Distinct spatial patterns of flanker interference differentiate visual crowding from flanker compatibility effects in the Eriksen task

Danai Papadaki[1], Rama Chakravarthi[1] & Søren K. Andersen[1,2]

(1. School of Psychology, University of Aberdeen, UK, 2. Department of Psychology, University of Southern Denmark, Denmark)

danai.papadaki3@abdn.ac.uk

Abstract

Recognising and responding to task-relevant stimuli may be hindered by nearby task-irrelevant flanker stimuli. Such effects occur both in visual crowding and in Flanker Compatibility Effects (FCE). Whereas crowding is a visual phenomenon that reflects a breakdown of object recognition in clutter, the FCE in the Eriksen flanker task is thought to be due to conflict during decision-making. In two experiments we investigated if and how these two seemingly independent phenomena are related. We employed an orientation categorisation task that allowed us to concurrently quantify crowding and FCEs. Specifically, we examined whether the spatial arrangement of stimuli affects the FCE in a similar way as in crowding. Interestingly, even when flankers were outside the crowding range, larger FCEs were observed for radially placed flankers compared to tangentially placed ones and for two compared to one flanker, corresponding to established patterns in crowding. However, inner flankers produced larger FCEs than outer flankers - the opposite of what is observed in crowding. In Experiment 2, we further investigated this reversed inner-outer asymmetry while manipulating the magnitude of crowding through varying target-flanker spacings. As expected, the outer flankers produced stronger crowding than inner ones. Crucially, the inner flankers produced a larger

reaction time FCE and this inner-flanker interference was highest at the largest spacing. These findings demonstrate that the spatial layout of visual stimuli modulates conflict at both visual and decision-making stages, but the opposite patterns of the inner-outer asymmetry in the two phenomena provide a clear demarcation between the processes underlying them.

Introduction

The visual environment is frequently cluttered. To successfully navigate and interact in it, irrelevant information needs to be filtered out from relevant. However, irrelevant, and potentially conflicting, nearby information ('flankers') often interferes with the processing of relevant information in the visual field. Such interference is thought to arise at both the visual processing and decision-making stages. Two phenomena associated with flanker interference at each of these processing stages are visual crowding (Bouma, 1970) and the flanker compatibility effect (FCE) as demonstrated by the Eriksen flanker task (Eriksen & Eriksen, 1974), respectively. While these phenomena have conceptual and experimental similarities, they have been studied independently. As a result, there is no overarching framework for understanding the combined consequences of flanker interference across the entire processing hierarchy, potentially limiting the applicability of lab findings to real-life settings where decision-making may be based on sub-optimal sensory information.

Crowding

Crowding is a breakdown of object recognition in clutter, i.e., an object that can be accurately identified in isolation becomes unrecognisable when flanked by other similar objects (Bouma, 1970; Chakravarthi & Cavanagh, 2007; Pelli & Tillman, 2008). Crowding is thought to be a fundamental constraint on how much information we can utilise from peripheral vision (Levi, 2008a; Pelli & Tillman, 2008) and is thought to result from interference at the visual processing stage

60   (Greenwood et al., 2009; Harrison & Bex, 2015; Parkes et al., 2001). Some
61   of the salient characteristics of crowding are that its strength increases
62   with a) decreasing target-flanker distance (e.g., Wolford & Chambers,
63   1983; Pelli et al., 2004; Toet & Levi, 1992) and b) increasing eccentricity
64   (Bouma, 1970; Toet and Levi, 1992). Flankers beyond a certain distance
65   from the target no longer interfere with it. This distance is commonly
66   termed as critical spacing (Pelli & Tillman, 2008). Critical spacing is
67   largely proportional to eccentricity and has been estimated to be roughly
68   half the eccentricity of the target from fixation (Bouma, 1970). This
69   proportionality has been recognised in the literature as the Bouma Law
70   (Pelli and Tillman, 2008). However, critical spacing is not constant: it is
71   systematically affected by various manipulations and can be substantially
72   larger or smaller than half the eccentricity under certain conditions (Soo et
73   al., 2018; Scolari et al., 2007; for a review see Strasburger, 2020).

74   Numerous accounts attempt to capture the mechanisms underlying
75   visual crowding (Strasburger et al., 1991). However, the main proposals
76   associated with crowding are *pooling*, *substitution* and *selective attention*
77   (Tyler & Likova, 2007). Pooling theories posit that under crowded
78   conditions target and flanker features are averaged (Balas et al., 2009;
79   Keshvari & Rosenholtz, 2016; Parkes et al., 2001; Pelli et al., 2004). Each
80   visual area has neurons with receptive fields that increase in size with
81   increasing eccentricity. Therefore, the further out in the periphery a
82   stimulus is presented, the bigger on average, the receptive fields of the
83   neurons responding to it (Fang & He, 2008; Levi et al., 1985; Pelli, 2008;
84   for review see Strasburger et al., 2011). When multiple stimuli fall within
85   the same receptive field, their features are "pooled" resulting in crowding
86   (Dayan & Solomon, 2010; Motter & Simoni, 2007; Van Den Berg et al.,
87   2010; Wolford, 1975). Crowding is stronger in the periphery than at
88   fixation, as targets and flankers need to be much farther apart in order not
89   to fall within the same receptive field (Freeman & Simoncelli, 2011;
90   however see Wallis et al., 2019). In contrast, substitution theories argue
91   that crowding results from mistaking the location of a target or its features
92   and reporting a flanker instead (Chastain, 1983; Estes et al., 1976; Ester et

al., 2014; Strasburger, 2005; 2014; Strasburger et al., 1991). Evidence for substitution is apparent when examining the types of errors participants make, where participants often report the identity of a flanker instead of the target (Freeman et al., 2012; Ester et al., 2014; Hanus & Vul, 2013; Harrison & Bex, 2015). The last account is selective attention. Selective attention serves to focus processing resources on relevant stimuli and attenuate the influence of irrelevant stimuli. It is thought to play a role in crowding, either as the source of the processing bottleneck (He et al., 1996; Chakravarthi & Cavanagh, 2007; 2009; Põder, 2007) or as a modulating influence (Huckauf & Heller, 2002; Scolari et al., 2007; Strasburger, 2005; Strasburger & Malania, 2013; Yeshurun & Rashal, 2010; Kewan-Khalayly et al., 2022; Mareschal et al., 2010; LaBerge et al., 1991; Bowen et al., 2023).

Eriksen Flanker Task

The Eriksen flanker task (Eriksen & Eriksen, 1974) is a conflict task in which a target stimulus and nearby flankers may evoke the same or opposing behavioural responses. The Stroop task (Stroop, 1935), Simon task (Simon & Rudell, 1967) and Navon's hierarchical letters (Navon, 1977) are other prominent examples of conflict tasks. A common aspect of these is the occurrence of longer reaction times when task-irrelevant information is associated with an incompatible response (incongruent) than when it invokes a compatible response (congruent) or is neutral. The difference in reaction times between congruent and incongruent trials in the Eriksen flanker task is known as the flanker compatibility effect (FCE) where the bigger the FCE, the stronger the interference induced by the flankers on the target (e.g., Miller, 1991). The Eriksen flanker task has been adapted in a large number of experimental settings to study a range of topics such as conflict monitoring (Gratton et al., 1988), creative intelligence during problem-solving (e.g., Rowe et al., 2007), executive control (Davelaar & Stevens, 2009), the breadth of attentional selection (Rowe et al., 2007) and ageing (Reuter-Lorenz & Cappell, 2008). In contrast to crowding, in the Eriksen flanker task, the identity of both target and flankers can be accurately identified. Since the identities of the target

126 and flankers have been processed and the conflict results from the
127 congruency (or its lack) between them, this conflict has been interpreted to
128 occur during the decision-making stage (Eriksen & Eriksen, 1974). Even
129 though most of the tested perceptual properties do not modulate the FCE
130 (Miller, 1991), certain stimulus properties such as target-flanker spacing
131 and colour similarity seem to do so (Baylis & Driver, 1992; however see:
132 Harms & Bundesen, 1983). Therefore, the visual processing stage might
133 play a more important role in the FCE than originally considered (Eriksen
134 & Schultz, 1979).

