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Vergence responses to vertical binocular disparity during lexical identification

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Abstract

Humans typically make use of both eyes during reading, which necessitates precise binocular coordination in order to achieve a unified perceptual representation of written text. A number of studies have explored the magnitude and effects of naturally occurring and induced horizontal fixation disparity during reading and non-reading tasks. However, the literature concerning the processing of disparities in different dimensions, particularly in the context of reading, is considerably limited. We therefore investigated vertical vergence in response to stereoscopically presented linguistic stimuli with varying levels of vertical offset. A lexical decision task was used to explore the ability of participants to fuse binocular image disparity in the vertical direction during word identification. Additionally, a lexical frequency manipulation explored the potential interplay between visual fusion processes and linguistic processes. Results indicated that no significant motor fusional responses were made in the vertical dimension (all $ps > .11$), though that did not hinder successful lexical identification. In contrast, horizontal vergence movements were consistently observed on all fixations in the absence of a horizontal disparity manipulation. These findings add to the growing understanding of binocularity and its role in written language processing, and fit neatly with previous literature regarding binocular coordination in non-reading tasks.

Keywords: *vertical vergence, fixation disparity, binocular fusion, reading*

23 1. Introduction

24
25 Humans sample their visual environment by continuously orienting their eyes towards objects of
26 interest in a sequence of saccades and fixations. Saccades are rapid ballistic movements of the eyes in
27 the same direction that serve to redirect the visual axes to a new location. They are interspersed with
28 brief periods of relative stillness, known as fixations, during which visual information is encoded (see
29 Rayner, 1998 for review). Even though we sample visual information with two frontally placed and
30 horizontally separated eyes, we perceive a single unified representation of the visual environment. This
31 single percept is achieved via the sophisticated mechanisms of binocular fusion, which have been made
32 functionally possible by the development of a vergence system that allows us to coherently merge the
33 visual input received by each eye (Howard & Rogers, 1995; Schor & Ciuffreda, 1983).

34
35 Binocular coordination is required for efficiently performing a variety of tasks, including reading,
36 which does not call for stereopsis, or large eye movements in depth (van Leeuwen et al., 1999). Since
37 humans typically make use of both eyes during reading, it is important to understand how binocular
38 coordination might impact on contributing processes involved in written language comprehension. It is
39 relatively recent that research has begun to focus on the detailed investigation of binocular coordination
40 during reading. A number of studies have revealed that during text processing, the two visual axes are
41 often slightly misaligned, resulting in small vergence errors (i.e. fixation disparities) of more than 1
42 character space in a significant proportion of fixations (Blythe, Liversedge, & Findlay, 2010; Blythe et
43 al., 2006; Juhasz et al., 2006; Liversedge et al., 2006a; Liversedge et al., 2006b; Nuthmann & Kliegl,
44 2009; Vernet & Kapula, 2009).

45
46 It has been established that because the stimulus in reading necessitates predominantly horizontal
47 yoked eye movements, some transient divergence occurs during saccades, followed by horizontal
48 misalignment on fixation onset (Collewijn et al. 1988; Hendriks, 1996; Yang & Kapoula 2003;
49 Zee, Fitzgibbon, & Optican, 1993). Fine-grained oculomotor adjustments are then made during
50 fixations in order to maximize the degree of correspondence between the two disparate retinal
51 input (Jainta et al., 2010; Jainta & Jaschinski, 2012; Leigh & Zee, 2006). Generally, in every task
52 – including reading - high-precision binocular vision is attained via the process of fusion, which
53 incorporates two integral components: motor and sensory fusion (Partt-Johnson & Tillson, 2001;
54 Schor & Tyler, 1981). Sensory fusion is a neurophysiological and psychological process whereby
55 two independent representations are combined in the visual cortex into a single unified percept as
56 a basic step for further processing (Howard & Rogers, 1995; Worth, 1921). Sensory fusion is only
57 possible within a limited range of retinal disparities known as Panum's fusional area (Schor,
58 Heckmann, & Tyler, 1989; Steinman, Steinman, & Garzia, 2000). Larger disparities typically
59 trigger a motor fusional response, or cause diplopia. Motor fusion comprises of the
60 aforementioned physiological mechanisms of vergence. That is, in subjects with normal binocular
61 vision, slow disconjugate eye movements mainly triggered by retinal disparity are made in order to

62 adjust the angle between the two visual axes (Schor, 1979).

63

64 To summarise, during reading, the visual system is primarily faced with horizontal disparities, which
65 might be the reason why research in written language processing has focused mainly on horizontal
66 binocular coordination (Blythe et al., 2010, Liversedge et al., 2009, see Kirkby et al., 2008 for review).
67 Indeed, few studies so far have systematically investigated misalignments in reading in other
68 dimensions, a limitation to the comprehensive understanding of binocular coordination that the current
69 work aimed to address.

70

71 When conceptualizing the visual system's response to binocular misalignment, it is important to note
72 that binocular motor fusion is characterised by horizontal vergence (along a plane containing the
73 interocular axis), vertical vergence (along a plane orthogonal to the interocular axis) and cyclovergence
74 (in opposite directions along the two visual axes, Boman & Kertesz, 1981; Howard & Rogers, 2012).

75 While a significant body of work has investigated vergence movements driven by horizontal
76 misalignments, the literature concerning responses to vertical and torsional disparities is considerably
77 limited, particularly in the context of lexical processing. Although Nuthmann and Kliegl (2009)
78 recently reported the presence of vertical misalignments in each reading fixation, their findings
79 regarding vertical disparity were purely descriptive and no claims were made about any potential
80 vertical vergence adjustments during fixations. In addition, Jainta, Blythe, Nikolova, Jones and
81 Liversedge (2014) recently conducted a detailed investigation of disparities occurring during natural
82 sentence reading. They reported that vertical disparities were of much smaller magnitude than
83 horizontal disparities, and suggested that the limited activation of the vertical vergence system during
84 reading could be due to functional differences between horizontal and vertical disparities and disparity
85 reducing mechanisms in relation to maintaining a single unified perception of the written text. Aside
86 from the two abovementioned accounts, no studies so far have systematically investigated the motor
87 fusional response to stereoscopically imposed vertical disparities during lexical processing.

