six experimental blocks during which the brightness of the light-source tablets was varied (343.30 cd/m^2 and
262 345.20 cd/m^2 for the two peripheral displays], medium [$69.01 \text{ cd/m}^2, 64.70 \text{ cd/m}^2$], or dark [$0.83 \text{ cd/m}^2, 0.88$
263 cd/m^2]) while the background of the target display remained gray. Each experimental block started with the
264 font size that the practice block had ended with. The order of the experimental blocks followed a
265 counterbalanced ABCABC design. In total, participants performed 375 trials in approximately 40 minutes.

266 Results

267 Task performance

268 For each participant and Brightness Level separately, we took the final font size of each block as a measure of
269 performance (because the Quest procedure varied font size depending on the participant's performance).



270 **Figure 6.** Discrimination performance increased with increasing peripheral brightness (and decreasing pupil
271 size). Lines correspond to individual participants. Dots correspond to different levels of peripheral brightness,
272 such that the highest peripheral brightness corresponds to the smallest pupil size. In addition, participants
273 with smaller overall pupils had higher discrimination performance.

274 To test whether peripheral brightness (and pupil size) affects performance, we conducted a linear mixed effects
275 model (LME) with Final Quest Value (on which font size was based) as dependent measure and Brightness as
276 fixed effect. We included by-participant random intercepts and slopes. There was an effect of Brightness ($t = -$
277 2.356, $p = .029$), indicating that discrimination performance increased with increasing peripheral brightness
278 (Figure 6).

279 To test whether individual differences in pupil size also affect performance, we determined, for each
280 participant separately, the mean pupil size during the entire experiment, and the mean Quest value during the

281 last half of all blocks. There was a clear correlation between the two measures ($r = -.508, p = .022$), indicating
282 that participants with smaller overall pupils had higher performance.

283 **Pupil size**

284 To test whether our brightness manipulation affects pupil size, we conducted an LME with Pupil Size as
285 dependent measure and Brightness as fixed effect. We included by-participant random intercepts and slopes.
286 There was an effect of Brightness ($t = -12.662, p < .001$), indicating that pupil size decreased with increasing
287 brightness of the flanking tablets. Pupil size was converted from arbitrary units to millimeters of diameter with
288 the same procedure as used for Experiments 1 and 2.

289 **Discussion**

290 As predicted, we found that small pupils (and increased peripheral brightness) improved discrimination
291 performance. In, addition we found that participants with small pupils had higher discrimination performance.
292 That is, there was a clear link between pupil size and discrimination performance, both when pupil size was
293 manipulated experimentally, and when considering individual differences.

294 **General Discussion**

295 Here we report that pupil size, when manipulated through peripheral brightness, has qualitatively different
296 effects on discrimination of fine stimuli in central vision and detection of faint stimuli in peripheral vision.

297 Specifically, we found that small pupils (and thus a bright periphery) lead to improved discrimination of small
298 letters presented in central vision. This is consistent with previous studies that showed a so-called positive-
299 polarity advantage; that is, it is easier to read dark letters on a bright background (positive polarity) than it is to
300 read bright letters on dark background (negative polarity) (Buchner et al., 2009; Dobres et al., 2017;
301 Piepenbrock et al., 2014b, 2014a; Taptagaporn & Saito, 1990). We observed this effect only (but highly
302 reliably) with very small letters that were at the limits of visual acuity. This is consistent with a previous study
303 showing that the positive-polarity advantage is most pronounced for small letters (Piepenbrock et al., 2014a).
304 The small-pupil benefit for discrimination is likely due to the fact that visual acuity is highest with small
305 pupils, which suffer less from optical distortions that reduce visual acuity (Campbell & Gregory, 1960; Liang
306 & Williams, 1997; M. Lombardo & Lombardo, 2010; Woodhouse, 1975; Bombeke et al., 2016).

307 We further found that large pupils (and thus a dark periphery) improved detection of faint stimuli that were
308 presented at an unpredictable location in peripheral vision. This large-pupil benefit for detection is likely due
309 to two factors. First, large pupils increase light influx, which increases the signal-to-noise ratio of vision,
310 which in turn facilitates detection of very faint stimuli (but perhaps not, or hardly, of stimuli that are presented
311 well above the detection threshold, as used for example by Thigpen et al., [2018]). Second, the dark periphery
312 that we used to induce large pupils resulted in reduced light scatter (M. Lombardo & Lombardo, 2010), in turn
313 resulting in increased image contrast, thus making it easier to detect stimuli. Therefore, reduced light scatter
314 likely also contributed to the large-pupil benefit (which is therefore in part likely a dark-periphery benefit).

315 Our results offer a possible explanation for why the pupils dilate in response to increased arousal (e.g. Mathôt,
316 2018; Mathôt & Van der Stigchel, 2015). Situations that require fine discrimination are often characterized by
317 low levels of arousal, and situations that require detection are often characterized by high levels of arousal. For
318 example, arousal is low when a person is reading a book, or when an animal is foraging for food. In such cases,
319 it is crucially important to identify what you're looking at. In contrast, arousal is high when a person is afraid,
320 or when an animal is on the lookout for predators. In such cases, it is crucially important to detect unexpected
321 dangers. In other words, pupil dilation in response to arousal may reflect an increased emphasis on visual
322 sensitivity, at the expense of visual acuity, to meet the demands of the situation.

323 An incidental yet striking result is that pupil size was larger during the detection task than during the
324 discrimination task. Because there was no systematic difference in difficulty between the two tasks, this pupil-
325 size difference is likely not due to differences in mental effort (which is known to affect pupil size, see e.g.
326 Mathôt, 2018). One possibility is that, in the detection task, the pupil dilated as a result of attention being
327 directed to peripheral rather than central vision (cf. Brocher, Harbecke, Graf, Memmert, & Hüttermann, 2018;
328 Daniels, Nichols, Seifert, & Hock, 2012). An even more interesting possibility is that the pupil automatically
329 assumes a size that is optimal for the current task, and that arousal-related pupil responses are merely one
330 example of this general principle.

331 Our results also have implications for the ergonomics of display design. First, as was already well-established,
332 visual information that requires fine discrimination, such as text, is best displayed on a bright background
333 (positive polarity), which induces small pupils (Buchner et al., 2009; Dobres et al., 2017; Piepenbrock et al.,
334 2014b, 2014a; Taptagaporn & Saito, 1990). Second, and this is a novel insight that results from our findings,
335 visual information that should capture attention, such as notifications, may be best displayed on a dark
336 background (negative polarity), which induces large pupils. Importantly, pupil size is determined by the overall
337 level of display brightness, although with a bias towards central vision (e.g. Crawford, 1936). Therefore, there

338 is no point in presenting notifications in a dark region of a display that is otherwise bright. This poses a
339 dilemma when designing displays that contain text as well as notifications. In such cases, the relative
340 importance of the different kinds of information should determine whether the display should use a positive or
341 a negative polarity.

342 In summary, we have shown that small pupils, induced through a bright periphery, lead to improved
343 discrimination of fine stimuli in central vision. In contrast, large pupils, induced through a dark periphery, lead
344 to improved detection of faint stimuli in peripheral vision.

345 **Materials and availability**

346 Data and experimental materials can found at <https://osf.io/h389s/>

347

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