The relationship between crowding and the FCE

136 Crowding and the FCE in the Eriksen flanker task have been treated
137 and examined separately in the literature. However, when comparing
138 them, it is clear that they share several characteristics. Even though they
139 are used in different contexts, both examine how irrelevant information
140 interferes with relevant information in our visual field and have employed
141 comparable experimental approaches. Additionally, both fields of research
142 have tested the role of target-flanker spacing. In both crowding (e.g.
143 Bouma, 1970; Pelli et al., 2004; Toet & Levi, 1992; for reviews see Levi,
144 2008; Whitney & Levi, 2011), and the FCE in the Eriksen flanker task
145 (Eriksen & Eriksen, 1974; Kelber et al., 2023; Kramer & Jacobson, 1991),
146 interference is stronger at closer than farther target-flanker spacings.
147 Moreover, both phenomena appear to be modulated by target-flanker
148 similarity, where interference is stronger between more similar objects
149 (Crowding: Kooi et al., 1994; Chakravarthi & Cavanagh, 2007; Kennedy &
150 Whitaker, 2010; Scolari et al., 2007; FCE: Eriksen & Schultz, 1979; Baylis
151 & Driver, 1992), although this relationship is well established in crowding,
152 it is still debated in the FCE (Harms & Bundesen, 1983).

153 Nevertheless, the conditions under which the two phenomena have
154 been studied also differ in some critical ways, suggesting that they might
155 indeed have different boundary conditions where it is possible to observe
156 only one or the other. Specifically, crowding has been predominantly
157 studied in the visual periphery, using unspeeded identification responses

and measured through identification accuracy (for a review see Whitney & Levi, 2011). In contrast, the FCE has been predominantly studied with stimuli presented at or close to fixation, using speeded categorisation responses measured with reaction times (for review see Ridderinkhof et al., 2021). Consequently, a clear separating line is that the Eriksen flanker task typically involves situations where flankers are outside the critical spacing of crowding i.e., where object identification is unproblematic, whereas crowding typically investigates situations in which flankers are close enough to impair object identification. The identification of both targets and flankers is a necessary condition for the FCE as the effect results from the potential conflict between the responses evoked by the two. Thus, the FCE might be attenuated or absent when identification becomes difficult, as when stimuli are crowded. However, since the two phenomena are typically studied separately it is unclear whether this is the case.

As mentioned above, crowding is thought to be due to interference during visual processing (Anderson et al., 2012; Chen et al., 2014; Chen et al., 2018; Freeman et al., 2011;Pelli, 2008; Strasburger, 2020) whereas the FCE is due to conflict during decision-making (Eriksen & Eriksen; Eriksen & Schultz, 1979). It is therefore likely that flanker interference in the two phenomena occurs sequentially, but their inter-dependence is currently unknown. Thus, it is not clear whether the specificities of visual processing leave any imprint on the later response selection stage when visual identification itself is unproblematic (e.g., no crowding). If the two types of flanker interference are linked, then stimulus manipulations that affect crowding should also affect the FCE. If this were the case, investigations of one phenomenon might be highly informative for the other, and much could be gained from integrating knowledge across both.

The current study

To examine the relationship between crowding and the FCE in the Eriksen flanker task, we studied the effect of spatial configuration of targets and flankers, as aspects of this are known to affect both

190   phenomena. Importantly, certain spatial effects have been argued to be
191   unique to crowding and thus to be diagnostic in distinguishing it from
192   other related phenomena (for a review see Strasburger, 2020). For
193   example, flanker interference in crowding depends not only on the target-
194   flanker distance but also on the position of the flankers relative to the
195   target. First, there is a radial-tangential anisotropy in peripheral vision for
196   crowding (Toet & Levi, 1992): radially presented flankers induce more
197   crowding than tangential ones (e.g., Greenwood et al., 2017; Kurzawski et
198   al., 2023; Kwon et al., 2014; Petrov & Meleshkevich, 2011; Toet & Levi,
199   1992; Van Den Berg et al., 2010, Wolford & Chambers, 1983). A second key
200   property, which is considered to be a diagnostic criterion of crowding, is
201   the inner-outer asymmetry (Banks et al., 1979; Chakravarthi et al., 2021;
202   Petrov et al., 2007; Shechter & Yashar, 2021; for a review see Strasburger,
203   2020). In particular, flankers that are presented between the target and
204   fixation (inner) induce less crowding than flankers presented further away
205   from fixation than the target (outer). It has also been noted that crowding
206   is stronger with two flankers compared to one (Bouma, 1970; Pelli et al.,
207   2004).

208   In Experiment 1, we examined whether the FCE in a modified
209   Eriksen flanker task also demonstrates (1) the inner-outer asymmetry, (2)
210   the radial-tangential anisotropy, and (3) if two flankers interfere more than
211   one. To ensure that these asymmetries and anisotropies were not simply
212   due to crowding, crowding was eliminated by placing the flankers well
213   outside the critical spacing. This allowed us to test whether the spatial
214   organisation of the scene continues to interfere with decision-making,
215   even when the targets (and flankers) are accurately identified. If the FCE
216   results exclusively from response conflict, the visual organisation of the
217   scene should not influence the magnitude of the effect, as long as both the
218   targets and flankers are adequately identifiable. Therefore, we would not
219   expect to see any anisotropies or asymmetries in the FCE. However, if
220   asymmetries follow the pattern seen in crowding, we would expect more
221   flanker interference from 1) outer compared to inner, 2) radial compared
222   to tangential and 3) two compared to one flanker. This would suggest that

the specifics of visual processing influence the FCE even when stimulus
identification is unproblematic. In Experiment 2, we further examined the
inner-outer asymmetry and tested it across multiple target-flanker
spacings. Since the inner-outer asymmetry has been used as a diagnostic
tool for crowding, we wanted to test this asymmetry in the FCE both with
and without crowding. This manipulation not only allowed us to examine
the two under the same experimental settings but also provided insight
into situations where decision-making is based on sub-optimal visual
information.

Experiment 1

Method

Participants

Experiment 1 tested eighteen volunteer participants (self-reported:
4 males; 2 left-handed; mean age = 26.8 years; age range = 23-39). All
participants reported having normal or corrected-to-normal visual acuity.
Participants were reimbursed £8 for their time. They provided informed
written consent prior to the study and the experiment was approved by the
ethics committee of the School of Psychology at the University of
Aberdeen.