88 Nevertheless, existing studies in non-reading tasks indicate that while serving complementary
89 functions, horizontal and vertical vergence are considered as two different mechanisms (Howard &
90 Rogers, 2012; Stevenson, Lott, & Yang, 1997). Research investigating the characteristics of vertical
91 vergence revealed that when compared to its horizontal counterpart, it is limited in both amplitude and
92 speed (Bharadvaj et al., 2007; Kertesz, 1981). Furthermore, Panum's fusion area has been shown to be
93 elliptical in shape, that is, sensory fusion is possible over a larger range of horizontal disparities than
94 vertical disparities (Fender & Julesz, 1967; Howard & Rogers, 1995; Jainta et al., 2014; Schor & Tyler,
95 1981). Interestingly, a recent study by Dysli, Vogel and Abegg (2014) investigated the assumption that
96 latent heterophoria may be causally involved in reading problems. The authors changed the vergence
97 tone of participants without reading difficulties using prisms that induced exophoria, esophoria and
98 vertical phoria. It was found that none of the prism conditions affected reading speed, average fixation
99 duration or saccadic amplitudes during paragraph reading. However, it is as yet unclear whether
100 induced vertical disparity in written linguistic stimuli would affect the efficiency of lexical processing,
101 or indeed what vergence adjustments would be made to compensate for any vertical misalignments.

102

103 One study to experimentally increased disparity within written linguistic stimuli during lexical
104 processing was conducted by Blythe et al. (2010). Using dichoptic presentations of single words with
105 varying levels of horizontal offset, they estimated that the size of Panum's fusional area for linguistic
106 stimuli was equal to approximately one character space for both children and adults. However, they did
107 not include a frequency manipulation in their stimuli, focusing instead on the differences between the
108 two participant groups. Another study to use dichoptic visual presentations during reading was
109 conducted by Liversedge et al. (2006a) and explored binocular saccadic targeting. The authors found
110 that conjugate eye movements in reading appear to be programmed on the basis of a combined signal
111 sent to both eyes and that saccades in reading were targeted on the basis of a fused percept attained at
112 an early processing stage. Both studies raise interesting questions regarding the response of the
113 vergence and saccadic targeting system to stereoscopically presented vertical disparities during lexical
114 processing.

115

116 We therefore set out to conduct a detailed investigation of vertical motor fusion in response to
117 symmetric vertical offset during a lexical decision task. There were several aims to the study. Firstly,
118 we were interested in the vertical vergence response to binocular image misalignment and its effect on
119 lexical identification processes. Secondly, we investigated the sensitivity of saccade targeting
120 mechanisms to vertical disparity in the parafovea. Finally, as a more specific exploration, we aimed to
121 investigate the influence of the vertical stereoscopic disparity manipulation on a well-established
122 finding in reading research: the frequency effect, or the increased efficiency of lexical processing for
123 commonly occurring words (Inhoff & Rayner, 1986; Rayner, 1998; White, 2008). The theoretical
124 motivation for this investigation is discussed in the context of the Interactive Activation (IA) model of
125 word recognition (McClelland & Rumelhart, 1981). It is possible that the fusion of binocular inputs,
126 both motor and sensory, is achieved at an earlier and separate stage of processing than lexical
127 identification, prior to the feature extraction stage of the IA model. If that were the case, adding a level
128 of complexity at the fusion stage of processing in the form of a disparity manipulation would cause an
129 equal global increase in total reaction times (RTs) for both high-frequency (HF) and low-frequency
130 (LF) words. However, it is also possible that visual fusion interferes with the feature extraction stage of
131 processing, as fusion is central for attaining high quality binocular visual information. Therefore,
132 making feature extraction more difficult by imposing vertical disparity in the stimuli would initially
133 slow down the processing of both HF and LF words, but at the following (letter and word) stages of
134 lexical identification, HF words would be processed faster. In other words, there might be an
135 interaction between the two factors, such that the cost of adding complexity at the visual fusion stage
136 would be larger for LF than for HF words. An alternative possibility would be that when presented
137 with induced disparities within the range of those observed in normal reading, the vertical vergence
138 system would remain inactive, which would indicate that vergence responses to this type of disparity
139 are quite different to those associated with horizontal disparities. This in turn would be consistent with
140 the claims of Jainta et al. (2014), who argue that vertical disparities provide much less useful

141 information for stereopsis than do horizontal disparities given the horizontal alignment of the two eyes
142 in the human visual system.

143

144 Based on previous findings, we made several predictions. We expected that, similar to Blythe et al.
145 (2010), there would be a time cost associated with attaining a stable unified percept of the disparate
146 dichoptic stimuli, which would be reflected in RTs on the lexical decision task. Furthermore, if
147 participants found it impossible to fuse the imposed vertical disparities due to the vertical vergence
148 limitations of the visual system, they might be unable to perform the lexical decision task, as it would
149 be extremely difficult to distinguish the words from the non-words (Fig. 1; see also Blythe et al., 2010).
150 Although we only attempted to actively drive vertical vergence, we expected that a small amount of
151 horizontal vergence would likely be observed following a horizontal saccade. More critically, if the
152 vertical disparity presentation triggered a vertical vergence response we would likely observe
153 additional changes in horizontal fusional responses that typically occur in reading. In terms of saccadic
154 programming, we expected that if saccades to dichoptically presented parafoveal targets were
155 programmed on the basis of the individual input received by each eye, then that would be reflected in
156 the direction and magnitude of the resulting fixation disparity. Finally, in terms of lexical processing,
157 any potential interaction between the vertical disparity presentation and the lexical frequency
158 manipulation would be informative as to the degree of interdependence between visual processes
159 related to fusion and linguistic processes related to lexical identification. Such an interaction was
160 observed in a recent study by Jainta, Blythe and Liversedge (2014), who found that the efficiency of
161 lexical processing was diminished in monocular reading conditions. On the other hand, previous
162 findings (Blythe et al., 2006; Juhasz et al., 2006) reported no influence of lexical frequency and
163 orthographic manipulations on horizontal binocular disparity. Therefore, we explored whether vertical
164 binocular disparity would interact with lexical processing, or if it would have an additive effect on total
165 processing times for both high-frequency (HF) and low-frequency (LF) words.

166

167 **2. Method**

168

169 *2.1. Participants*

170

171 Participants were 8 native English speakers from the University of Southampton, who took part in the
172 experiment in exchange for Psychology course credits, or payment at the rate of £6 per hour. All
173 participants had normal or corrected to normal vision (with soft contact lenses) and no diagnosed
174 reading difficulties. Testing their visual acuity with a Landolt C acuity chart confirmed that there were
175 no considerable differences in acuity between the two eyes (best-corrected acuity in each eye in
176 decimal units was 1.00 or higher). Additionally, a Titmus Stereotest indicated that all participants had
177 functional stereopsis (minimal stereoacuity of 40 seconds of arc).

