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Distinct Spatial Patterns of Flanker Interference Differentiate Visual Crowding From Flanker Compatibility Effects in the Eriksen Task

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Recognizing 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 (FCEs). Whereas crowding is a visual phenomenon that reflects a breakdown of object recognition in clutter, the conflict in the Eriksen flanker task is generally thought to occur during decision-making. In two experiments, we investigated if and how these two seemingly independent phenomena are related. We employed an orientation categorization 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 with tangentially placed ones and for two compared with 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 the 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.

Public Significance Statement
Our world is filled with multiple objects, some of which are relevant to our current goals and others are not and might even be detrimental. The irrelevant objects often impair our ability to process relevant ones. This interference has been studied separately in the fields of perception and cognition, primarily through the phenomena of visual crowding and flanker compatibility effects, respectively, leading to distinct conclusions about their mechanisms. Here, we sought to find the link between the two approaches and found that although there are similarities between them in the form of visual processing modulating later stages, there are also clear differences, highlighting the separation between the two stages.

Keywords: Eriksen flanker task, flanker compatibility effect, crowding, spatial asymmetries, visual processing

The visual environment is frequently cluttered. To successfully navigate and interact in it, irrelevant information needs to be filtered out from the relevant. However, irrelevant and potentially conflicting nearby information ("flankers") often interferes with

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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 (EFT; Eriksen & Eriksen, 1974), respectively. Although 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 suboptimal sensory information.

Crowding

Crowding is a breakdown of object recognition in clutter, that is, an object that can be accurately identified in isolation becomes unrecognizable 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 use from peripheral vision (Levi, 2008; Pelli & Tillman, 2008) and is thought to result from interference at the visual processing stage (Greenwood et al., 2010; Harrison & Bex, 2015; Parkes et al., 2001). Some of the salient characteristics of crowding are that its strength increases with (a) decreasing target–flanker distance (e.g., Pelli et al., 2004; Toet & Levi, 1992; Wolford & Chambers, 1983) and (b) increasing eccentricity (Bouma, 1970; Toet & Levi, 1992). Flankers beyond a certain distance from the target no longer interfere with it. This distance is commonly termed the critical spacing (Pelli & Tillman, 2008). Critical spacing is largely proportional to eccentricity and has been estimated to be roughly half the eccentricity of the target from fixation (Bouma, 1970). This proportionality has been recognized in the literature as the Bouma Law (Pelli & Tillman, 2008). However, critical spacing is not constant: it is systematically affected by various manipulations and can be substantially larger or smaller than half the eccentricity under certain conditions (Soo et al., 2018; Scolari et al., 2007; van der Burg et al., 2017; for a review, see Strasburger, 2020).

Numerous accounts attempt to capture the mechanisms underlying visual crowding (Strasburger et al., 1991). The main proposals associated with crowding are *pooling*, *substitution*, *selective attention*, and *grouping* (Tyler & Likova, 2007). Pooling theories posit that under crowded conditions, target and flanker features are averaged (Balas et al., 2009; Keshvari & Rosenholtz, 2016; Parkes et al., 2001; Pelli et al., 2004). Each visual area has neurons with receptive fields that increase in size with increasing eccentricity. Therefore, the further out in the periphery a stimulus is presented, the bigger, on average, the receptive fields of the neurons responding to it (Fang & He, 2008; Levi et al., 1985; Pelli, 2008; for review see Strasburger et al., 2011). When multiple stimuli fall within the same receptive field, their features are "pooled" resulting in crowding (Dayan & Solomon, 2010; Motter & Simoni, 2007; Van Den Berg et al., 2010; Wolford, 1975). Crowding is stronger in the periphery than at fixation, as targets and flankers need to be much farther apart in order not to fall within the same receptive field (Freeman & Simoncelli, 2011; however, see Wallis et al., 2019). In contrast, substitution theories argue that crowding results from mistaking the location of a target or its features 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). Previous research has also shown that a common process can produce results resembling substitution, pooling, and object-level crowding (Dakin et al., 2010; Harrison & Bex, 2015). A third account is a limitation of selective attention. Selective attention serves to focus processing resources on relevant stimuli and attenuate the influence of irrelevant stimuli. It has been argued that attention has a minimal resolution and objects separated by less than this spacing cannot be individuated separately, leading to crowding (Chakravarthi & Cavanagh, 2007, 2009; He et al., 1996; Põder, 2007). Others have proposed that attention modulates crowding (Bowen et al., 2023; Huckauf & Heller, 2002; Kewan-Khalayly et al., 2022; LaBerge et al., 1991; Mareschal et al., 2010; Scolari et al., 2007; Strasburger, 2005; Strasburger & Malania, 2013; Yeshurun & Rashal, 2010). Finally, some have argued that crowding is not a low-level bottleneck resulting from limitations in attentional or neural processing resolution. Instead, it is a segmentation problem, where targets and flankers, when grouped, cannot be independently processed, whereas equally close flankers that do not group with the target do not lead to crowding (Chicherov & Herzog, 2015; Herzog & Manassi, 2015; Saarela et al., 2010). This proposal invokes top–down recurrent processing that allows the target to be segregated from its flankers without loss of fine-grained information in the early visual cortex.

Eriksen Flanker Task

The EFT (Eriksen & Eriksen, 1974) is a conflict task in which a target stimulus and nearby flankers may evoke the same or opposing behavioral 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. In the EFT, a target is presented at or near the fovea. Participants are asked to categorize it into one of two (or more) groups or responses. The target is often flanked by task-irrelevant items, which might either have the same response (i.e., belong to the same group) as the target (congruent) or have an opposite response (i.e., belong to another group; incongruent). Reaction times (RTs) are slower for incongruent trials compared with congruent trials or in the presence of neutral flankers. The difference in RTs between congruent and incongruent trials in this task is known as the FCE, where larger FCEs indicate stronger interference induced by the flankers on the target (e.g., Miller, 1991). The EFT 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 aging (Reuter-Lorenz & Cappell, 2008). Accordingly, there are many variations of the basic paradigm outlined earlier, which include, for example, simplified versions where each target group only contains a single stimulus (Botvinick et al., 1999), use of more than two types of flankers (e.g., congruent, incongruent, and neutral), and variations

with four-way response choices allowing for the distinction between flanker-related and nonflanker-related errors (Maier et al., 2011). In contrast to crowding, in the EFT, the identity of both the target and flankers can be accurately identified. The FCE in the EFT has been interpreted as arising at visual and decision-making stages of processing, with varying conclusions about the extent to which each stage contributes to the observed interference. On one hand, the identities of the target and flankers have to be processed for the conflict to arise, which results primarily from the congruency (or its lack) in responses. Furthermore, manipulations of perceptual stimulus properties, such as attentional focus, visual transients, and perceptual load, do not modulate the FCE (Miller, 1991). Hence, this conflict has been predominantly interpreted to occur during the decision-making stage (Egeth & Santee, 1981; Eriksen & Eriksen, 1974; Harms & Bundesen, 1983; Sanders & Lamers, 2002). On the other hand, certain stimulus properties such as target–flanker spacing, grouping, and color similarity seem to modulate the FCE (Baylis & Driver, 1992; Bjork & Murray, 1977; Braem et al., 2014; Kornblum et al., 1990; Jeong & Cho, 2019; Lee & Cho, 2013). Therefore, the visual processing stage might play a more important role in the FCE than originally considered (Eriksen & Schultz, 1979).