Sample size calculation

We computed the required sample size based on previously reported
effect sizes for three distinct effects: the 1) flanker compatibility effect
(Barzykowski et al., 2022), 2) radial tangential anisotropy (Kurzawski et
al., 2023) in crowding, and 3) inner-outer asymmetry (Chakravarthi et al.,
2021) in crowding. We desired the sample size that would yield a power of
at least 95% to detect the *smallest* of these effects. Specifically, for the
FCE, the mean difference in RT between correct congruent and
incongruent trials (n=466, mean=-44.2 ms, SD=23.9 ms; Barzykowski et
al., 2022) has a standardised effect size ('delta', a standardised effect size
in the Cohen's d family in which the standard deviation of the difference

254 between conditions is used as the denominator) of 1.85, and hence n=7
255 yields a power of 95% to detect the FCE. For the radial-tangential
256 anisotropy, the mean difference between radial and tangential critical
257 spacing at 5 degrees eccentricity (n=50, mean= 0.65, SD=0.21; Kurzawski
258 et al., 2023) gives a delta effect size of 3.1; therefore, n=4 will provide a
259 power of 95% to detect the anisotropy. For the inner-outer asymmetry, the
260 mean difference between in and out critical spacing at 7.5 degrees
261 eccentricity (n= 38, mean=1.35, SD = 0.72; Chakravarthi et al., 2021)
262 gives a 'delta' effect size of 1.87 where n=6 yields power of 95%. Previous
263 studies have typically used participant numbers in the range of 4-12. Here,
264 we sought to determine if there would be any spatial asymmetries. Hence,
265 to ensure that we were adequately powered, we chose to triple the number
266 of participants suggested by the power analysis, and hence we tested at
267 least 18 individuals. These calculations were done using the power
268 calculator provided by Gregory Francis
269 (http://www1.psych.purdue.edu/~gfrancis/calculators/means_dependent_
270 power.shtml).

Materials and Stimuli

272 The experiment was conducted on a Dell computer, using
273 PsychToolbox extensions (Brainard, 1997; Kleiner et al., 2007) for
274 MATLAB (Mathworks, Natick, MA). A Cambridge Research Systems 32″
275 Display++ LCD monitor set to 1920 x 1080 pixels resolution and 120 Hz
276 refresh rate was used for stimulus presentation and viewed at 57 cm.
277 Participants' head position was secured with a chin rest. The target and
278 flanker stimuli were clock-like objects: a circle with an oval hand along the
279 radius. The thickness of the widest point of the hand was equal to the
280 thickness of the circle. A target clock with a diameter of 1.5° of visual angle
281 (dva) was presented at an eccentricity of 4° on the horizontal meridian to
282 the left or the right of the fixation cross. Two stimulus groups ('up' and
283 'down') were created based on the orientation of the clock hand (Figure
284 1C). Each stimulus group had three orientations: up (45°, 90°, 135°) and

285 down (225°, 270°, 315°)[1]. The target appeared in isolation, with one, or
286 with two flanking clocks.

287   To ensure that modulation of flanker compatibility effects could not
288 be attributed to crowding, we presented flankers outside the critical
289 spacing, i.e., ensured that accuracy in all conditions was above 90%. Pilot
290 data were collected to find a stimulus configuration that satisfied the above
291 condition while also producing stable reaction time FCEs. Based on this,
292 we reduced target-flanker similarity to reduce crowding (Kooi et al., 1994;
293 Rashal & Yeshurun, 2014; Scolari et al., 2007) by decreasing the size of the
294 flankers to two thirds that of the target (1° diameter). This allowed us to
295 present flankers at a centre-to-centre distance of 2° from the target
296 without inducing crowding. Note that, while we could have reduced
297 crowding by instead moving flankers further away, it would have moved
298 the inner flanker close to or on top of the fixation cross.

299   Flankers were either from the same response group as the target
300 (congruent) or from the other group (incongruent). Flankers were never
301 identical to each other or to the target. Four flanker locations were used
302 relative to the target (inner, outer, above, and below), which were
303 combined with the manipulation of the number of flankers (one or two) to
304 yield 6 flanker position conditions: three tangential (above, below, above &
305 below) and three radial (inner, outer, inner & outer). To clearly indicate
306 the target location and avoid ambiguity due to its changing relative
307 location across flanker configurations, its position was indicated by four
308 diagonal straight lines with a dot at the end (length 2°, thickness 0.15°).
309 This location cue was of opposite luminance polarity to the target and
310 flanker stimuli to prevent it from inducing crowding.

311   The luminance of target and flanker stimuli, the location cue, and the
312 background were 9.03 cd/m^2, 66.76 cd/m^2, and 37.86 cd/m^2, respectively.
313 Accordingly, Weber contrast[2] of targets, flankers, and the location cue was

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1 [1] Angles are given relative to the x-axis (0°) and increase in counterclockwise direction,
2 as is usual in Cartesian coordinate systems.
3 [2] Weber Contrast C was calculated as , where I is the luminance of the stimulus and I_b is
4 the luminance of the background.

314 ±0.76, with targets and flankers having a negative, and the location cue
315 having a positive contrast.

Procedure

317   The fixation cross and location cues (one on each side of fixation)
318 were presented on the screen throughout the experiment. In each trial,
319 one of the six target clocks was presented unpredictably to the left or the
320 right side of the fixation cross for 208 ms in isolation or surrounded by one
321 or two flankers, in one of the six flanker position conditions. The flankers,
322 when presented, were either both congruent or both incongruent. The
323 inter-trial interval was randomly sampled between 808-1208 ms.
324 Participants were asked to perform a categorisation task and indicate, by
325 pressing the 'up' or 'down' arrow key, the group of the target letter (Figure
326 1). Participants were instructed to fixate at the centre of the screen and
327 respond as quickly and as accurately as possible. The short stimulus
328 presentation duration was chosen to prevent eye movements. Maximum
329 response time was set to 1500 ms; if a response was not made within that
330 time window, the next trial was presented, and the trial was counted as an
331 error. At the end of each trial, participants received auditory feedback in
332 the form of a beep for error responses. At the end of each block, average
333 accuracy and reaction times for that block were presented to participants.
334 Participants proceeded to the next block after a self-paced break.

335   Each participant completed 1176 trials across 7 blocks. There were
336 168 different types of trials: 2 presentation sides (left, right), 2 response
337 groups (up, down), 3 target identities within each group, 2 flanker
338 congruency (congruent, incongruent) types, and 7 flanker positions
339 (above, below, above & below, inner, outer, inner & outer, no flanker).
340 Each block included a single presentation of each type of trial and all trials
341 in each block were shown in random order. For calculation of accuracy and
342 median reaction time, we pooled responses across presentation side,
343 response group and target identity. Accordingly, behavioural data were
344 analysed in terms of flanker position and congruency with 84 trials per
345 condition, except for the no-flanker condition, which was tested with 168

346 trials. For each condition, the median reaction time was calculated from
347 correct trials (93.7% of all trials).

348   Prior to the experiment, participants completed two sets of practice
349 blocks. First, 72 trials with no flankers were presented to ensure
350 participants became familiar with the response groups. A second practice
351 block with 168 trials identical to a block from the main experiment
352 including all experimental conditions was then completed. If participants
353 scored less than 90% accuracy across all trials, this block was repeated. All
354 participants were able to perform above 90% accuracy within a maximum
355 of two blocks of practice.