178

179 *2.2. Apparatus*

180

181 Binocular eye movements were measured using two Fourward Technologies Dual Purkinje Image
182 (DPI) eye trackers, which recorded the position of both eyes every millisecond (sampling rate of 1000
183 Hz, spatial resolution < 1 min arc). Stereoscopic presentation of the target items was achieved through

184 use of Cambridge Research Systems FE1 shutter goggles, which blocked the visual input received by
185 each eye alternatively every 8.33 ms (corresponding to a 120 Hz refresh rate). The shutter goggles were
186 synchronized with the eye trackers and interfaced with a Pentium 4 computer and a Philips 21B582BH
187 21" monitor. The experimental equipment made it possible to simultaneously track binocular eye
188 movements whilst manipulating the unique visual input received by each eye. The monitor was situated
189 at a viewing distance of 100 cm. To minimize head movements, participants leaned against two
190 cushioned forehead rests and bit on an individually prepared bite bar.

191

192 2.3. Materials and Design

193

194 All participants viewed 208 trials, each consisting of a single 6-letter item. The item was either one of
195 52 high-frequency (HF) words (e.g., *summer*), one of 52 low-frequency (LF) words (e.g., *acumen*) or
196 one of 104 non-words (e.g., *worzer*). Non-words were formed in a similar fashion to Blythe et al.
197 (2010) by substituting a single letter in the center of a word and creating an obvious misspelling (e.g.,
198 *summer* to *sumxer*). The 52 HF items had an average frequency of 118.48 counts per million (ranging
199 from 18 to 850) and the 52 LF items had an average frequency of 2.58 counts per million (ranging from
200 0 to 9), as indexed in the English language CELEX lexical database (Baayen, Piepenbrock, & Gulikers,
201 1995). A *t*-test confirmed that HF words were significantly more frequent than LF words, $t(51) = 5.31$,
202 $p < .001$.

203 All items were presented in red 20pt Courier New font on a black background. At the viewing distance
204 of 100 cm, each letter height extended to 0.32 deg of visual angle. Each of the items was viewed by
205 participants in one of four dichoptic presentation conditions: (1) aligned, where the two images were
206 centered on the display monitor; (2) offset vertically by a total of 0.05 deg, (3) offset vertically by a
207 total of 0.11 deg; (4) offset vertically by a total of 0.16 deg. The disparity presentation was
208 symmetrical, i.e., the monocular images were offset by an equal amount in opposite directions in each
209 eye. Conditions were counterbalanced such that every word appeared in each of the experimental
210 conditions across participants. Additionally, whether the image presented to the left eye appeared
211 above or below the image presented to the right eye was randomized and counterbalanced across
212 conditions.

213

214 ----- Insert Figure 1 about here -----

215

216 2.4. Procedure

217

218 The experimental procedure was approved by the University of Southampton Ethics and Research
219 Governance Office and followed the conventions of the Declaration of Helsinki. Informed written
220 consent was obtained from each participant after explanation of the procedure of the experiment.

221

222 Each trial consisted of a fixation point appearing on the left-hand side of the screen for 1 second,
223 followed by the item (word or non-word) presented in the centre of the screen. The distance between
224 the fixation point and the left edge of each stimulus/item was 2.54 deg visual angle.

225

226 Participants were instructed to look at the fixation point before looking at the word presented on the
227 screen. They were asked press a button to indicate as quickly and accurately as possible whether the
228 stimulus was a word or a non-word. They were not told that some of the stimuli would be presented
229 with varying degrees of disparity. There were four practice trials to help participants become familiar
230 and comfortable with the task.

231

232 Calibration was monocular (i.e., the left eye was occluded by the shutter goggle during calibration of
233 the right eye, and vice versa). For calibration, participants were instructed to look at each of nine points
234 in a 3x3 grid in a set sequence from the top left to the bottom right. Horizontal separation of the
235 calibration points was 3.44 deg and the vertical separation was 1.26 deg relative to screen centre.

236 Afterwards, the calibration was checked for accuracy and repeated if necessary. Once both eyes had
237 been calibrated successfully, the experiment began. Calibration was checked for accuracy following
238 every four trials and, if the drift in eye position was more than 0.06 degrees, the eye trackers were
239 recalibrated.

240

241 2.5. Analyses

242

243 Custom-designed software was used for the data analyses. Saccades and fixations were manually
244 identified in order to avoid contamination by dynamic overshoots (Deubel & Bridgeman, 1995) or
245 artefacts due to blinks. From the separate signals of the two eyes, we calculated the horizontal and
246 vertical conjugate eye component $[(\text{left eye} + \text{right eye})/2]$; i.e., the version signal] and the horizontal
247 and vertical disconjugate eye component $[\text{left eye} - \text{right eye}]$; i.e., the vergence signal]. Several
248 parameters of binocular coordination were calculated for each fixation period: (1) vertical fixation
249 disparity at the start and end of fixations, where a value of 0 represents alignment of the two eyes at eye
250 height; positive values represent left-hyper fixations and negative values represent right-hyper
251 fixations; (2) horizontal fixation disparity at the start and end of fixation; a value of 0 represents
252 alignment of the two eyes at the depth of the screen, positive values represent crossed fixations, where
253 the point of fixation is in front of the screen, and negative values represent uncrossed fixations, where
254 the point of fixation is behind the screen; (3) net vertical and horizontal drift in vergence (Jainta et al.,
255 2010; Liversedge, White, et al., 2006; Nuthmann & Kliegl, 2009; Vernet & Kapoula, 2009), which is
256 the change in fixation disparity between the beginning and the end of the fixation period and (4) total
257 change in vertical and horizontal eye position between the beginning of the first fixation and the end of
258 the final fixation on each item. In addition, we calculated total reaction time (RT) and total number of
259 fixations for each item.

260

261 For data analyses, we used linear mixed-effects models (lmer from package lme4 (Pinheiro & Bates,
 262 2000) in R (R Development Core Team, 2009). P-values were estimated using posterior distributions
 263 for the model parameters obtained by Markov Chain Monte Carlo sampling, which include a typical
 264 sample size of 10000 (Baayen, Davidson, & Bates, 2008). The model was applied to the non-
 265 aggregated data and participants and items were treated as random effects, while lexical frequency (HF
 266 vs. LF) and binocular image disparity (0 deg, 0.05 deg, 0.11 deg or 0.16 deg) were treated as fixed
 267 effects.