There is a tradition of interpreting the FCE as arising from an attentional selection process (Kelber et al., 2023). These proposals seem to mirror the distinction in attributing the FCE to visual processing versus decision-making stages. Specifically, two computational models invoking attentional selectivity over time as a source of the FCE are the shrinking spotlight model and the dual-stage two-phase model (Grange, 2016). The shrinking spotlight model argues that, over time, spatial selective attention gradually spatially shrinks toward fixation (White et al., 2011). Thus, it would initially also select the flankers and allow the activation of its associated response, leading to conflicts. In contrast, the dual-stage two-phase model argues that selective attention is poor and broad at the initial stage, where response conflicts can arise between a target and its flankers. Later, at a discrete point in time, attention suddenly becomes narrowly focused on the target (or sometimes the flanker), eliciting the response associated with that object (Hübner et al., 2010). A consensus has not been reached as to which model is a better explanation of the FCE. This debate between the two models resembles the distinction on whether there is continuous interference all the way from the visual perception stage through decision-making or whether the two stages are discrete and interference occurs solely in response selection.

Relatedly, a key debate has been regarding the locus of attention associated with the FCE (Yantis & Johnston, 1990). The locus is determined by whether the selection of the stimulus occurs before (early selection) or after (late selection) identification. Because the FCE results from the interference that the identities of the flankers have on the target, it would suggest that selection occurs after both the target and flankers have been identified. Most of the research on the FCE favors the late selection proposal (Yantis & Johnston, 1990). However, there is some evidence for interference occurring during early visual processing and hence for early attentional selection being the underlying cause. The target is often presented at the center of vision in between flankers, placing it in the optimal attentional position for early selection to occur. In a feature-based variation of the EFT, attentional modulation of stimulus processing in early visual cortex was found to be predictive of response errors (Steinhauser & Andersen, 2019). Furthermore, posterror adjustments of early attentional selection were tightly linked with behavioral performance on the subsequent trial. These findings support the case for early selection as a source of the FCE. Overall, the source and mechanisms of interference in the EFT remain highly debated.

The Relationship Between Crowding and the FCE

Crowding and the FCE in the EFT have often been treated and examined separately in the literature. However, when comparing them, it is clear that they share several characteristics. Even though they are investigated in different contexts, both examine how irrelevant information interferes with relevant information in our visual field and have employed comparable experimental approaches. In addition, both fields of research have tested the role of target–flanker spacing. In both crowding (e.g., Bouma, 1970; Pelli et al., 2004; Toet & Levi, 1992; for reviews, see Levi, 2008; Whitney & Levi, 2011), and the FCE in the EFT (Eriksen & Eriksen, 1974; Kelber et al., 2023; Kramer & Jacobson, 1991), interference is stronger at closer than farther target–flanker spacings. Moreover, both phenomena appear to be modulated by target–flanker similarity, where interference is stronger between more similar objects (Crowding: Chakravarthi & Cavanagh, 2007; Kooi et al., 1994; Kennedy & Whitaker, 2010; Scolari et al., 2007; FCE: Baylis & Driver, 1992; Eriksen & Schultz, 1979). Although this relationship is well established in crowding, it is still debated in the FCE (Harms & Bundesen, 1983; Moore et al., 2021).

Nevertheless, the conditions under which the two phenomena have been studied also differ in some critical ways, suggesting that they might indeed have different boundary conditions where it is possible to observe only one or the other. Specifically, crowding has been predominantly studied in the visual periphery, using unspeeded identification responses and measured through identification accuracy (Levi, 2008; Pelli & Tillman, 2008; 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 categorization responses measured with RTs (for review see Ridderinkhof et al., 2021). Consequently, a clear separating line is that the EFT typically involves situations where flankers are outside the critical spacing of crowding, that is, where object identification is unproblematic, whereas crowding typically investigates situations in which flankers are close enough to impair object identification. The identification[1] 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, because the two phenomena are typically studied separately, it is unclear whether this is the case.

As mentioned earlier, 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 there are conflicting accounts for the

[1] "Identification" here does not necessarily entail conscious awareness of flanker identity, but response relevant flanker features must have been processed and identified up to a level where they can cause a response conflict.

FCE with predominant proposals attributing the interference to occur during decision-making (Eriksen & Eriksen, 1974; Eriksen & Schultz, 1979; Sanders & Lamers, 2002). It is therefore likely that flanker interference in the two phenomena occurs sequentially, but their interdependence 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 EFT, we studied the effect of the spatial configuration of targets and flankers, as aspects of this are known to affect both phenomena. Importantly, certain spatial effects have been argued to be unique to crowding and thus to be diagnostic in distinguishing it from other related phenomena (for a review, see Strasburger, 2020). For example, flanker interference in crowding depends not only on the target–flanker distance but also on the position of the flankers relative to the target. First, there is a radial-tangential anisotropy in peripheral vision for crowding (Toet & Levi, 1992): Radially presented flankers induce more crowding than tangential ones (e.g., Greenwood et al., 2017; Kurzawski et al., 2023; Kwon et al., 2014; Petrov & Meleshkevich, 2011; Toet & Levi, 1992; Van Den Berg et al., 2010; Wolford & Chambers, 1983). A second key property, which is considered to be a diagnostic criterion of crowding, is the inner–outer asymmetry (Banks et al., 1979; Chakravarthi et al., 2021; Petrov et al., 2007; Shechter & Yashar, 2021; for a review see Strasburger, 2020). In particular, and counterintuitively, flankers that are presented between the target and fixation (inner) induce less crowding than flankers presented further away from fixation than the target (outer). It has also been noted that crowding is stronger with two flankers compared with one (Bouma, 1970; Pelli et al., 2004).

In Experiment 1, we examined whether the FCE in a modified EFT also demonstrates (a) the inner–outer asymmetry, (b) the radial-tangential anisotropy, and (c) if two flankers interfere more than one. To ensure that these asymmetries and anisotropies were not simply due to crowding, crowding was eliminated by placing the flankers well outside the critical spacing, resulting in near ceiling accuracy. If the FCE and crowding were entirely independent phenomena, we would not expect the FCE to exhibit the established asymmetries and anisotropies observed in crowding under these circumstances (but manipulations of flanker positions may still affect overall performance). However, if the FCE were to follow the pattern seen in crowding, we would expect more flanker interference from (a) outer compared with inner, (b) radial compared with tangential and (c) two compared with one flanker. This would suggest that both phenomena might share some underlying mechanisms. In Experiment 2, we further examined the inner–outer asymmetry and tested it across multiple target–flanker spacings. Because 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 to provide insight into situations where decision-making is based on suboptimal visual information.