356
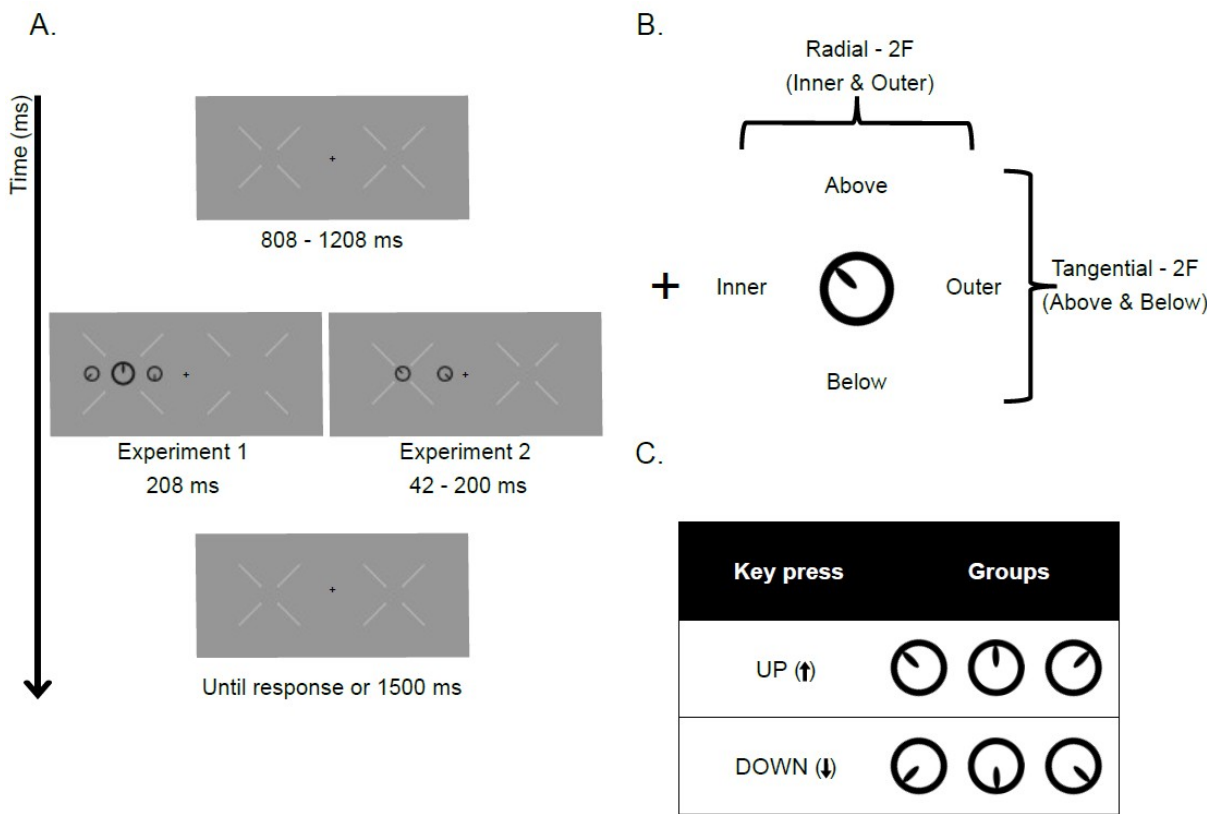
357 Figure 1: **A.** *Example trial from Experiments 1 & 2 showing the sequence of events:*
358 *fixation, stimulus presentation and screen until response. Experiment 1: an*
359 *incongruent trial showing flanker location 'inner & outer'. The correct response*
360 *would be "up". Experiment 2: an incongruent trial showing flanker location "inner" at*
361 *2.7 degrees target-flanker spacing. The correct response would be "up".* **B.**
362 *Representation of flanker positions.* **C.** *Target groups and corresponding key*
363 *responses. Participants were asked to perform a categorisation task and indicate, by*
364 *pressing an arrow key, the group of the target.*

Results

As intended, each participant's categorisation accuracy reached or exceeded 90% in all conditions. Thus, flankers were presented outside the critical spacing defined as 90% of asymptote (Coates et al., 2018; Kurzawski et al., 2023) and any effects found, therefore, cannot be attributed to crowding. Categorisation accuracy and median reaction times, averaged over participants, as well as the difference between congruent and incongruent conditions for both measures, at all flanker positions, are plotted in Figure 2.
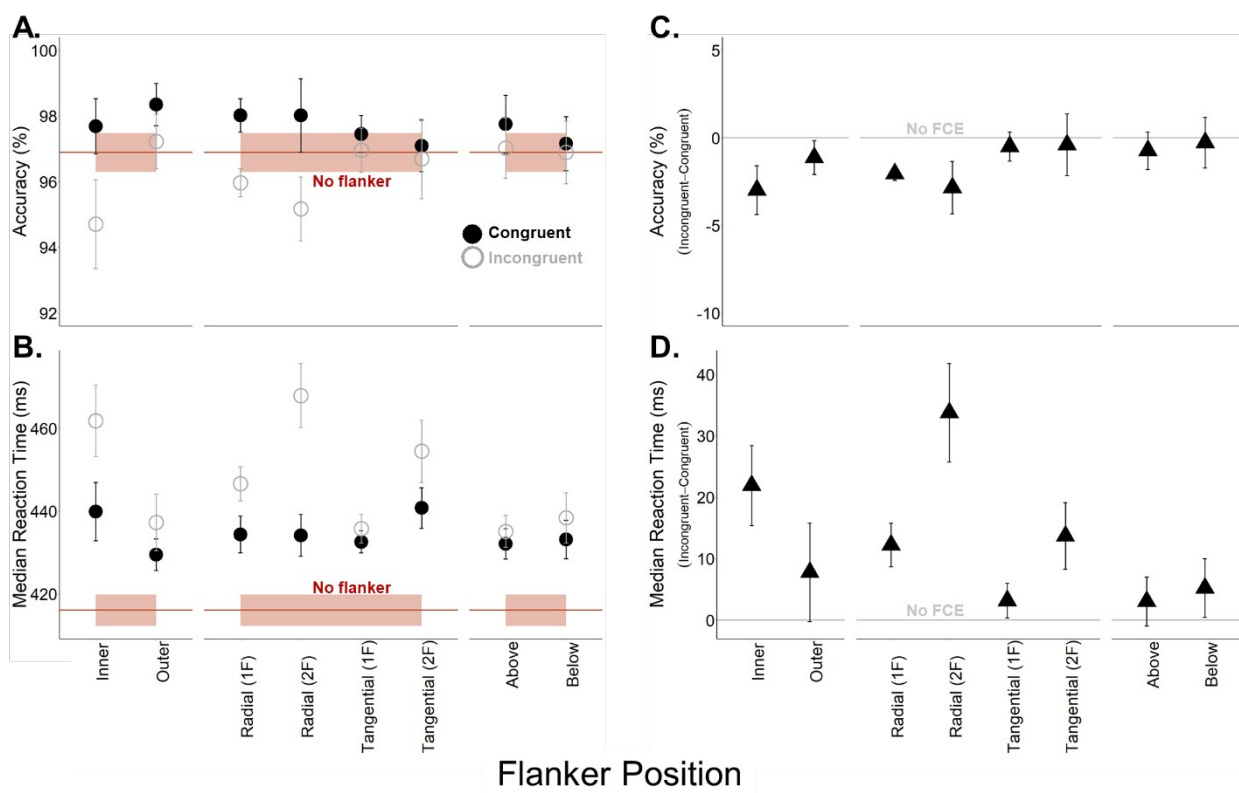