268

269 **3. Results**

270

271 In the following sections, we report a variety of analyses based on different eye movement measures.
 272 Approximately 1.5% of the data were excluded due to tracker loss, resulting in a total of 5657 fixations
 273 on which the following analyses are based. We begin by giving a short descriptive account of the
 274 overall findings from the lexical decision task (3.1), then focus on the initial reaction of the vergence
 275 system to our disparity manipulation (3.2), changes in disparity throughout the duration of an entire
 276 multiple fixation trial (3.3.) and cases where only one fixation was made per trial (3.4.). Before
 277 reporting further results regarding eye movement measures, it is important to clarify certain terms that
 278 will be used throughout the following sections. Binocular image disparity refers to the induced offset
 279 between the dichoptic images presented on the screen. Binocular fixation disparity refers to the
 280 differences in position between the left and the right eye in degrees of visual angle, as measured by the
 281 eye trackers.

282

283 *3.1. Lexical decision accuracy, reaction times (RTs) and number of fixations*

284

285 The overall response accuracy in this experiment was 96%. Correct responses during lexical
 286 identification were taken as the behavioural indication that participants were able to successfully fuse
 287 the binocularly misaligned images. Table 1 contains information about participants' accuracy at the
 288 lexical decision task, mean RTs, fixation durations and number of fixations in all of the frequency and
 289 disparity conditions. Evidently, participants responded faster, made fewer fixations and were more
 290 accurate when identifying HF words than LF words and non-words.

291

292 ----- Insert Table 1 about here -----

293

294 To further explore the frequency effect, an LME analysis was applied to the log-transformed RT values
 295 with participants and items as random effects and frequency and binocular image disparity as fixed
 296 effects. The results revealed a significant effect of frequency: participants were faster at identifying HF
 297 words than LF words ($t = 4.24, p < .001$) and non-words ($t = 5.13, p < .001$), with no significant
 298 difference between the latter two ($t < 1$). The size of the frequency effect was approximately 145 ms
 299 on average. There was no effect of binocular image disparity ($t = 1.13, p = .24$) and the interaction
 300 between the two fixed effects was not close to significant ($t < 1$). These results are also summarised in
 301 Figure 2. Clearly, participants were able to perform the lexical decision task without any interference

302 from the vertical disparity manipulation. The following sections explore this by focusing on vergence
303 responses during fixations.

304

305 ----- Insert Figure 2 about here -----

306

307

308 3.2. Initial reaction to vertical disparity

309

310 With regard to binocular landing positions, *Figure 3* represents the distribution of disparities at the start
311 of the first fixation on each item, plotted onto a Cartesian coordinate system. Positive values on the x-
312 axis denote crossed disparities, and positive values on the y-axis represent left hyper-vertical disparities
313 (where the left eye is fixating above the right eye). Negative values on the x-axis correspond to
314 uncrossed disparities, and negative values on the x-axis represent right hyper-vertical disparities (where
315 the right eye is fixating above the left eye). The data clearly indicate that horizontal disparities were
316 predominantly uncrossed, while vertical disparities were predominantly left-hyper.

317

318 ----- Insert Figure 3 about here -----

319 Furthermore, we were interested in the sensitivity of the saccade programming system to vertical
320 disparity in the parafovea. More specifically, we explored the relationship between the nature of the
321 dichoptic presentation (left-hyper or right-hyper) and the resulting disparity at the start of each trial.
322 Close correspondence between the two categorical variables would indicate that during the initial
323 saccade onto the stimulus, each of the eyes targeted the monocular image presented to it separately via
324 the shutter goggles. Recall that 75% of our stimuli were presented with some degree of vertical
325 misalignment. Regardless of presentation condition, 38% of vertical disparities at the start of the initial
326 fixation were right-hyper and 62% were left-hyper. A Chi-square test revealed that right-hyper and
327 left-hyper disparities did not closely correspond to presentation conditions. In fact, left-hyper
328 disparities were the predominant case, regardless of the binocular image manipulation ($\chi^2(1) = 15.10$,
329 $p < .001$).

330

331 The following part of the analyses focuses on how the vergence system responded when presented with
332 a disparate image upon initial fixation on the target on trials with multiple fixations. We only included
333 fixation disparities and fixation durations within 2SD of each participant's mean, which resulted in
334 exclusion of approximately 3% of the data. 1375 fixations in total were analysed. *Figure 4* illustrates
335 the distribution of horizontal and vertical disparities at the start (a) and at the end (b) of the initial
336 fixation. The distribution of vertical disparities in both cases is clearly more leptokurtic, indicating that
337 vertical disparities are generally smaller in magnitude than horizontal disparities. Fixation disparity at
338 the start was not significantly affected by either lexical frequency, disparity manipulation or the
339 interaction between the two ($t_s < 1$, n.s.). Disparities at the end of fixations were also not influenced by
340 either manipulation (all $p_s > .13$). The average vertical disparity was 0.12 deg ($SD = 0.09$) at the start
341 of the initial fixation and 0.11 deg ($SD = 0.10$) at the end of the fixation. A *t*-test revealed no difference

342 in the drift in vertical fixation disparity throughout the fixation ($t < 1$). These results indicate that no
343 considerable vertical vergence movements were made during the initial fixation on the target.

344

345 ----- Insert Figure 4 about here -----

346

347 Interestingly, however, we observed a small but significant change in horizontal disparity during the
348 initial fixation. Horizontal disparities at the start of the fixation had an average magnitude of 0.18 deg
349 ($SD = 0.15$), which was reduced to 0.16 deg ($SD = 0.14$) by the end of the fixation, $t = 2.98$, $p < .01$. A
350 tendency for disparity-reducing vergence movements seemed to emerge as early as the first fixation on
351 an item, even in the absence of any horizontal stereoscopic manipulation. This was not affected by
352 either the frequency or the binocular image manipulation ($ts < 1$). Furthermore, there was no significant
353 correlation between the magnitude of horizontal and vertical fixation disparities at the start or at the
354 end of the initial fixation ($ps > .19$, n.s.). In other words, we observed a rapid horizontal vergence
355 response during the first fixation on each item, following the horizontal saccade onto the stimulus, but
356 no vertical vergence response to our disparity manipulation. The following sections further explore this
357 pattern across all fixations made during a trial.

