# Visual search in 3D: Effects of monoscopic and stereoscopic cues to depth on the validity of Feature Integration Theory and Perceptual Load Theory

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## Conflict of interest statement

## Author contribution statement

CMG and BR designed the study, with the assistance of JB and AH. CMG programmed the experimental paradigms and conducted the statistical analysis. JB, AH, SK, SH and SK collected the data and assisted with analysis. CMG wrote the paper with BR. All authors approved the final manuscript.

## Keywords

## Abstract

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Previous research has successfully used feature integration theory to operationalise the predictions of Perceptual Load Theory, while simultaneously testing the predictions of both models. Building on this work, we test the extent to which these models hold up in a 3D world. In two experiments, participants responded to a target stimulus within an array of shapes whose apparent depth was manipulated using a combination of monoscopic and stereoscopic cues. The search task was designed to test the predictions of (a) feature integration theory, as the target was identified by a single feature or a conjunction of features and embedded in search arrays of varying size, and (b) perceptual load theory, as the task included congruent and incongruent distractors presented alongside search tasks imposing high or low perceptual load. Findings from both experiments upheld the predictions of feature integration theory, regardless of 2D/3D condition. Longer search times in conditions with a combination of monoscopic and stereoscopic depth cues suggests that binding features into three-dimensional objects requires greater attentional effort. This additional effort should have implications for perceptual load theory, yet our findings did not uphold its predictions; the effect of incongruent distractors did not differ between conjunction search trials (conceptualised as high perceptual load) and feature search trials (low perceptual load). Individual differences in susceptibility to the effects of perceptual load were evident and likely explain the absence of load effects. Overall, our findings suggest that feature integration theory may be useful for predicting attentional performance in a 3D world.

## Contribution to the field

Visual search is an important process in day-to-day life, used when searching for a particular fruit in the supermarket, searching for a friend in a crowded room or searching for a particular car in a busy car-park. Crucially, these activities all take place in a three-dimensional world, but cognitive models of visual search have relied on data from two-dimensional representations, such as tasks on a computer screen. In this study, we aimed to validate two influential models of visual search – feature integration theory and perceptual load theory - by establishing whether their predictions hold up if the stimuli are rendered in 3D. Feature integration theory proposes that visual features are automatically processed, and that attention is required to bind these features into objects. The predictions of this model were upheld in the present study, but we observed that binding monocular and stereoscopic cues to depth into a single 3D object requires additional attention. These data validate the use of feature integration theory in real world settings. We could not replicate the basic findings of perceptual load theory – which makes predictions about processing of distractor stimuli under attentionally demanding conditions – and so were not able to validate the model under 3D conditions.

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In review

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**Visual search in 3D: Effects of monoscopic and stereoscopic cues to depth on the validity of Feature**

**Integration Theory and Perceptual Load Theory**

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14    **Abstract**

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16    Perceptual Load Theory, while simultaneously testing the predictions of both models. Building on this

17    work, we test the extent to which these models hold up in a 3D world. In two experiments, participants

18    responded to a target stimulus within an array of shapes whose apparent depth was manipulated using

19    a combination of monoscopic and stereoscopic cues. The search task was designed to test the

20    predictions of (a) feature integration theory, as the target was identified by a single feature or a

21    conjunction of features and embedded in search arrays of varying size, and (b) perceptual load theory,

22    as the task included congruent and incongruent distractors presented alongside search tasks imposing

23    high or low perceptual load. Findings from both experiments upheld the predictions of feature

24    integration theory, regardless of 2D/3D condition. Longer search times in conditions with a

25    combination of monoscopic and stereoscopic depth cues suggests that binding features into three-

26    dimensional objects requires greater attentional effort. This additional effort should have implications

27    for perceptual load theory, yet our findings did not uphold its predictions; the effect of incongruent

28    distractors did not differ between conjunction search trials (conceptualised as high perceptual load)

29    and feature search trials (low perceptual load). Individual differences in susceptibility to the effects of

30    perceptual load were evident and likely explain the absence of load effects. Overall, our findings

31    suggest that feature integration theory may be useful for predicting attentional performance in a 3D

32    world.