Figure 2: *Results from Experiment 1. Accuracy and median reaction times averaged across participants as a function of flanker position with within-subjects 95% confidence intervals as error bars* (Cousineau, 2005) (Morey, 2008). *Plots A&B show average performance where black filled circles represent performance in the congruent trials and grey open squares performance in the incongruent trials. The solid red line with the shaded area is performance in the no flanker condition. Plots C&D show the difference in performance in the incongruent and congruent conditions (incongruent – congruent), for each flanker position. Here, more negative values for accuracy, and more positive values for reaction times represent stronger FCE. Zero represents no FCE which is indicated with a solid grey line. For the flanker positions coded as (1F), we pooled trials across single flanker presentations where inner and outer locations yield a 'Radial (1F)' condition and above and below locations yield a 'Tangential (1F)' condition.*

388   In Experiment 1, we examined: (1) the inner-outer asymmetry, (2) the
389   radial-tangential anisotropy and (3) interference from two compared to
390   one flanker, in the FCE, as tested by the Eriksen flanker task. To evaluate
391   the inner-outer asymmetry we computed a two-way repeated measures
392   ANOVA with factors *congruency* (congruent, incongruent) and *flanker*
393   *position* (inner, outer) for accuracy and s. As expected, accuracy was
394   higher in congruent than in incongruent trials ($F(1,17) = 34.11$, $p < 0.001$,
395   = 0.67) and interestingly it was higher with the outer than with the inner
396   flanker ($F(1,17) = 7.56$, $p = 0.01$,   = 0.31). However, there was no
397   significant interaction between the two factors ($F(1,17) = 3.03$, $p = 0.10$,
398   = 0.15). Therefore, in terms of accuracy, there was no significant inner-
399   outer asymmetry for the FCE. However, it should be noted that accuracy
400   was, as aimed for, near ceiling (Figure 2A, first panel), and thus the
401   sensitivity to detect such an interaction, if it were there, would have been
402   limited. Reaction times were also faster in congruent than in incongruent
403   trials ($F(1,17) = 99.86$, $p < 0.001$,   = 0.85) and with outer than with inner
404   flanker ($F(1,17) = 20.21$, $p < 0.001$,   = 0.54). However, here a two-way
405   interaction between the factors showed that the FCE was stronger for the
406   inner than for the outer flanker ($F(1,17) = 5.02$, $p = 0.04$,   = 0.23) (see
407   Figure 2D, first panel). That is, (a) there was an inner-outer asymmetry for
408   the FCE, observed in reaction times, even when there was no crowding and
409   (b) surprisingly, this asymmetry was in the opposite direction to the one we
410   would expect from crowding. For the full set of comparisons see Table 1A.

411   To test for the radial-tangential anisotropy and the effect of number of
412   flankers, a three-way repeated-measures ANOVA with factors *congruency*
413   (congruent, incongruent), *flanker position* (radial, tangential) and *flanker*
414   *number* (one, two) was computed. Accuracy and reaction times for radial
415   and tangential for one flanker were computed by averaging across inner
416   and outer and above and below flanker positions, respectively. Accuracy
417   was again higher in congruent compared to incongruent trials ($F(1,17) =$
418   17.81, $p < 0.001$,   = 0.51) and there was an interaction between
419   congruency and flanker location where the FCE was stronger for radial
420   compared to tangential flanker positions ($F(1,17) = 11.23$, $p = 0.003$,   =

421 0.40) (see Figure 2A, middle panel). That is, a radial-tangential anisotropy
422 was found in the same direction as seen in crowding. Reaction times were
423 faster in congruent compared to incongruent trials ($F(1,17) = 160.03$, $p <$
424 0.001, = 0.90) and with one compared to two flankers ($F(1,17) = 67.27$, p
425 < 0.001, = 0.80). A three-way interaction was found between congruency,
426 flanker position, and number of flankers where the FCE, in terms of
427 reaction times, was larger in the presence of radial flankers compared to
428 tangential flankers, and this effect was even more pronounced when there
429 were two flankers present compared to one ($F(1,17) = 5.04$, $p = 0.04$, =
430 0.23) (see Figure 2D, middle panel). For the full set of comparisons see
431 Table 1B. Therefore, we observed a radial-tangential anisotropy in the FCE
432 with stronger interference from radial than tangential flankers; we also
433 observed that FCE was stronger in the presence of two compared to one
434 flanker. These findings were in line with what we would expect from
435 crowding experiments.

436   Single flankers above or below the target induced slower reaction
437 times when they were incongruent compared to congruent ($F(1,17) = 6.05$,
438 $p = 0.02$, = 0.26). Reaction times did not differ depending on whether
439 flankers were above or below the target and there was no interaction
440 (Figure 2D, last panel). Accuracy showed neither main effects nor
441 interactions for this manipulation. For the full set of comparisons please
442 see (Table 1C).

443   Table 1: Statistics for data from Experiment 1. *A) Two-way repeated measures*
444 *ANOVA with factors Congruency (congruent, incongruent) and Flanker position*
445 *(inner, outer flankers). B) Three-way repeated measures ANOVA with factors*
446 *Congruency (congruent, incongruent), Flanker position (radial, tangential), and*
447 *Number of flankers (one, two). C) Two-way repeated measures ANOVA with factors*
448 *Congruency (congruent, incongruent) and Flanker position (above, below).*

	Accuracy			Reaction Time		
	F(1,17)	p		F(1,17)	p	
A. Inner-Outer (I/O) Asymmetry						
Congruency	34.11	**< 0.001**	0.67	99.86	**< 0.001**	0.85

Flanker Position (I/O)	7.56	**=0.01**	0.30	20.21	**< 0.001**	0.54
Congruency x Fl. Position (I/O)	3.03	0.10	0.15	5.02	**0.04**	0.23
B. Radial-Tangential (R/T) Anisotropy & One vs. Two Flankers						
Congruency	17.81	**< 0.001**	0.51	160.03	**< 0.001**	0.90
Flanker Position (R/T)	1.25	0.28	0.07	2.15	0.16	0.11
Number of Flankers	1.22	0.29	0.07	67.27	**< 0.001**	0.80
Congruency x Fl. Position (R/T)	11.23	**0.003**	0.40	23.27	**< 0.001**	0.58
Congruency x Num of Flankers	0.21	0.65	0.01	30.39	**< 0.001**	0.64
Fl. Position (R/T) x Num of Flankers	0.14	0.71	0.01	0.56	0.46	0.03
Cong x Fl. Position (R/T) x Num of Flankers	0.74	0.40	0.04	5.04	**0.04**	0.23
C. Above-Below (A/B) Flanker Positions						
Congruency	1.15	0.30	0.06	6.05	**0.02**	0.26
Flanker Position (A/B)	7.81	0.39	0.04	0.61	0.44	0.03
Congruency x Fl. Position (A/B)	2.66	0.61	0.02	0.42	0.53	0.02

449

In Experiment 1 we examined whether the spatial layout of targets and flankers affects FCEs in the same or similar way as the well-established counterparts in crowding. We tested conditions in which accuracy was well above 90% to ensure that any observed effects were not due to crowding. Radial flankers produced a larger FCE than tangential flankers and two flankers produced a larger FCE than one flanker. These effects are consistent with corresponding effects in crowding (Toet & Levi, 1992; Pelli et al., 2004). We also observed an inner-outer asymmetry for the FCE, with inner flankers producing a larger FCE than outer flankers, which is the opposite pattern to that commonly observed in crowding (Chakravarthi et al., 2021; Petrov et al., 2007). In conclusion, we found that spatial organisation of the flankers does modulate the FCE and that it had a specific pattern. There were some similarities between crowding and the

463 FCE, but there was also one major difference, which signifies a clear
464 demarcation between the two phenomena and possible underlying
465 mechanisms.