358

359 *3.3. Reaction to vertical disparity throughout an entire trial*

360

361 The previous sections demonstrate that the vertical and horizontal vergence system seem to make very
362 different initial responses to parafoveal stereoscopic targets. Recall, however, that participants typically
363 made more than one fixation on each item, hinting at the possibility that vergence movements occurred
364 after the initial fixation. Therefore, a comparison was made between the start of the first fixation and
365 the end of the final fixation on each multiple fixation item in order to capture any change in vergence
366 throughout the duration of each trial. There was no significant difference in vertical fixation disparity
367 between the two measures ($t < 1$, $p > .16$). In addition, an LME analysis investigated the magnitude of
368 change in vertical fixation disparity between the start of the initial fixation and the end of the final
369 fixation. There was no significant effect of lexical frequency, binocular image disparity, or the
370 interaction between the two fixed factors ($ts < 1$). The average magnitude of vertical fixation disparity
371 at the end of the final fixation on each item was 0.16 deg ($SD = .13$). Considering that the last fixation
372 of each trial was the one during which participants pressed the button to indicate their lexical decision,
373 this mean magnitude could be taken as an approximation of the amount of vertical fixation disparity
374 which the visual system could easily tolerate in order to successfully process lexical information. Note,
375 however, that no disturbances in fusion were reported by any of the participants, suggesting that the
376 vertical limits of Panum's fusional area are likely larger than the reported value.

377

378 As for horizontal disparity, a consistent vergence response was observed throughout the duration of
379 each trial: participants displayed a tendency for disparity-reducing vergence movements and a
380 transition from uncrossed to aligned binocular disparities. This effect was significant ($t = 4.12$, $p <$
381 $.001$), despite the absence of a stimulus that was intended to actively drive horizontal vergence.

382 Horizontal disparities at the end of the final fixation on each trial were on average 0.02 deg smaller
383 than they were at the start. In addition, an LME analysis confirmed that horizontal vergence measures
384 at the end of each trial were not affected by the vertical disparity manipulation ($t < 1$), nor were they
385 correlated with the magnitude of vertical fixation disparity, $r(1373) = .03, p = .29$.

386

387 3.4. Single fixation trials

388

389 As a final step in our investigation, we explored cases in which only one fixation was made per trial. It
390 was important to include single fixation trials in the analyses, as they would undoubtedly provide
391 insight into any potential interactions between low-level visual processes involved in disparity
392 processing and high-level lexical identification processing. In addition, cases in which vertical disparity
393 was dealt with in a single fixation would enable us to closely monitor any potential vergence responses
394 to our vertical manipulation. Note, however, that single fixations were made on only 17% of trials.
395 Data were included in the analyses if fixation duration, horizontal and vertical disparities at the start
396 and the end of fixations fell within 2 *SD* of each participant's mean. This resulted in 5% data loss – 240
397 fixations in total were analysed.

398

399 Reaction time data are presented in Table 1. A significant lexical frequency effect of 119ms was
400 observed in single fixation trials, $t = 3.38, p < .001$. There was no significant effect of binocular image
401 disparity or the interaction between the two fixed effects ($ts < 1$). Therefore, it appears that single
402 fixation trials did not differ significantly from multiple fixation trials in terms of participants' responses
403 during the lexical decision task. Again, it is evident from these results that although a robust frequency
404 effect was observed in the data, it was not affected by the visual disparity manipulation.

405

406 As for disparity measures, the mean magnitude of vertical disparity was 0.12 deg ($SD = 0.10$) at the
407 start and 0.11 deg ($SD = 0.09$) at the end of single fixation trials. No significant vertical vergence
408 movements were observed throughout the fixation ($t < 1$). In addition, LME analyses revealed that
409 vertical disparities at the start and the end of the fixations were not affected by the frequency
410 manipulation ($t_{\text{start}} = 1.55, p = .12; t_{\text{end}} < 1$), the disparity manipulation ($t_{\text{start}} = 1.63, t_{\text{end}} = 1.54, ps = .11$)
411 or the interaction between the two fixed effects ($ts < 1$). However, once again we observed a consistent
412 disparity-reducing vergence response in the horizontal dimension. A tendency emerged for horizontal
413 disparities to move from uncrossed to aligned throughout a fixation. The mean magnitude of disparity
414 was 0.15 deg ($SD = 0.13$) at the start and 0.12 ($SD = 0.10$) at the end of the trial. Disparity was reduced
415 by an average of 0.03 deg throughout the duration of the fixation, $t = 3.97, p < .001$. There was no
416 significant correlation between the magnitude of horizontal and vertical disparity at the end of fixations
417 ($r(238) = .09, p = .19$), and an LME analysis revealed no effect of the vertical disparity manipulation
418 on horizontal disparity measures ($t = 1.31, p = .19$).

419

420 4. Discussion

421

422 Binocular coordination is critical to successfully attaining a fused stable representation of the visual
423 environment, which is essential for performing a variety of tasks, including reading. Recent findings
424 have begun to explore the role of binocularity in reading, the way it affects language processing and the
425 relative importance of various binocular visual processes for written language comprehension (see
426 Kirkby et al., 2008 for review). The present study adds to that growing literature by making an
427 exploration of the role of vertical binocular disparities in lexical processing. We focused on
428 investigating the motor fusional response to induced vertical misalignments in the parafovea and, upon
429 fixation, its potential influence on horizontal vergence movements that typically occur following
430 saccades in reading, and its effect on lexical identification.

431

432 Our findings revealed that when participants made a horizontal saccade onto a centrally presented
433 stimulus with induced vertical disparity, no change was observed in the vertical vergence system. That
434 is, participants did not make significant disparity reducing vertical vergence movements during the
435 initial saccade, nor when first fixating on the target or even throughout the duration of a trial.

436 Importantly, there was a clear dissociation between the presentation on the monitor and the perceptual
437 experience of our participants. Their subjective reports did not indicate any experience of diplopia or
438 visual disturbances, or any awareness of our manipulation. This was further evidenced by the high
439 lexical decision accuracy in all disparity conditions, as well as the robust frequency effect we observed
440 across single and multiple fixation trials. The present findings are in direct contrast to the vergence
441 responses to words presented with a horizontal disparity observed by Blythe et al. (2010), who used
442 dichoptic presentation of single words with equal amount of horizontal offset (from 0 to 0.74 deg in
443 total, or up to 2 character spaces), and reported that the measured vergence responses were rapid
444 and direction-appropriate.