In summary, our two experiments seek to clarify the relationship between crowding and the FCE by establishing the extent to which manipulations of flanker positions affect both phenomena in similar ways. Depending on the outcomes, this may either provide cues toward shared underlying mechanisms or determine demarcations between these two phenomena, which have hitherto been studied independently.

Experiment 1

Method

Transparency and Openness

Transparency and Openness Data were collected in 2021 (Experiment 1) and 2022 (Experiment 2). Our Experiment scripts, data and data analysis for both experiments are available at (Papadaki et al. 2024): https://osf.io/5fgc4/overview?view_only=abe474927d9a44b6ad5d77b914e85ab1. The design and data analysis for the two experiments were not preregistered.

Participants

Experiment 1 tested 18 volunteer participants (self-reported: four males; two 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 before 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: (a) FCE (Barzykowski et al., 2022), (b) radial-tangential anisotropy (Kurzawski et al., 2023) in crowding, and (c) 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 ($n = 466$, $M = -44.2$ ms, $SD = 23.9$ ms; Barzykowski et al., 2022) has a standardized effect size ("delta," a standardized effect size in the Cohen's d family in which the standard deviation of the difference between conditions is used as the denominator) of 1.85, and hence $n = 7$ yields a power of 95% to detect the FCE. For the radial-tangential anisotropy, the mean difference between radial and tangential critical spacing at 5° eccentricity ($n = 50$, $M = 0.65$, $SD = 0.21$; Kurzawski et al., 2023) gives a delta effect size of 3.1; therefore, $n = 4$ will provide a power of 95% to detect the anisotropy. For the inner–outer asymmetry, the mean difference between in and out critical spacing at 7.5° eccentricity ($n = 38$, $M = 1.35$, $SD = .72$; Chakravarthi et al., 2021) gives a "delta" effect size of 1.87, where $n = 6$ yields power of 95%. Previous studies have typically used participant numbers in the range of 4–12. Here, we sought to determine if there would be any spatial asymmetries. Hence, to ensure that we were adequately powered, we chose to triple the number of participants suggested by the power analysis. However, the COVID-19 restrictions at the time of testing and the limited pool

of participants available then made recruitment challenging. Because our study was already powered sufficiently, we decided to limit our sample to triple the number required to detect the inner–outer asymmetry; hence, we tested 18 participants. These calculations were done using the power calculator provided by Gregory Francis (http://www1.psych.purdue.edu/~gfrancis/calculators/means_dependent_power.shtml).

Materials and Stimuli

The experiment was conducted on a Dell computer, using PsychToolbox extensions (Brainard, 1997; Kleiner et al., 2007) for MATLAB (Mathworks, Natick, MA). A Cambridge Research Systems 32″ Display++ LCD monitor set to 1,920 × 1,080 pixels resolution and 120 Hz refresh rate was used for stimulus presentation and viewed at 57 cm. Participants' head position was secured with a chin rest. The target and flanker stimuli were clock-like objects: a circle with an oval hand along the radius. The thickness of the widest point of the hand was equal to the thickness of the circle. A target clock with a diameter of 1.5° of visual angle was presented at an eccentricity of 4° on the horizontal meridian to the left or the right of the fixation cross. Two stimulus groups ("up" and "down") were created based on the orientation of the clock hand (Figure 1C). Each stimulus group had three orientations: up (45°, 90°, and 135°) and down (225°, 270°, and 315°).[2] The target appeared in isolation, with one or with two flanking clocks.

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

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

The luminance of target and flanker stimuli, the location cue, and the background were 9.03 cd/m^2, 66.76 cd/m^2, and 37.86 cd/m^2, respectively. Accordingly, Weber contrast[3] of targets, flankers, and the location cue was ±0.76, with targets and flankers having a negative contrast, and the location cue having a positive contrast.

Procedure

The fixation cross and location cues (one on each side of fixation) were presented on the screen throughout the experiment. In each trial, one of the six target clocks was presented unpredictably to the left or the right side of the fixation cross for 208 ms in isolation or surrounded by one or two flankers, in one of the six flanker position conditions. The flankers, when presented, were either both congruent or both incongruent relative to the target but never identical to each other or the target. The intertrial interval was randomly sampled between 808 and 1,208 ms. Participants were asked to perform a categorization task and indicate, by pressing the "up" or "down" arrow key, the group category of the target clock (see Figure 1). Participants were instructed to fixate at the center of the screen and respond as quickly and as accurately as possible. The short stimulus presentation duration was chosen to prevent eye movements. Maximum response time was set to 1,500 ms; if a response was not made within that time window, the next trial was presented, and the trial was counted as an error. At the end of each trial, participants received auditory feedback in the form of a beep for error responses. At the end of each block, average accuracy and RTs for that block were presented to participants. Participants proceeded to the next block after a self-paced break.

Each participant completed 1,176 trials across seven blocks. There were 168 different types of trials: two presentation sides (left and right), two response groups (up and down), three target identities within each group, two flanker congruency types (congruent and incongruent), and seven flanker positions (above, below, above and below, inner, outer, inner and outer, and no flanker). Each block included a single presentation of each type of trial, and all trials in each block were shown in random order. For the calculation of accuracy and median RT, we pooled responses across presentation side, response group and target identity. Accordingly, behavioral data were analyzed in terms of flanker position and congruency with 84 trials per condition, except for the no-flanker condition, which was tested with 168 trials. For each condition, the median RT was calculated from correct trials (93.7% of all trials).