Experiment 2

467 Crowding exhibits an inner-outer asymmetry where flanker interference
468 by the outer flanker is stronger compared to that by the inner flanker.
469 Even though in Experiment 1 we did find an inner-outer asymmetry for
470 the FCE in the Eriksen task, the direction of that asymmetry was the
471 opposite of the one typically reported in crowding experiments (e.g.
472 Chakravarthi et al., 2021; Petrov, 2007; Shechter & Yashar, 2021). In
473 Experiment 2, we sought to verify this unexpected finding and test
474 whether it is affected by crowding. This was done by manipulating the
475 magnitude of crowding by varying the target-flanker spacing.

Method

Participants:

478   Experiment 2 tested twenty-three participants, one was excluded
479 due to performance being near chance in the 'no flanker' condition, leaving
480 twenty-two participants (self-reported: 8 males, 2 left-handed, mean
481 age = 25 years, age range = 18-47). The same ethics criteria and
482 reimbursement as in Experiment 1 were implemented.

Stimuli and Procedure

484   The design of Experiment 2 was identical to that of the previous
485 experiment except for a few differences: 1) we manipulated centre to
486 centre target-flanker spacing (1.3°, 2°. 2.7°), 2) we tested only two flanker
487 locations (inner, outer), 3) the target and flanker stimuli had the same size
488 (1° of visual angle), and 4) we adjusted stimulus duration individually for
489 participants to equate the overall level of accuracy.

490   Prior to the main experiment, participants underwent a staircase
491 procedure in which stimulus duration was adjusted to ensure the selected
492 spacings corresponded to points close to the critical spacing. This

leverages the finding that critical spacing for crowding is modulated by stimulus duration, with longer exposure leading to a smaller zone of interference (Tripathy and Cavanagh, 2002; Tripathy et al., 2014; Soo et al., 2018). We used an adaptive staircase driven by the QUEST algorithm (Watson & Pelli, 1983) to estimate the stimulus duration at which each participant's average performance across conditions (excluding the no flanker condition) was 85% correct (duration mean = 106 ms, range: 42-200 ms). The estimate was computed with 80 trials, with the flanker configuration randomly drawn from the possible set of combinations excluding the no flanker condition. The maximum stimulus duration used was 200 ms to prevent eye movements. If QUEST indicated that a duration over 200 ms was required for a participant, then the staircase procedure was repeated. If this again yielded a display duration above 200 ms, the participant completed the main experiment at the maximum duration. During the main experiment, display duration was re-evaluated after each block and if accuracy was below 80% display duration was increased by one frame (8.3 ms) and if it was above 90% it decreased by one frame. Each condition was tested with 84 trials.

Results

Accuracy and reaction times across spacings and the corresponding FCEs are shown in Figure 3.
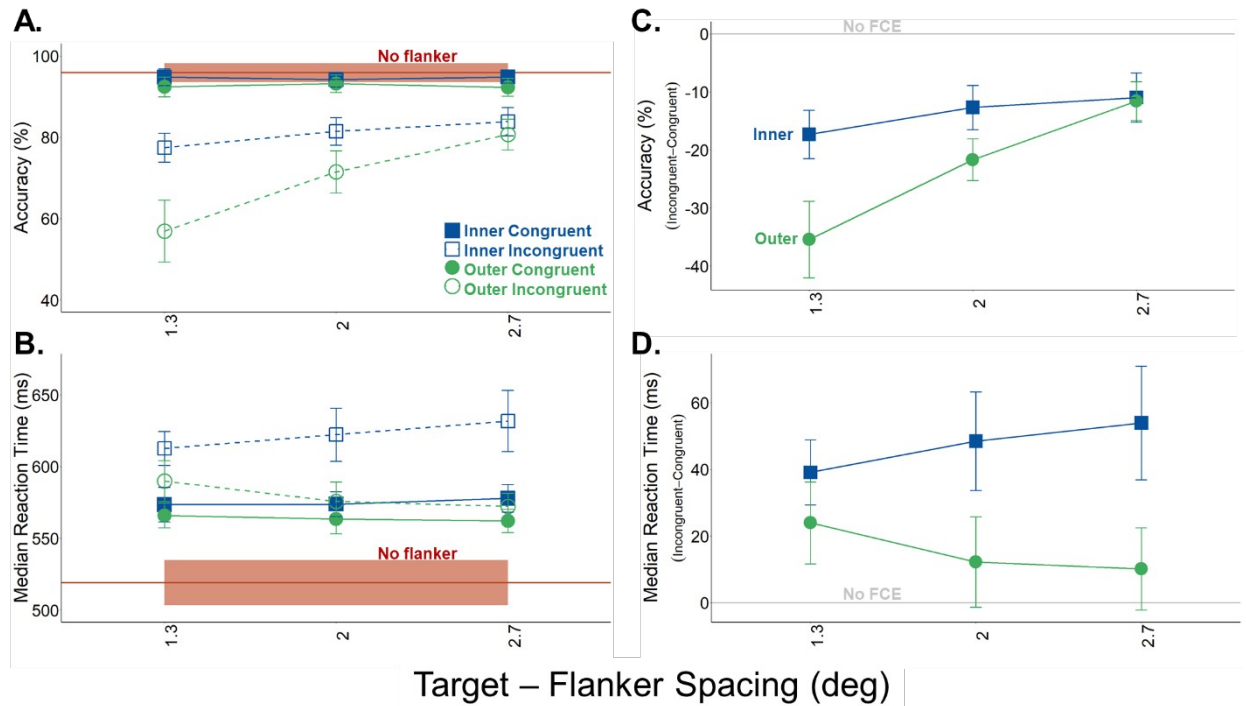
Figure 3: *Results from Experiment 2. Average accuracy and reaction times across participants as a function of target-flanker spacing with within-subjects 95% confidence intervals as error bars (Cousineau, 2005; Morey, 2008). Plots A&B show average performance where blue lines with square symbols represent performance in the presence of inner flankers and the green lines with the circle symbols represent performance in the presence of outer flankers. Solid lines and filled symbols represent the congruent trials and dashed lines with open symbols represent the incongruent trials. The solid red line with the shaded area is performance in the no flanker condition. Plots C&D show the difference in performance between the congruent and the incongruent conditions (incongruent-congruent). Here, more negative values for accuracy, and more positive values for reaction times represent stronger interference from incongruent flankers. Zero (no congruency effect) is represented with a solid grey line.*

We computed a three-way repeated measures ANOVA with factors *congruency* (congruent, incongruent), *flanker position* (inner, outer), and *target-flanker spacing* (1.3°, 2°, 2.7°) for accuracy and reaction times. Greenhouse-Geisser (GG) correction was applied for the factor *spacing* and its interactions due to the multiple levels of the factor. As expected, accuracy was higher in congruent trials compared to incongruent ($F(1,21)$ = 112.59, $p < 0.001$, = 0.84) (see solid lines compared to dashed lines in Fig. 3A), in the presence of inner compared to outer flankers ($F(1,21)$ = 14.63, $p < 0.001$, = 0.41) (see blue lines compared to green lines in Fig. 3A) and when target-flanker spacing increased ($F(1.48, 31.01)$ = 43.84, p

540 < 0.001, = 0.68). Accuracy was near ceiling in congruent trials, and thus
541 effects of *flanker position* and *target-flanker spacing* were mainly observed
542 in incongruent trials (see two-way interactions with *congruency* in Table
543 2). Accuracy dropped faster when outer flankers were closer to the target
544 (interaction *flanker position* x *target-flanker spacing* $F(1.82, 38.16)$ =
545 20.39, $p < 0.001$, = 0.49), but this was the case only in incongruent trials
546 (three-way interaction: $F(1.33, 27.93) = 29.96$, $p < 0.001$, = 0.59). This
547 drop in accuracy at closer target-flanker distances, which is more
548 pronounced for the outer flanker, is the typical pattern observed in
549 crowding. The fact that this was only observed for incongruent trials (and
550 that it therefore shows up as an interaction with *congruency* in the
551 analysis) is most likely because pooling or substitution was likely to yield a
552 percept associated with the incorrect response only with incongruent, but
553 not congruent, flankers: in congruent trials, the "clock hands" of target
554 and flankers all point in the same overall direction, but in incongruent
555 trials this is not the case).