445

446 Furthermore, we were interested in the sensitivity of the saccadic targeting system to disparity in the
447 parafovea. Previous findings regarding horizontal disparity have revealed that the vergence system
448 reacts actively to disparity from fixation onset, but makes no adjustments during saccades when stimuli
449 are presented stereoscopically (Blythe et al., 2012; but see Kapoula, Eggert & Bucci, 1995 for an
450 alternative account). Furthermore, Blythe et al. (2010) observed that when making a horizontal saccade
451 onto a stereoscopic stimulus, participants targeted the preferred viewing location (O'Regan, 1981;
452 Rayner, 1979) for an unfused letter string with a length equal to the combined length of the two
453 monocular images. For instance, if a 6-letter word was presented independently to each eye with 2
454 character spaces of stereoscopic disparity, then the resulting letter string appeared 8 characters long on
455 the screen. This is an important point to consider: it appears that when inducing horizontal disparity
456 within single words, the disparate images were combined, but not fused prior to fixation. In addition,
457 Liversedge et al. (2006a) presented different parts of a target word within a sentence individually to
458 each eye (e.g. for the word cowboy, cowb was only seen by one eye and wboy was only seen by the
459 other eye). They found that saccades were targeted to stereoscopic lexical stimuli based on a combined
460 percept, regardless of which constituent of the target word was available to which eye monocularly.
461 Recall that the majority of the stimuli in the present study were presented with some degree of vertical

462 disparity and we explored the relationship between the direction of the visual offset in the stimuli and
463 the resulting fixation disparity, as measured by the eye-trackers. Evidence for close correspondence
464 between the two categorical variables would hint at the possibility of independent monocular saccade
465 targeting, as outlined by Liversedge et al. (2006a), which would in turn violate Hering's law of equal
466 innervation. Our findings, however, indicated otherwise. Similar to Liversedge et al. (2006a), the
467 present results indicated that landing positions on the vertically disparate stimuli were not affected by
468 the direction of the visual presentation. Vertical disparities at the start of the initial fixation on the
469 target were predominantly left-hyper, regardless of whether the left monocular image appeared above
470 or below the right monocular image. The left-hyper predominance was also observed in trials where the
471 dichoptic images were presented without disparity. In addition, the magnitude of vertical fixation
472 disparity at the start or at the end of each trial was not affected by the magnitude of binocular image
473 disparity present on the screen. Indeed, vertical disparities larger than 1 character space were only
474 measured on less than 10% of fixations, regardless of the fact that in 75% of trials the vertically
475 disparate stimuli exceeded the height of one character by up to 50%. Therefore, it appears that when
476 presented with a relatively small magnitude of vertical disparity in the parafovea, participants
477 performed parallel saccades in both eyes, regardless of the vertical disparity in the stimulus. That is to
478 say, the two monocular dichoptic images on the screen did not appear to have been used as separate
479 saccade targets for each eye.

480

481 Interestingly, while participants made no vertical vergence movements in response to the vertical
482 disparity manipulation, we observed significant systematic horizontal vergence movements as early as
483 the first fixation on the stimulus, even in the absence of a horizontal disparity manipulation. In other
484 words, the horizontal motor fusional system was automatically activated following a horizontal
485 saccade, as is typically observed in normal reading, whereas the vertical system showed no significant
486 activation. Importantly, we found no correlation between the magnitude of horizontal and vertical
487 disparity and drift measures, indicating that in the current study, the two systems did not interact during
488 lexical processing. Furthermore, the LME analyses found no effect of the vertical disparity
489 manipulation on horizontal disparity magnitude and drift measures. All these findings suggest that the
490 horizontal and vertical vergence systems react differently to imposed vertical disparities, which is
491 compatible with early studies investigating horizontal and vertical vergence responses to symmetric
492 disparity presentations (Perlmutter & Kertesz, 1978). Future studies would ideally investigate the
493 interaction between horizontal and vertical vergence when disparities are induced in both dimensions
494 simultaneously, as well as the degree of automaticity in horizontal vergence during sentence reading.

495

496 Another potential direction for future research would be to explore the natural vertical limitations of
497 fusion, that is, the thresholds for vertical vergence in reading. Such research could show how vertical
498 fusion limits could impact on reading processes and more specifically, potentially interact with reading
499 difficulties. However, recent work by Dysli et al. (2014) demonstrated that inducing vertical phoria
500 (vertical disparity) of up to 2 prism diopters (approximately 1 degree of visual angle) had no effect on
501 reading performance while participants read a paragraph of text aloud. Note though that differences

502 exist between eye movements during silent reading and reading aloud (e.g. longer fixation durations in
503 the latter condition, see Rayner, 1998 for review).

504

505 When contrasting our findings about vertical disparity patterns with those reported by Nuthmann et al.
506 (2009), several points become immediately apparent. Firstly, we observed a larger proportion of exo
507 (uncrossed) than eso (crossed) horizontal disparities, while Nuthmann and colleagues reported the
508 opposite pattern. These differences in the direction of horizontal disparities, as reported in different
509 studies, have been discussed in detail elsewhere (Kirkby et al., 2013). Importantly, it has been
510 suggested that viewing conditions associated with different data acquisition techniques (e.g., light text
511 over dark background or vice versa) amongst a variety of other factors, such as font colour and viewing
512 distance, might affect the pattern of horizontal disparities in reading. As for vertical disparities, we
513 observed the same left-hyper predominance in all induced vertical disparity conditions as Nuthmann et
514 al. (2009) observed during sentence reading. It appears, therefore, that vertical disparities that occur
515 during language processing are much less sensitive to viewing conditions than their horizontal
516 counterpart. Furthermore, our findings regarding the range of horizontal and vertical disparities over
517 which fusion is possible are compatible with the notion of an elliptical pattern for Panum's fusional
518 area, indicating that fusion operates over a limited range of vertical disparities and a larger range of
519 horizontal disparities. More critically, the vertical motor fusional mechanisms showed limited
520 activation, even in the presence of a disparity manipulation designed to elicit a vergence response.
521 While these findings differ from Nuthmann et al.'s (2009) report of approximately equal magnitude of
522 horizontal and vertical disparity in reading, the present data fit neatly with studies in non-reading tasks,
523 which suggest that the vertical limitations in Panum's area are caused in part by the visual system's
524 diminished capacity to compensate for vertical misalignments with disparity reducing vergence
525 movements (Houtman, Roze, & Scheper, 1977; Steinmann et al., 2000). This is also consistent with
526 Jainta et al.'s (2014) accounts of vertical disparity in normal reading, and suggests that the difference in
527 activation between the two oculomotor systems may be due to the separate but complementary
528 functions that they serve.