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

Results

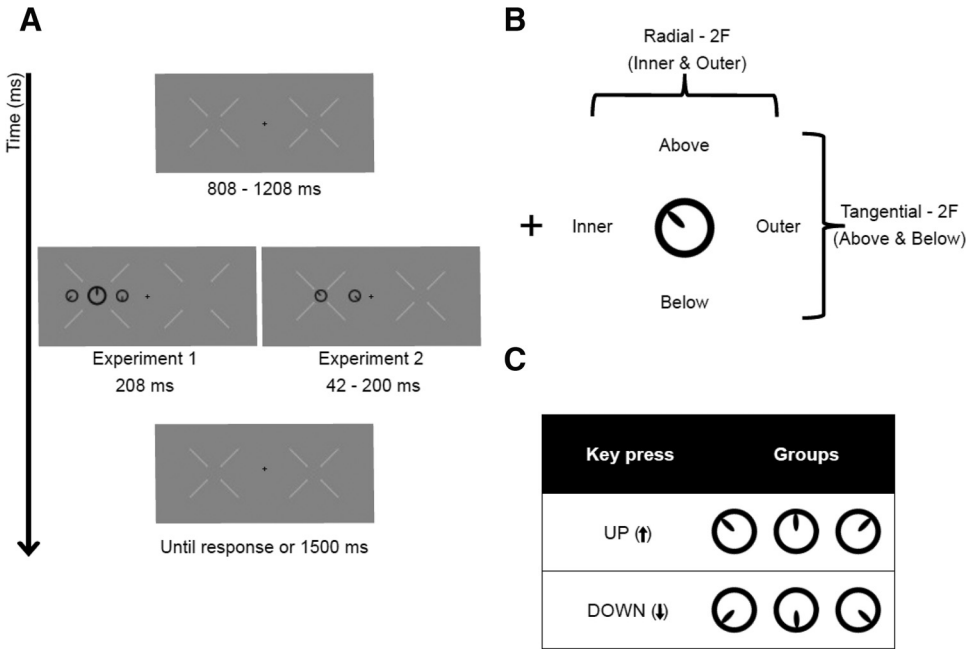
As intended, each participant's categorization accuracy reached or exceeded 90% in all conditions. Thus, flankers were presented outside the critical spacing defined as 90% of asymptote (Coates et al., 2018; Kurzawski et al., 2023; Scolari et al., 2007) and any

[2] Angles are given relative to the x-axis (0°) and increase in counterclockwise direction, as is usual in Cartesian coordinate systems.

[3] Weber Contrast C was calculated as $C = (I - I_b)/(I_b)$, where I is the luminance of the stimulus and I_b is the luminance of the background.

Figure 1

Experimental Trial Sequence, Flanker Configurations, and Response Mapping in Experiments 1 and 2



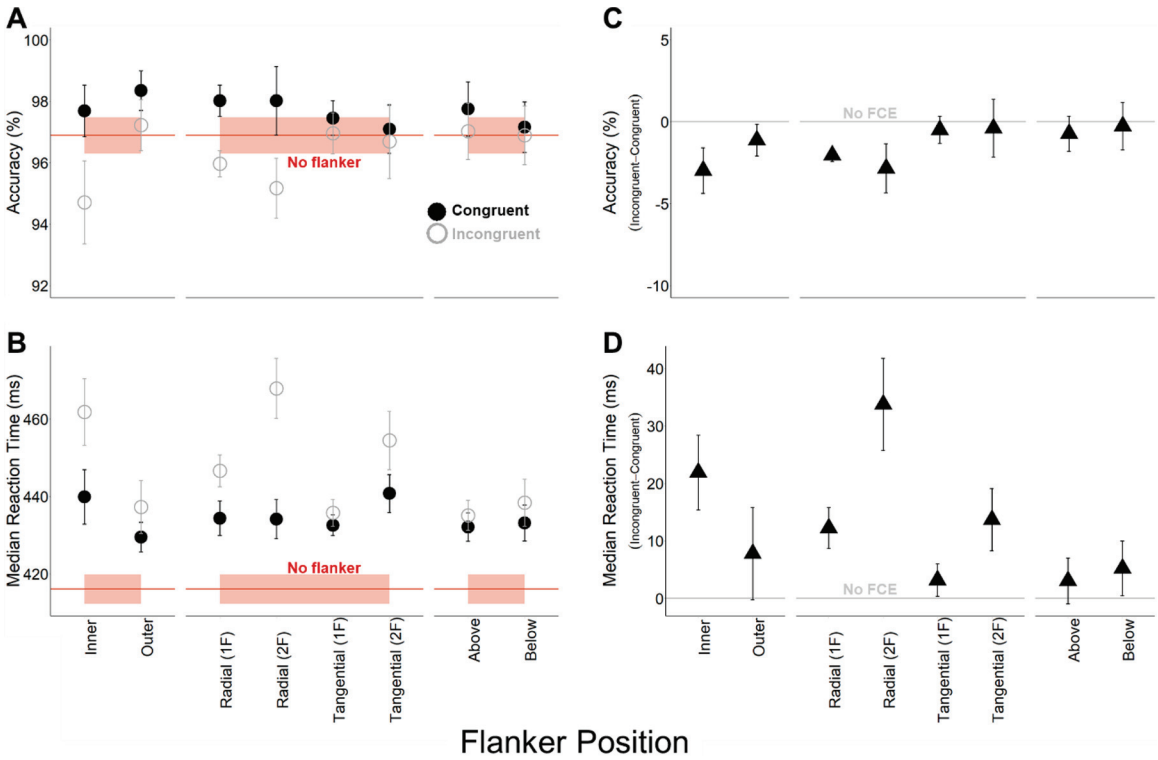
Note. (A) Example trial From Experiments 1 and 2 showing the sequence of events: Fixation, stimulus presentation and screen until response. Experiment 1: an incongruent trial showing flanker location "inner and outer." The correct response would be "up." Experiment 2: an incongruent trial showing flanker location "inner" at 2.7° target–flanker spacing. The correct response would be "up." (B) Representation of flanker positions. (C) Target groups and corresponding key responses. Participants were asked to perform a categorization task and indicate, by pressing an arrow key, the group of the target.

effects found, therefore, cannot simply be attributed to crowding as it is commonly defined experimentally. Categorization accuracy and median RTs, 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. In the following, analyses for both accuracy and RT data are reported; however, greater emphasis should be placed on the RT results as the accuracy data are constrained by possible ceiling effects by design.

In Experiment 1, we examined: (a) the inner–outer asymmetry, (b) the radial-tangential anisotropy and (c) interference from two compared with one flanker, in the FCE, as tested by the EFT. To evaluate the inner–outer asymmetry, we computed a two-way repeated-measures ANOVA with factors *congruency* (congruent and incongruent) and *flanker position* (inner and outer) for accuracy and RT. As expected, accuracy was higher in congruent than in incongruent trials, $F(1, 17) = 34.11$, $p < .001$, $\eta_p^2 = 0.67$, and interestingly it was higher with the outer than with the inner flanker, $F(1, 17) = 7.56$, $p = .01$, $\eta_p^2 = 0.31$. However, there was no significant interaction between the two factors, $F(1, 17) = 3.03$, $p = .10$, $\eta_p^2 = 0.15$. Therefore, in terms of accuracy, there was no significant inner–outer asymmetry for the FCE. However, it should be noted that accuracy was, as aimed for, near ceiling (Figure 2A, first panel), and thus the sensitivity to detect such an interaction, if it were there, would have been limited. RTs were also faster in congruent than in incongruent trials, $F(1, 17) = 99.86$, $p < .001$, $\eta_p^2 = 0.85$, and with outer than with inner flanker, $F(1, 17) = 20.21$, $p < .001$, $\eta_p^2 = 0.54$. However, here a two-way interaction between the factors showed that the FCE was stronger for the inner than for the outer flanker, $F(1, 17) = 5.02$, $p = .04$, $\eta_p^2 = 0.23$ (see Figure 2D, first panel). That is, (a) there was an inner–outer asymmetry for the FCE, observed in RTs, even when there was no crowding, and (b) surprisingly, this asymmetry was in the opposite direction to the one we would expect from crowding. For the full set of comparisons, see Table 1A.