556   Reaction times were also faster in congruent compared to
557 incongruent trials ($F(1,21) = 21.09$, $p < 0.001$, = 0.50) (see solid lines
558 compared to dashed in Fig. 3B). Surprisingly, they were also faster in trials
559 with outer compared to inner flankers ($F(1,21) = 23.34$, $p < 0.001$, = 0.52)
560 (see green lines compared to blue in Fig. 3B). The FCE was stronger in the
561 presence of inner compared to outer flankers (interaction *congruency* x
562 *flanker position*: $F(1,21) = 14.21$, $p < 0.001$, = 0.40). Increasing spacing
563 had opposite effects on reaction time FCE with inner and outer flankers
564 (interaction *congruency* x *flanker position* x *spacing*: $F(1.92, 40.39) = 3.33$,
565 $p = 0.007$, = 0.23): in the presence of outer flankers, increasing spacing
566 reduced the reaction time FCE whereas it increased for inner flankers (see
567 blue line compared to green in Fig. 3D). This unexpected pattern seems
568 easier to comprehend when considering the data in terms of flanker
569 eccentricity (i.e., the largest spacing for the inner flanker corresponds to
570 the smallest flanker eccentricity and the largest spacing for the outer
571 flanker to the largest eccentricity), as opposed to target-flanker spacing:

572 the larger the flanker eccentricity, the smaller the FCE (Fig. 3D). For the
573 full set of comparisons see Table 2.

574 In summary, our data confirmed that we successfully manipulated
575 crowding: accuracy decreased with decreasing target-flanker spacing.
576 This effect was more pronounced for outer flankers, reflecting the
577 established inner-outer asymmetry in crowding. We also confirmed the
578 unexpected finding of Experiment 1, that the inner-outer asymmetry is
579 reversed for the congruency effect in terms of reaction times, with inner
580 flankers producing stronger interference. Finally, Experiment 2 revealed a
581 new, unexpected effect in the form of an interaction: target-flanker spacing
582 had opposite effects on reaction time FCE for inner and outer flankers:
583 whereas smaller spacings led to larger reaction time FCE for outer
584 flankers, it led to smaller reaction time FCE for inner flankers.

585 Table 2: Statistics for data from Experiment 2. *Three-way repeated measures*
586 *ANOVA with factors Congruency (congruent/ incongruent), Flanker position*
587 *(inner/outer), and Target-flanker spacing (1.3°, 2°. 2.7°)}. Greenhouse-Geisser (GG)*
588 *correction has been applied for spacing and its interactions.*

	Accuracy				Reaction Time (correct)			
	DFn, DFd	F	p		DFn, DFd	F	p	
Congruency	1, 21	112.59	**< 0.001**	0.84	1, 21	21.09	**< 0.001**	0.50
Flanker Position (I/O)	1, 21	14.63	**< 0.001**	0.41	1, 21	23.34	**< 0.001**	0.52
TF Spacing	1.48, 31.01	43.84	**< 0.001**	0.68	1.46, 30.72	0.21	0.74	0.01
Congruency x Fl. Position (I/O)	1, 21	8.14	**< 0.001**	0.28	1, 21	14.21	**< 0.001**	0.40
Congruency x TF Spacing	1.53, 32.13	53.25	**< 0.001**	0.72	1.84, 38.7	0.02	0.97	0.00
Fl. Position (I/O) x TF Spacing	1.82, 38.16	20.39	**< 0.001**	0.49	1.78, 37.39	6.12	**0.007**	0.23
Congruency x Fl. Position (I/O) x TF Spacing	1.33, 27.93	29.96	**< 0.001**	0.59	1.92, 40.39	3.33	**0.047**	0.14

589

General Discussion

We examined the differences and similarities between crowding and the Flanker Compatibility Effect (FCE) in the Eriksen flanker task over two experiments where the spatial arrangement of flankers was manipulated. In line with established effects in crowding, larger reaction time FCEs were found for radial compared to tangential flankers and for two compared to one flanker. These observations were made under conditions without crowding and thus do not simply signify a downstream effect of difficulties in object recognition. In sharp contrast, inner flankers produced a larger reaction time FCE than outer flankers, a pattern opposite to that commonly observed in crowding (Chakravarthi et al., 2021; Petrov et al., 2007; Shechter & Yashar, 2021). Interestingly, this pattern persisted even when flankers were moved close enough to cause crowding, although the difference in reaction time FCEs between inner and outer flankers was reduced under such conditions. Even more surprisingly, the reaction time FCE decreased when the inner flanker was closer to the target; that is, it produced less, not more, interference. This is the opposite of what was observed for the outer flanker. It is also contrary to what has been previously reported for both crowding (Wolford & Chambers, 1983; Pelli et al., 2004; Toet & Levi, 1992) and the Eriksen flanker task (Eriksen & Eriksen, 1975). As will be discussed later, this unexpected finding can possibly be explained by flanker eccentricity, rather than target-flanker spacing, being the more relevant factor here. In summary, our findings show similarities, and also pronounced differences, in the effects of the spatial layout of the stimuli on flanker interference in crowding and the Eriksen flanker task. Although it is possible to observe both phenomena under the same conditions, these differences present a clear demarcation between them.

Our results from Experiment 2 show that substantial flanker interference both in the form of crowding and FCEs can occur concurrently, as seen at the closest target-flanker spacing. That both phenomena can be observed together was not clear a priori: the Eriksen

622 flanker task is commonly conducted under conditions without crowding
623 and crowding studies typically neither manipulate flanker compatibility
624 nor report reaction times, thus providing no information on FCEs. One
625 could argue that crowding should attenuate the FCE, since it degrades
626 target identification at the very least, and the FCE depends on targets and
627 flankers being identified and categorised to opposite responses. Instead,
628 both effects seemed to be largely independent here, as the conditions with
629 the strongest crowding did not show an overall different level of FCE.