529

530 In addition, the functional differences between vertical and horizontal fusional mechanisms are
531 particularly relevant to understanding of the interplay between visual and linguistic processes in the
532 present experiment. Our findings indicated that word identification was not disturbed by the particular
533 nature of the binocular presentation. We observed no interaction between lexical frequency and vertical
534 disparity, but also found no additive effect of the disparity presentation on global processing times for
535 HF and LF words. A robust significant frequency effect was observed, regardless of the magnitude of
536 disparity present in the stimuli. These findings are different from those reported by Blythe et al.
537 (2010), who found that increasing horizontal disparity also increased the time taken to make a lexical
538 decision. Note, however, that the magnitude of disparity they introduced in their stimuli was larger than
539 the present experiment. In addition, their study did not include a lexical frequency manipulation, and
540 they only reported the effect of induced disparity on total trial viewing times. Jainta et al. (2014), on the
541 other hand, observed that presenting text monocularly, rather than binocularly, significantly reduced

542 the frequency effect for HF words. Although we are cautious when comparing data from natural
543 reading and lexical decision experiments, what we can nevertheless glean from those findings is that in
544 the present study, despite the disparity manipulation, participants were able to derive the benefits of
545 binocular vision during word identification and display the well-documented increased efficiency of
546 lexical processing for HF words. It is likely that a fused percept of our stimuli was obtained at an early
547 stage of visual processing, possibly prior to the feature extraction stage of lexical identification.
548 Furthermore, it may well be the case that induced vertical disparities of the magnitude typically
549 observed in reading caused no disturbance in lexical processing because they are informative in a
550 different way to horizontal disparities. As Jainta et al. (2014) suggested, this dissociation between the
551 two oculomotor responses is very likely due to the physical arrangement of the visual system and the
552 resulting effect on binocular coordination, the computation of depth and stereopsis.

553

554 In conclusion, the present study demonstrated that during lexical identification, the visual system
555 responds differently to stereoscopic vertical disparity than it does to horizontal disparity. Our findings
556 suggest that the visual system programs saccades to vertically misaligned lexical stimuli based on a
557 fused percept attained at an early stage of processing, as indicated by the observed pattern of landing
558 positions and the reported vergence and disparity measures. Further work is needed to investigate the
559 response of the visual system to induced disparities in all directions during lexical processing in order
560 to quantify the degree of interdependence between horizontal and vertical fusional mechanisms.

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563 Word count: 7000 words

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694

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Figure 1. Dichoptic presentation of the experimental stimuli without fusion (A) and with fusion (B)

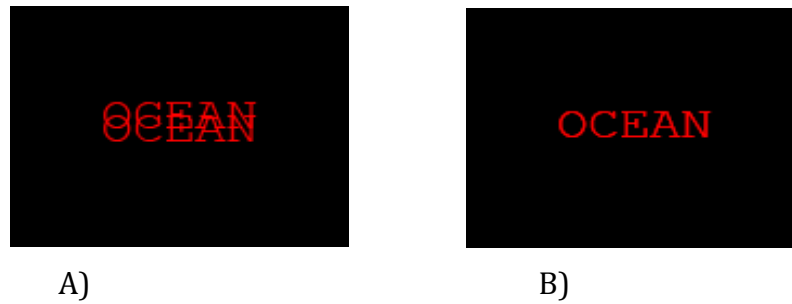


Figure 2. Mean differences in total reaction times (RTs) between high-frequency words (HF), low-frequency words (LF) and non-words (NW) in the different disparity conditions.

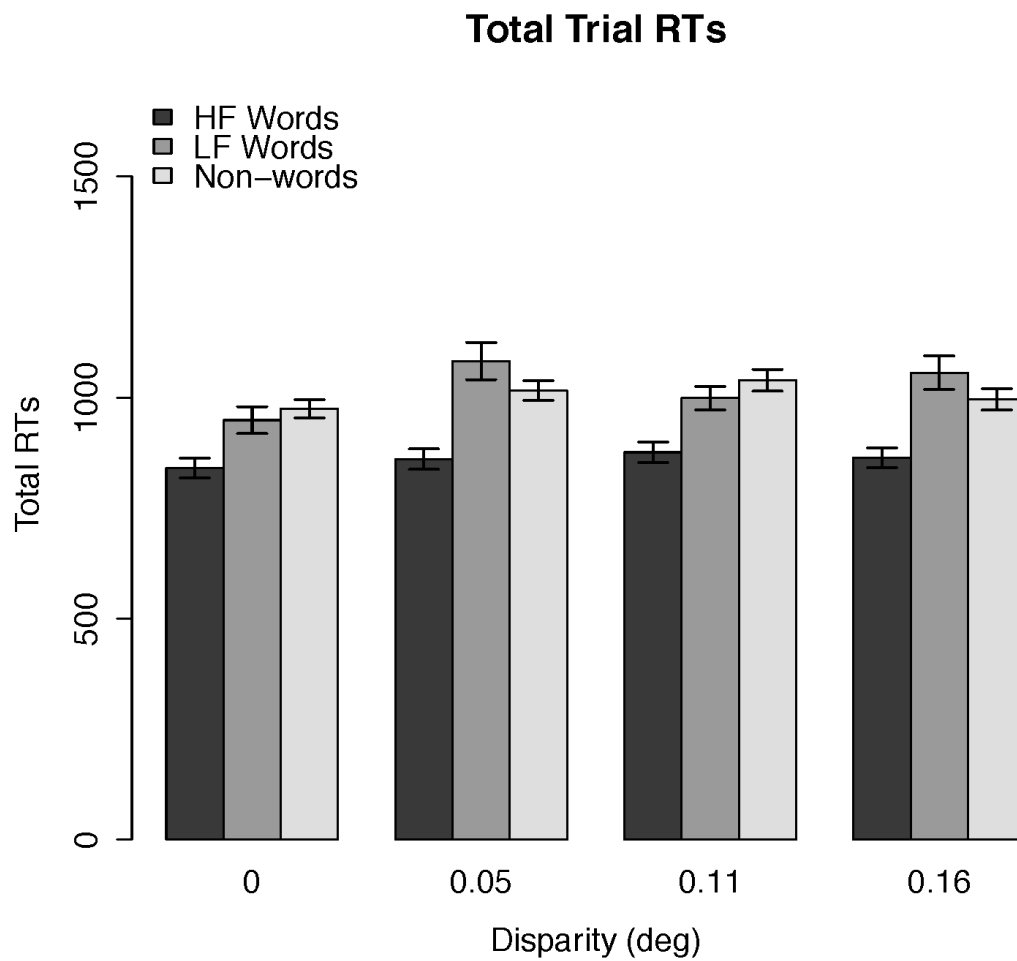


Figure 3. Horizontal and vertical disparities at the start of the initial fixation on each item plotted on a Cartesian coordinate system