33

34    **Keywords:** visual search, 3D, stereoscopic depth, monoscopic depth, feature integration, load theory,

35    distractor congruency

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**Contribution to the field statement** (max 200 words)

Visual search is an important process in day-to-day life, used when searching for a particular fruit in the supermarket, searching for a friend in a crowded room or searching for a particular car in a busy car-park. Crucially, these activities all take place in a three-dimensional world, but cognitive models of visual search have relied on data from two-dimensional representations, such as tasks on a computer screen. In this study, we aimed to validate two influential models of visual search – feature integration theory and perceptual load theory - by establishing whether their predictions hold up if the stimuli are rendered in 3D. Feature integration theory proposes that visual features are automatically processed, and that attention is required to bind these features into objects. The predictions of this model were upheld in the present study, but we observed that binding monocular and stereoscopic cues to depth into a single 3D object requires additional attention. These data validate the use of feature integration theory in real world settings. We could not replicate the basic findings of perceptual load theory – which makes predictions about processing of distractor stimuli under attentionally demanding conditions – and so were not able to validate the model under 3D conditions.

54      **Introduction**

55      In order to be useful, cognitive theories must be simplified models of a complex world, from which we

56      can derive specific predictions. In order to be meaningful, these models must also be scalable and

57      applicable to real world situations. Models of visual search are principally based around perception of

58      two-dimensional (2D) stimuli such as shapes on a computer screen, but are used to make inferences

59      about our interaction with the three-dimensional (3D) world around us. When attempting to test the

60      ecological validity of such models, researchers typically add complexity in a controlled manner, one

61      variable at a time. In this paper we attempt to scale two models of visual search – Treisman's feature

62      integration theory and Lavie's perceptual load theory– by incorporating monoscopic and stereoscopic

63      cues to depth into an existing paradigm in which both models can be tested simultaneously. Both

64      feature integration theory and perceptual load theory are simplified models of the type described

65      above, from which useful predictions about the world have been generated. By the simple addition of

66      a third dimension we literally add depth to the models, and test their validity in a three-dimensional

67      world.

68

69      *Feature Integration Theory*

70      Feature integration theory (Treisman, 1988; Treisman & Gelade, 1980) is a model of visual attention

71      in which perception occurs at the level of features rather than objects; once perceived, attentional

72      resources are required to bind features into coherent objects. While feature-level perception can and

73      does occur in parallel, the integration of features into objects occurs serially. The classic finding in

74      feature integration theory is therefore that reaction times for identifying objects on the basis of a

75      single feature (e.g. colour) are relatively unaffected by the number of distractor items in the search

76      array. In contrast, when items must be identified on the basis of a conjunction of features (e.g. colour

77      and shape) each item in the array must be processed in turn and reaction time to identify the target

78      will therefore increase linearly with the number of items in the array (Treisman & Gelade, 1980).

79  Feature integration theory has been supported by a plethora of research (see Humphreys, 2016;

80  Quinlan, 2003 for reviews), and while it has been partially subsumed into more comprehensive

81  theories (e.g. Desimone & Duncan, 1995; Duncan & Humphreys, 1989), it has undeniably made a

82  significant contribution to our understanding of visual attention. While early work using this model

83  was largely restricted to analysis of basic features such as colour and shape, subsequent work has

84  included dynamic features such as direction of motion (Dick et al., 1987; Thornton & Zdravković, 2020)

85  and axis of rotation (Schill et al., 2020). Recently, feature integration theory has been particularly

86  useful in the development of a concrete operationalisation of perceptual load.

87

88  *Perceptual load theory*

89  The premise of perceptual load theory (Lavie, 1995; Lavie et al., 2004) is that perceptual capacity is

90  limited, and that perceptual processing continues automatically until that capacity is filled. If a task or

91  scene imposes high perceptual load then, according to the model, all available capacity will be used

92  up in processing the central stimuli and no resources will be available to process additional distractor

93  stimuli. In contrast, if the task imposes a low level of perceptual load, leftover attentional resources

94  will 'spill over' and process peripheral or distractor stimuli. Thus, perceptual load theory predicts that

95  distractor perception will be reduced or eliminated under high perceptual load. This is typically

96  assessed using flanker tasks in which a peripheral distractor stimulus requires a response that is either

97  congruent or incongruent with the response to the target stimulus (Lavie, 2005). For example, a typical

98  paradigm requires participants to search an array of letters and report the presence of either an X or