630   The radial-tangential anisotropy found in the FCE was in line with the
631 anisotropy found in crowding (e.g., Greenwood et al., 2017; Toet & Levi,
632 1992). Interestingly, the radial-tangential anisotropy is present in other
633 visual phenomena such as surround suppression (Petrov & McKee, 2006)
634 and redundancy masking (Yildirim et al., 2020 ,2021). This asymmetry
635 therefore might be a more general property of peripheral processes
636 (Greenwood et al., 2017; Nandy & Tjan, 2012). An alternative explanation
637 is that it is easier to process stimuli along the horizontal meridian
638 compared to other locations (Abrams et al., 2012; Carrasco et al., 2001,
639 2002, 2004). In our stimulus set up, radial flankers were presented on the
640 horizontal meridian, but tangential ones were not. Hence, the radial
641 flankers might have been processed better than tangential ones leading to
642 a stronger FCE. This horizontal advantage might be due to the visual
643 system's inherent propensity for improved processing of a variety of
644 stimuli in specific spatial locations (for a review see Yashar & Carrasco,
645 2024) or might be reading related, which prioritises horizontal processing
646 (Martelli et al., 2009; Pelli et al., 2007).

647   An inner-outer asymmetry for the FCE was observed in our study but
648 with stronger interference from the inner than the outer flanker, which was
649 unexpected and contrary to that found in crowding. The presence of these
650 two asymmetries, radial-tangential and inner-outer, provides evidence that
651 flanker interference effects most likely arising in retinotopically organised
652 visual cortex affect the FCE, even when there is no crowding. However, in
653 contrast to radial-tangential anisotropy, the inner-outer asymmetry

654 appears to be unique to crowding and indeed has been used as a diagnostic
655 tool for crowding to distinguish it from other visual phenomena (Pelli et al.,
656 2004). Taken together, the above findings suggest that the FCE may
657 partially result from stimulus interactions in the visual cortex, but that this
658 interference is distinct from that in crowding.

659   One of the few perceptual properties that has been known to modulate
660 the FCE is the spacing between the target and its flankers: as the
661 separation between them increases, the FCE decreases (Eriksen &
662 Eriksen, 1974). However, not many other perceptual factors seem to
663 influence the phenomenon. Miller (1991) tested the role of target-flanker
664 spacing, attentional focus, visual transients, and perceptual load and found
665 that the FCE is only dependent on the target-flanker spacing. Additionally,
666 conflicting findings have been reported on whether the FCE is affected by
667 colour similarity (Baylis & Driver, 1992) or not (Harms & Bundesen, 1983)
668 and grouping between target and nearby flankers, which have well-
669 established effects on crowding(Herzog & Manassi, 2015; Herzog et al.,
670 2016; Kooi et al., 1994; Rashal & Yeshurun, 2014; Scolari et al., 2007).
671 Therefore, the extent to which conflict during decision-making is affected
672 by perceptual manipulations in situations where identification is intact,
673 remains unclear. Since not many perceptual manipulations affect the FCE,
674 the radial-tangential anisotropy found in the current paper, is surprising. It
675 is plausible that there is something distinctive regarding spatial
676 properties, including target-flanker separation and spatial organisation, in
677 the FCE that is not translatable to other visual properties. It could be that
678 the spatial layout of targets and flankers affects the speed and strength of
679 identification processes, which then modulates decision-making.

680   Another intriguing finding of our study was that, in Experiment 2, the
681 FCE decreased with increasing spacing for the outer flanker but increased
682 for the inner flanker. On the face of it, this finding seems inexplicable.
683 However, this unexpected finding can be accounted for if we consider the
684 changes to the representation of the flanker stimulus at various
685 eccentricities as it changes with different target-flanker spacings. As the

686 target-flanker spacing increases for the inner flanker, it moves closer to the
687 fovea, resulting in a stronger neural representation due to cortical
688 magnification. However, when the target-flanker spacing increases for the
689 outer flanker, it moves further into the visual periphery, and hence its
690 representation is weakened. If one assumes that the FCE results from a
691 competition between target and flanker stimuli for response selection,
692 then the observed changes in the magnitude of the FCE are consistent with
693 the changes in the strength of the representation of the flanker stimulus as
694 a function of its eccentricity. The same explanation could also account for
695 the stronger FCE from two flankers and from radial than tangential
696 flankers in experiment 1, as the former benefit from being placed along the
697 horizontal meridian.

698   By comparison, in crowding, pooling theories provide an explanation
699 for the inner-outer asymmetry, where the outer flanker leads to more
700 interference than the inner one. Each visual area has neurons with
701 receptive fields that increase in size with increasing eccentricity.
702 Therefore, the further out in the periphery a stimulus is presented, the
703 bigger on average are the receptive fields of the neurons responding to it
704 (Freeman & Simoncelli, 2011). Consequently, the outer flanker is more
705 likely to fall within the same receptive field as the target compared to the
706 inner one (Chen et al., 2023; Dayan & Solomon, 2010; Pelli & Tillman,
707 2008; Shechter & Yashar, 2021; for review see: Rosenholtz et al., 2019).
708 When stimuli fall within the same receptive field of a neuron, their features
709 are "pooled" leading to crowding (Dayan & Solomon, 2010; Motter &
710 Simoni, 2007; Van Den Berg et al., 2010), which explains the stronger
711 crowding by the outer flanker than the inner one. Equivalently, the outer
712 flanker is closer to the target in terms of cortical distance than the inner
713 flanker and hence interferes more strongly (Pelli, 2008). Note that the
714 substitution theory of crowding can potentially also explain this asymmetry
715 by positing more spatial uncertainty for the outer, more peripheral, flanker
716 than for the inner one. Increased spatial uncertainty leads to more
717 confusion of features or whole objects leading to stronger crowding.
718 However, there is no consensus on whether there are more substitution

errors for the inner or the outer flanker. Strasburger and colleagues (Strasburger, 2014; Strasburger, 2020) show that even though the outer flanker might induce more crowding, more substitution errors are present for the inner flanker. That is, there seems to be more positional uncertainty for the inner flanker. These substitution errors for the inner flanker depend on eccentricity where the higher the eccentricity, the more substitution errors (Strasburger & Malania, 2013; Strasburger, 2014; Strasburger, 2020). However, more substitution errors have also been reported for the outer flanker compared to the inner as positional uncertainty is greater with increased eccentricity (Shechter & Yashar, 2021).

Our findings have practical value for studies investigating cognitive control using the Eriksen flanker task: placing the flanker, rather than the target, at or near fixation increases the magnitude of the FCE. This can yield higher power to detect interactions of the FCE with other factors, as is commonly studied in performance Yildirim(Debener et al., 2005; Steinhauser & Andersen, 2019) or conflict monitoring (Yeung et al., 2004) experiments, where the FCE is modulated by errors or response conflict (incongruent stimuli) on preceding trials. However, unlike the present experiments, it may be desirable to allow participants to focus attention on target positions under such circumstances, as the effects of interest may depend on selective attention (e.g. McDermott et al., 2017; Steinhauser & Andersen, 2019).

Conclusion

In conclusion, we studied interference from task-irrelevant visual stimuli ('flankers') through the Eriksen flanker task and visual crowding. In order to explore possible links between them, we examined whether well-established characteristics of crowding are also observable in the Eriksen flanker task. In line with crowding, we found that radial flankers induce stronger FCEs compared to tangential, and two flankers lead to stronger FCEs compared to one flanker. In contrast, we observed an inner-outer asymmetry where interference was stronger from the inner compared to

the outer flanker, which is the opposite direction of the asymmetry observed in crowding. This highlights the differences in the mechanisms that lead to the two phenomena. We propose that changes in the strength of flanker representation due to its position in retinotopic space can account for its potency to induce a FCE. Consequently, unlike in crowding where outer flankers interfere most with visual processing, inner flankers drive stronger response selection conflicts. These findings show that the visuo-spatial configuration of objects affects downstream response conflict while also highlighting a clear demarcation between crowding and response compatibility effects.

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