To test for the radial-tangential anisotropy and the effect of the number of flankers, a three-way repeated-measures ANOVA with factors *congruency* (congruent and incongruent), *flanker position* (radial and tangential) and *flanker number* (one and two) was computed. Accuracy and RTs for radial and tangential for one flanker were computed by pooling across inner and outer and above and below flanker positions, respectively. Accuracy was again higher in congruent compared with incongruent trials, $F(1, 17) = 17.81$, $p < .001$, $\eta_p^2 = 0.51$, and there was an interaction between congruency and flanker location where the FCE was stronger for radial compared with tangential flanker positions, $F(1, 17) = 11.23$, $p = .003$, $\eta_p^2 = 0.40$ (see Figure 2A, middle panel). That is, a radial-tangential anisotropy was found in the same direction as seen in crowding. RTs were faster in congruent compared with

Figure 2
Results From Experiment 1



Note. 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) and (B) show average performance, where black filled circles represent performance in the congruent trials and grey open circles represent performance in the incongruent trials. The solid red line with the shaded area is performance in the "no-flanker" condition. Plots (C) and (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 flanker compatibility effect (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. See the online article for the color version of this figure.

incongruent trials, $F(1, 17) = 160.03$, $p < .001$, $\eta_p^2 = 0.90$, and with one compared with two flankers, $F(1, 17) = 67.27$, $p < .001$, $\eta_p^2 = 0.80$. A three-way interaction was found between congruency, flanker position, and number of flankers where the FCE, in terms of RTs, was larger in the presence of radial flankers compared with tangential flankers, and this effect was even more pronounced when there were two flankers present compared with one, $F(1, 17) = 5.04$, $p = .04$, $\eta_p^2 = 0.23$ (see Figure 2D, middle panel). For the full set of comparisons, see Table 1B. Therefore, we observed a radial-tangential anisotropy in the FCE with stronger interference from radial than tangential flankers; we also observed that FCE was stronger in the presence of two compared with one flanker. These findings were in line with what we would expect from crowding experiments.

Single flankers above or below the target induced slower RTs when they were incongruent compared with congruent, $F(1, 17) = 6.05$, $p = .02$, $\eta_p^2 = 0.26$. RTs did not differ depending on whether flankers were above or below the target and there was no interaction (Figure 2D, last panel). Accuracy showed neither main effects nor interactions for this manipulation. For the full set of comparisons, please see Table 1C.

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 (Pelli et al., 2004; Toet & Levi, 1992). 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 the spatial organization of the flankers does modulate the FCE and that it had a specific pattern. There were some similarities between crowding and the FCE, but there was also one major difference, which signifies a clear demarcation between the two phenomena and possible underlying mechanisms.

Table 1
Statistics for Data From Experiment 1

Effect	Accuracy			Reaction time		
	$F(1, 17)$	p	η_p^2	$F(1, 17)$	p	η_p^2
A. Inner–outer (I/O) asymmetry						
Congruency	34.11	**<.001**	0.67	99.86	**<.001**	0.85
Flanker position (I/O)	7.56	**.01**	0.30	20.21	**<.001**	0.54
Congruency × Fl. position (I/O)	3.03	.10	0.15	5.02	**.04**	0.23
B. Radial-tangential (R/T) anisotropy and one vs. two flankers						
Congruency	17.81	**<.001**	0.51	160.03	**<.001**	0.90
Flanker position (R/T)	1.25	.28	0.07	2.15	.16	0.11
Number of flankers	1.22	.29	0.07	67.27	**<.001**	0.80
Congruency × Fl. position (R/T)	11.23	**.003**	0.40	23.27	**<.001**	0.58
Congruency × number of flankers	0.21	.65	0.01	30.39	**<.001**	0.64
Fl. position (R/T) × number of flankers	0.14	.71	0.01	0.56	.46	0.03
Cong × Fl. position (R/T) × number of flankers	0.74	.40	0.04	5.04	**.04**	0.23
C. Above–below (A/B) flanker positions						
Congruency	1.15	.30	0.06	6.05	**.02**	0.26
Flanker position (A/B)	7.81	.39	0.04	0.61	.44	0.03
Congruency × Fl. position (A/B)	2.66	.61	0.02	0.42	.53	0.02

Note. (A) Two-way repeated-measures ANOVA with factors congruency (congruent and incongruent) and flanker position (inner and outer flankers). and (B) Three-way repeated-measures ANOVA with factors congruency (congruent and incongruent), flanker position (radial and tangential), and number of flankers (one and two). and (C) Two-way repeated-measures ANOVA with factors congruency (congruent and incongruent) and flanker position (above and below). Bold p values indicate significance.

Experiment 2

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

Method

Participants

Experiment 2 tested 23 participants, one was excluded due to performance being near chance in the "no-flanker" condition, leaving 22 participants (self-reported: eight males, two left-handed, mean age = 25 years, age range = 18–47) to be included in the final analysis. The same ethics criteria and reimbursement policy as in Experiment 1 were implemented. We sampled slightly more participants in Experiment 2 out of concern that the increased task difficulty due to crowding might lead to more participants being excluded. However, this turned out to not be an issue, leaving a larger final sample than in Experiment 1.

Stimuli and Procedure

The design of Experiment 2 was identical to that of the previous experiment except for a few differences: (a) we manipulated center to center target–flanker spacing (1.3°, 2°, and 2.7°), (b) we tested only two flanker locations (inner and outer), (c) the target and flanker stimuli had the same size (1° of visual angle), and (d) we adjusted stimulus duration individually for participants to equate the overall level of accuracy.