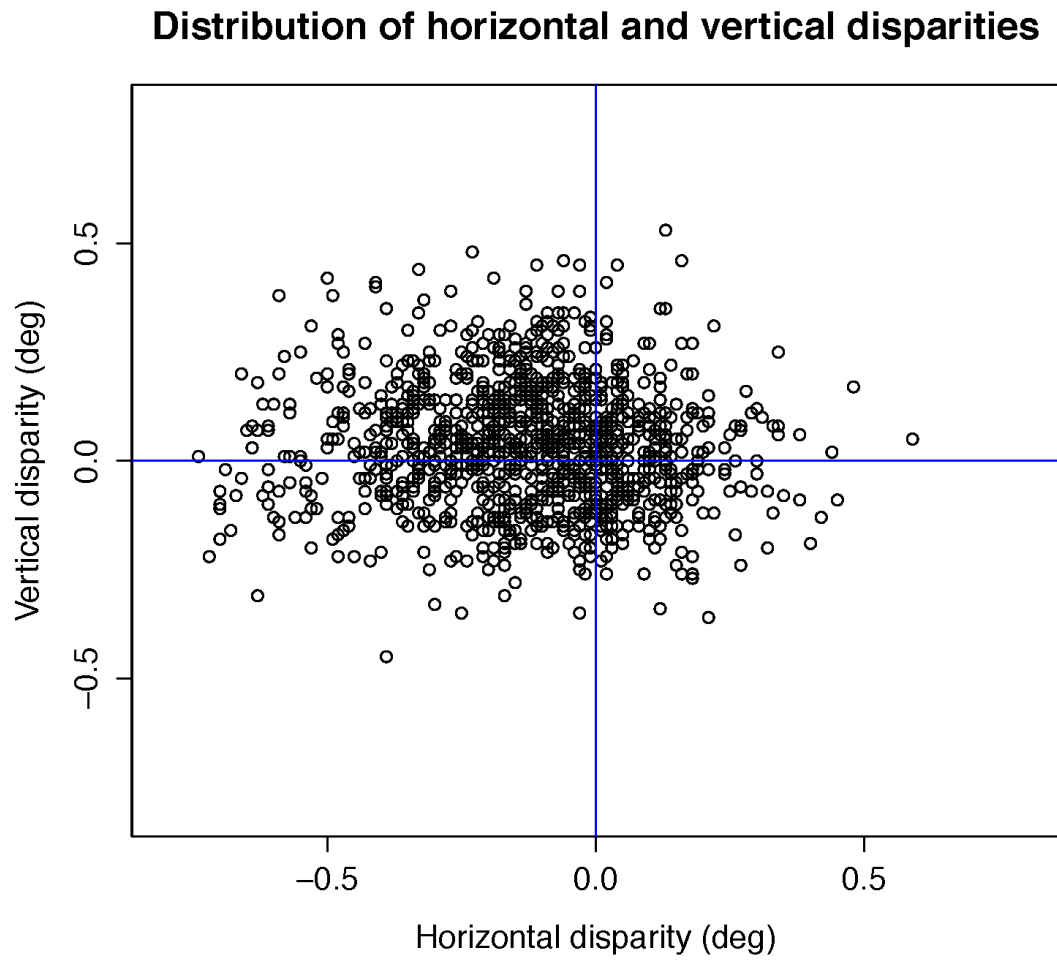
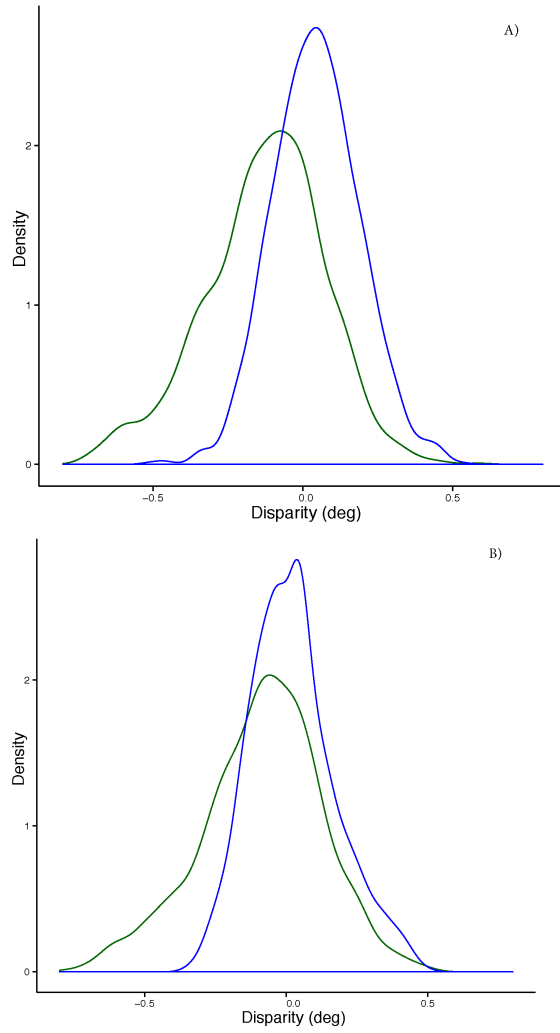


Figure 4. Distribution of horizontal (green) and vertical (blue) disparities between the start (A) and the end (B) of the initial fixation on each item



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701 Table 1.

Descriptive data about lexical decision accuracy, total reaction times (RTs), first fixation duration (FFD), single fixation duration (SFD) and mean number of fixations per trial (*SDs* in parentheses) for high-frequency words (HF), low-frequency words (LF) and non-words (NW).

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		Frequency		Disparity (deg)	
		0	0.5	0.11	0.16
Lexical decision accuracy	HF	100%	99%	99%	99%
	LF	92%	92%	93%	93%
	NW	97%	98%	98%	98%
Total RTs (ms)	HF	840.79 (22.23)	860.70 (23.16)	876.05 (23.11)	864.24 (22.48)
	LF	948.84 (30.05)	1082.37 (42.08)	998.53 (27.01)	1056.15 (37.91)
	NW	974.39 (20.27)	1015.50 (22.55)	1038.97 (24.49)	995.83 (24.13)
FFD (ms)	HF	407.32 (23.03)	393.01 (19.49)	414.57 (20.11)	371.73 (17.34)
	LF	374.74 (19.04)	369.03 (23.13)	369.03 (23.13)	378.81 (23.05)
	NW	399.41 (15.48)	380.71 (15.44)	401.20 (15.58)	362.49 (14)
SFD (ms)	HF	608.14 (31.35)	712.56 (65)	683.92 (46.73)	733.96 (48)
	LF	736.40 (170.27)	857.92 (98.16)	805.79 (66.16)	813.67 (75.12)
	NW	733.11 (54.89)	710.62 (69)	679.75 (55.50)	758.52 (60.64)
Number of fixations per trial	HF	2.41 (.07)	2.47 (.07)	2.42 (.07)	2.45 (.07)
	LF	2.78 (.10)	2.87 (.11)	2.66 (.09)	2.85 (.11)
	NW	2.71 (.06)	2.77 (.07)	2.78 (.07)	2.79 (.07)