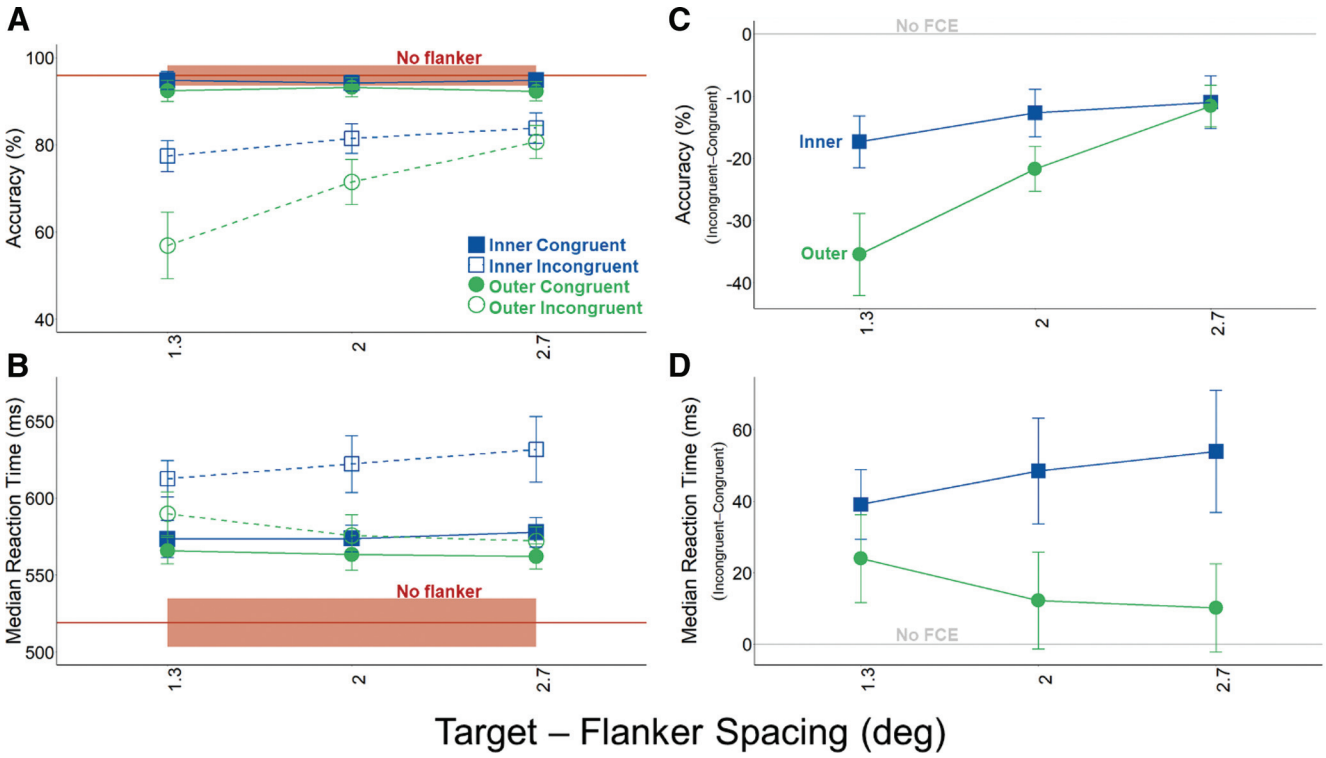
Before the main experiment, participants underwent a staircase procedure in which stimulus duration was adjusted to ensure the selected spacings corresponded to points close to the critical spacing. This leverages the finding that critical spacing for crowding is modulated by stimulus duration, with longer exposure leading to a smaller zone of interference (Tripathy & 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 M = 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 reevaluated 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 RTs across spacings and the corresponding FCEs are shown in Figure 3.

The mean accuracy across conditions was 86% (SD = 3.5), confirming the success of the staircase adjustment of stimulus duration to control overall task difficulty. We computed a three-way repeated-measures ANOVA with factors *congruency* (congruent and incongruent), *flanker position* (inner and outer), and *target–*

Figure 3
Results From Experiment 2



Note. 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) and (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) and (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. See the online article for the color version of this figure.

flanker spacing (1.3°, 2°, and 2.7°) for accuracy and RTs. Greenhouse–Geisser 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 with incongruent, $F(1, 21) = 112.59, p < .001, \eta_p^2 = 0.84$ (see solid lines compared with dashed lines in Figure 3A), in the presence of inner compared with outer flankers, $F(1, 21) = 14.63, p < .001, \eta_p^2 = 0.41$ (see blue lines compared with green lines in Figure 3A) and when target–flanker spacing increased, $F(1.48, 31.01) = 43.84, p < .001$, $\eta_p^2 = 0.68$. Accuracy was near ceiling in congruent trials, and thus effects of *flanker position* and *target–flanker spacing* were mainly observed in incongruent trials (see two-way interactions with *congruency* in Table 2). Accuracy dropped faster when outer flankers were closer to the target, interaction *flanker position* × *target–flanker*

Table 2
Statistics for Data From Experiment 2

Effect	Accuracy				Reaction time (correct)			
	DFn, DFd	*F*	*p*	η_p^2	DFn, DFd	*F*	*p*	η_p^2
Congruency	1, 21	112.59	**<.001**	0.84	1, 21	21.09	**<.001**	0.50
Flanker position (I/O)	1, 21	14.63	**<.001**	0.41	1, 21	23.34	**<.001**	0.52
TF spacing	1.48, 31.01	43.84	**<.001**	0.68	1.46, 30.72	0.21	.74	0.01
Congruency × Fl. position (I/O)	1, 21	8.14	**<.001**	0.28	1, 21	14.21	**<.001**	0.40
Congruency × TF spacing	1.53, 32.13	53.25	**<.001**	0.72	1.84, 38.7	0.02	.97	0.00
Fl. position (I/O) × TF spacing	1.82, 38.16	20.39	**<.001**	0.49	1.78, 37.39	6.12	**.007**	0.23
Congruency × Fl. position (I/O) × TF spacing	1.33, 27.93	29.96	**<.001**	0.59	1.92, 40.39	3.33	**.047**	0.14

Note. Three-way repeated-measures ANOVA with factors congruency (congruentor and incongruent), flanker position (inner and outer), and target–flanker spacing (1.3°, 2°, 2.7°). Greenhouse–Geisser correction has been applied for spacing and its interactions. Bold *p* values indicate significance.

spacing $F(1.82, 38.16) = 20.39$, $p < .001$, $\eta_p^2 = 0.49$, but this was the case only in incongruent trials, three-way interaction: $F(1.33, 27.93) = 29.96$, $p < .001$, $\eta_p^2 = 0.59$. This drop in accuracy at closer target–flanker distances, which is more pronounced for the outer flanker, is the typical pattern observed in crowding. The fact that this was only observed for incongruent trials (and that it therefore shows up as an interaction with *congruency* in the analysis) is most likely because pooling or substitution was likely to yield a percept associated with the incorrect response only with incongruent, but not congruent, flankers: in congruent trials, the "clock hands" of target and flankers all point in the same overall direction, but in incongruent trials this is not the case).

RTs were also faster in congruent compared with incongruent trials, $F(1, 21) = 21.09$, $p < .001$, $\eta_p^2 = 0.50$ (see solid lines compared with dashed in Figure 3B). Surprisingly, they were also faster in trials with outer compared with inner flankers, $F(1, 21) = 23.34$, $p < .001$, $\eta_p^2 = 0.52$ (see green lines compared with blue in Figure 3B). The FCE was stronger in the presence of inner compared with outer flankers, interaction *congruency* × *flanker position:* $F(1, 21) = 14.21$, $p < .001$, $\eta_p^2 = 0.40$. Increasing spacing had opposite effects on RT FCE with inner and outer flankers, interaction *congruency* × *flanker position* × *spacing:* $F(1.92, 40.39) = 3.33$, $p = 0.047$, $\eta_p^2 = 0.14$: In the presence of outer flankers, increasing spacing reduced the RT FCE, whereas it increased for inner flankers (see blue line compared with green in Figure 3D). This unexpected pattern seems easier to comprehend when considering the data in terms of flanker eccentricity (i.e., the largest spacing for the inner flanker corresponds to the smallest flanker eccentricity and the largest spacing for the outer flanker to the largest eccentricity), as opposed to target–flanker spacing: the larger the flanker eccentricity, the smaller the FCE (Figure 3D). For the full set of comparisons, see Table 2.

In summary, our data confirmed that we successfully manipulated crowding: accuracy decreased with decreasing target–flanker spacing. This effect was more pronounced for outer flankers, reflecting the established inner–outer asymmetry in crowding. We also confirmed the unexpected finding of Experiment 1, that the inner–outer asymmetry is reversed for the congruency effect in terms of RTs, with inner flankers producing stronger interference. Finally, Experiment 2 revealed a new, unexpected effect in the form of an interaction: target–flanker spacing had opposite effects on RT FCE for inner and outer flankers: whereas smaller spacings led to larger RT FCE for outer flankers, it led to smaller RT FCE for inner flankers.

General Discussion

We examined the differences and similarities between crowding and the FCE in the EFT over two experiments where the spatial arrangement of flankers was manipulated. In line with established effects in crowding, larger RT FCEs were found for radial compared with tangential flankers and for two compared with 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 induced a larger RT 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 magnitude of the inner–outer asymmetry in terms of RT FCE was reduced under such conditions. Even more surprisingly, the RT 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 (Pelli et al., 2004; Toet & Levi, 1992; Wolford & Chambers, 1983) and the EFT (Eriksen & Eriksen, 1974). 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 EFT. 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 obvious a priori: the EFT is commonly conducted under conditions without crowding, and crowding studies typically neither manipulate flanker compatibility nor report RTs, thus providing no information on FCEs. One could argue that crowding should attenuate the FCE, because it degrades target identification at the very least, and the FCE depends on targets and flankers being identified and categorized to different responses. Instead, both effects seemed to be largely independent here, as the conditions with the strongest crowding did not show an overall higher level of FCE.

Spatial Asymmetries

The radial-tangential anisotropy found in the FCE was similar to the anisotropy found in crowding (e.g., Greenwood et al., 2017; Toet & Levi, 1992). Interestingly, the radial-tangential anisotropy is present in other visual phenomena such as surround suppression (Petrov & McKee, 2006) and redundancy masking (Yildirim et al., 2020, 2021). This asymmetry therefore might be a more general property of peripheral processes (Greenwood et al., 2017; Nandy & Tjan, 2012). An alternative explanation is that it is easier to process stimuli along the horizontal meridian compared with other locations (Abrams et al., 2012; Carrasco et al., 2001, 2002, 2004). In our stimulus setup, radial flankers were presented on the horizontal meridian, but tangential ones were not. Hence, the radial flankers might have been processed better than the tangential ones, leading to a stronger FCE. This horizontal advantage might be due to the visual system's inherent propensity for improved processing of a variety of stimuli in specific spatial locations (for a review, see Yashar & Carrasco, 2025) or might be reading-related, which prioritizes horizontal processing (Martelli et al., 2009; Pelli et al., 2007). However, it is important to keep in mind that the same pattern of effects does not necessitate identical underlying causes. Accordingly, the unexpectedly large influence of the inner flanker (see Figure 2D) is likely to have contributed substantially to the observed radial-tangential anisotropy in RT FCE in Experiment 1.

An inner–outer asymmetry for the FCE was observed in our study but with stronger interference from the inner than the outer flanker, which was unexpected and contrary to that found in crowding. However, in contrast to the radial-tangential anisotropy, the inner–outer asymmetry appears to be unique to crowding and indeed has been used as a diagnostic tool for crowding to distinguish it from other visual phenomena (Pelli et al., 2004). Taken together, the above findings suggest that the FCE may partially result from stimulus interactions in the visual cortex, but that this interference is distinct from that in crowding.

One of the few perceptual properties that has been known to modulate the FCE is the spacing between the target and its flankers: as the separation between them increases, the FCE decreases (Eriksen & Eriksen, 1974). However, not many other perceptual factors seem to influence the phenomenon. Miller (1991) tested the role of target–flanker spacing, attentional focus, visual transients, and perceptual load and found that the FCE is only dependent on the target–flanker spacing. In addition, conflicting findings have been reported on whether the FCE is affected by color similarity (Baylis & Driver, 1992) or not (Harms & Bundesen, 1983) and grouping between target and nearby flankers, which have well-established effects on crowding (Herzog & Manassi, 2015; Herzog et al., 2016; Kooi et al., 1994; Rashal & Yeshurun, 2014; Scolari et al., 2007). Therefore, the extent to which conflict manifests in the FCE is affected by perceptual manipulations in situations where identification is intact, remains unclear. Because not many perceptual manipulations affect the FCE, the radial-tangential anisotropy found in the current article is surprising. It is plausible that there is something distinctive regarding spatial properties, including target–flanker separation and spatial organization, in the FCE that is not translatable to other visual properties. It could be that the spatial layout of targets and flankers affects the speed and strength of identification processes, which then modulates decision-making.

Another intriguing finding of our study was that, in Experiment 2, the FCE decreased with increasing spacing for the outer flanker but increased for the inner flanker. On the face of it, this finding seems inexplicable. However, this unexpected finding can be accounted for if we consider the changes to the representation of the flanker stimulus at various eccentricities as it changes with different target–flanker spacings. As the target–flanker spacing increases for the inner flanker, it moves closer to the fovea, resulting in a stronger neural representation due to cortical magnification. However, when the target–flanker spacing increases for the outer flanker, it moves further into the visual periphery, and hence its representation is weakened. If one assumes that the FCE results from a competition between target and flanker stimuli for response selection, then the observed changes in the magnitude of the FCE are consistent with the changes in the strength of the representation of the flanker stimulus as a function of its eccentricity. The same explanation could also account for the stronger FCE from two flankers and from radial than tangential flankers in Experiment 1, as the former benefit from being placed along the horizontal meridian.

By comparison, in crowding, pooling theories provide an explanation for the inner–outer asymmetry, where the outer flanker leads to more interference than the inner one. Each visual area has neurons with receptive fields that increase in size with increasing eccentricity. Therefore, the further out in the periphery a stimulus is presented, the bigger on average are the receptive fields of the neurons responding to it (Freeman & Simoncelli, 2011). Consequently, the outer flanker is more likely to fall within the same receptive field as the target compared with the inner one (Chen et al., 2023; Dayan & Solomon, 2010; Pelli & Tillman, 2008; Shechter & Yashar, 2021; for review, see: Rosenholtz et al., 2019). When stimuli fall within the same receptive field of a neuron, their features are "pooled" leading to crowding (Dayan & Solomon, 2010; Motter & Simoni, 2007; Van Den Berg et al., 2010), which explains the stronger crowding by the outer flanker than the inner one. Equivalently, the outer flanker is closer to the target in terms of cortical distance than the inner flanker and hence interferes more strongly (Pelli, 2008). Note that the substitution theory of crowding can potentially also explain this asymmetry by positing more spatial uncertainty for the outer, more peripheral, flanker than for the inner one. Increased spatial uncertainty leads to more confusion of features or whole objects, leading to stronger crowding. However, there is no consensus on whether there are more substitution errors for the inner or the outer flanker. Strasburger (2014, 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: the higher the eccentricity, the higher the substitution errors (Strasburger & Malania, 2013; Strasburger, 2014, 2020). However, more substitution errors have also been reported for the outer flanker compared with the inner as positional uncertainty is greater with increased eccentricity (Shechter & Yashar, 2021).

EFT, Crowding, and Perceptual Load

Load theory (e.g., Lavie & Tsal, 1994; Lavie, 1995) provides a framework for understanding differences in the magnitude of FCEs. According to this theory, effective early attentional selection depends on high perceptual load and physical separation between target and flanker stimuli. When perceptual load (e.g., number of items in display or processing demands for stimuli) is low, spare processing capacity is allocated to flankers, resulting in poor attentional selection and thus large FCEs. However, even with a large perceptual load, early selection requires sufficient physical (e.g., spatial) separation of stimuli.

Although Lavie and Tsal (1994) interpret a wide selection of studies that report dependencies of spatial target–flanker separation on FCEs within Load Theory, its application to our findings or crowding more generally seems less obvious. Crowding renders objects that are perfectly recognizable in isolation entirely unidentifiable in clutter (Levi, 2008; Pelli & Tillman, 2008). It thus reflects a much stronger perceptual effect than the load manipulations considered by Lavie and Tsal (1994). Importantly, crowding varies dramatically even when the number of objects on the screen (a proxy for perceptual load) does not change. In contrast, the effects of perceptual load are not a local interference process, as all displayed objects are often beyond the crowding distance of each other. Hence, despite some conceptual similarities, there are marked differences between crowding and manipulations of perceptual load.

We could, nevertheless, assume that increased crowding (closer target–flanker spacing) reflects higher perceptual load. In that case, we would expect smaller FCEs under conditions of strong crowding.

However, this contradicts our findings in Experiment 2, where stronger crowding was associated with larger FCEs for outer flankers.

Implications for Typical Eriksen Flanker and Crowding Tasks

There are substantial differences in the experimental design of studies investigating crowding and the EFT. This in itself does not, however, mean that the two phenomena are distinct: a person stepping on a bathroom scale to determine bodyweight and an astronomer investigating the motion of planets are both observing effects of gravity. Our experiments focused on the conceptual links between crowding and FCEs, and to allow for this, their design deviated in multiple ways from typical studies in either field. In the following, we will consider the possible implications of those methodological choices.

Compared with more typical implementations of the EFT, we presented stimuli in the periphery and randomly varied the target position between the left and right sides. Therefore, in our experiments, participants were not able to allocate attention to the target position as well as in a standard Eriksen paradigm, and thus effects mediated by attention may be weakened. In addition, the processing of inner flankers will have benefited from their lower eccentricity compared with the target, unlike more typical paradigms in which the target stimulus is presented centrally. Crowding is very weak in central vision, and thus, flankers will be well beyond the critical spacing in typical Eriksen flanker experiments.

In crowding experiments, flankers do not necessarily belong to any target set and thus may not induce a response conflict (but see Reuther & Chakravarthi, 2020). But even when they do, researchers commonly average data across such conditions, thereby obscuring any effects of response competition. Also, responses in crowding experiments are typically unspeeded and RTs are ignored in the analysis.

Due to these differences, it is likely that the effects of crowding and FCEs have been well-isolated in the vast majority of published studies, with the clearest separating line being that the FCE is typically studied in situations where flankers are outside the critical spacing, that is, where object identification is unproblematic, whereas crowding is studied in situations in which identification is impaired, but there is no categorization of the target stimulus. Therefore, our findings do not necessarily shift interpretations of the vast majority of studies. However, the reversed inner–outer asymmetry does establish a clear demarcation between both phenomena, which may be used to distinguish their effects when needed in future studies. It is worth noting that the reduced FCEs for outer flankers in our experiments may, at least in part, have been due to flankers becoming less visible at larger eccentricities. This could be counteracted by equating flanker visibility across eccentricities through, for example, contrast or size adjustments. However, the inner–outer asymmetry in crowding occurs robustly without such adjustment (Banks et al., 1979; Chakravarthi et al., 2021; Petrov et al., 2007; Shechter & Yashar, 2021), as was also observed here. In summary, the reversed inner–outer asymmetry demarcates the two phenomena, but future work is needed to identify the causes of this inner–outer asymmetry in FCEs, for example by equating flanker visibility across eccentricities

In more complex settings (e.g., the real world), the two phenomena may not be easily isolated. Therefore, a clearer understanding of interactions between crowding and FCEs will yield a better understanding of real-life situations where decision-making might be based on suboptimal visual information. For example, imagine driving on a rainy night. As the traffic light ahead turns green, a careless pedestrian starts to cross the street. Conflict tasks, such as the EFT, commonly employed in cognitive psychology, help us understand decision-making in such incongruent situations (traffic light: go; pedestrian: stop), but this perspective is less interested in the visual parameters of the scene (poor visibility). Research on visual perception (e.g., crowding), on the other hand, informs us of what the driver sees but is less interested in the resulting process of decision-making. Combining the two approaches allows us to understand such situations.

Our findings have practical value for studies investigating cognitive control using the EFT: 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 (Debener et al., 2005; Steinhauser & Andersen, 2019; Yildirim et al., 2020) 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 EFT and visual crowding. To explore possible links between them, we examined whether well-established characteristics of crowding are also observable in the EFT. In line with crowding, we found that radial flankers induce stronger FCEs compared with tangential, and two flankers lead to stronger FCEs compared with one flanker. In contrast, we observed an inner–outer asymmetry where interference was stronger from the inner compared with 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 the visual field can account for its potency to induce an 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 visuospatial configuration of objects affects downstream response conflict while also highlighting a clear demarcation between crowding and response compatibility effects.

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