99  an N. The search array is flanked by a distractor stimulus that may be response-congruent (e.g. an X

100  when the target is an X) or response-incongruent (an X when the target is an N). Distractor processing

101  is indicated by longer reaction times on incongruent trials because response competition between the

102  target and distractor must be resolved before a response can be made. While a substantial congruency

103  effect is expected under low perceptual load, this is predicted to be reduced or eliminated under high

104     load. In this standard paradigm, perceptual load is manipulated by varying the features of the non-

105     target items in the search array; in the low perceptual load condition, the target is presented in an

106     array of O's while in the high load condition the non-target items are angular letters such as M, H and

107     Z.

108     Although perceptual load theory has been influential over the past twenty years, the concept of

109     perceptual load has been criticised for its vagueness and lack of a clear operational definition (Murphy

110     et al., 2016). Murphy & Greene (2017b) recently described a series of experiments demonstrating that

111     the classic comparison in feature integration theory – between feature and conjunction searches –

112     could act as an operationalisation of perceptual load theory. The five experiments reported in that

113     paper tested the predictions of both feature integration theory and perceptual load theory within a

114     single paradigm, and found that both were upheld. Following Lavie (1995), Murphy & Greene noted

115     that feature and conjunction searches could be conceived of as low and high perceptual load tasks,

116     respectively. In the most basic form of their paradigm, participants search a visual array for a specific

117     target (a red triangle) and report its orientation while ignoring a distractor triangle whose orientation

118     may be congruent (i.e. both pointing up) or incongruent with the target (one pointing up, one pointing

119     down). The target is contained in a search array of between 2 and 10 items from which the target can

120     be discriminated on the basis of one feature (e.g. a red triangle in a field of yellow triangles) or on the

121     basis of a conjunction of features (e.g. a red triangle in a field of yellow triangles and red or yellow

122     squares). They observed that response times in this paradigm followed the typical pattern expected

123     of feature vs. conjunction searches, with fast responses to feature searches irrespective of the number

124     of distractors, and slower responses to conjunction searches that required a serial inspection of each

125     item in the array. The reaction time data also fit the predictions of perceptual load theory, with

126     reduced distractor congruency effects under high load compared with low load. Subsequent

127     experiments found similar results with this paradigm under a range of different conditions in which

128     the stimulus presentation time, distractor location and stimulus complexity were varied, leading

129     incrementally towards a more ecologically valid design. It has been suggested that the reduction in

distractor interference under high load conditions may sometimes be caused by the presence in the array of neutral items which share visual features with the distractor, and thus dilute its effects (Benoni & Tsal, 2013; Tsal & Benoni, 2010). The paradigm described above controls for dilution as both low load and high load displays contain neutral stimuli which share a feature (shape) with the distractor triangle. Low load and high load displays are thus differentiated only by whether the target can be identified on the basis of a single feature or a conjunction of features (see Murphy & Greene, 2017b for further discussion of dilution as it pertains to this paradigm).

*Ecological validity in a 3D world*

The lateral separation of human eyes means that each has a slightly different view of the world and the disparity between these views occurs along a single horizontal dimension. This binocular disparity is greater for objects that are closer to us than those that are farther away. Using this rule, the visual system can map objects along three dimensions of the visual field; a process referred to as stereoscopic vision or stereopsis (Qian, 1997). In an exploration of the function of stereoscopic depth perception, Read (2015) points to the understanding that predatory animals acquire superior ability to detect and distinguish camouflage in visually complex environments via binocular stereopsis. The importance of this ability is underscored by the finding that human participants with normal stereoscopic vision typically out-perform counterparts with reduced or no stereoscopic vision on visuomotor skills tasks (Mazyn et al., 2004; O'Connor et al., 2010). The influential two-stream hypothesis (Goodale & Milner, 1992) provided a neurological account of vision that separated such visuospatial information processing for visually guided behaviour (dorsal stream) from slower identification or recognition processes (ventral stream). Since then, reviews and critiques have rejected the extreme claim that these visual tasks are based on functionally independent neurological processing pathways (McIntosh & Schenk, 2009; Milner & Goodale, 2008). Despite mounting evidence for considerable crosstalk between streams (Milner, 2017), there is consensus that a less extreme

155 version of the two-stream hypothesis can be a useful model for generating hypotheses about visual

156 performance in the real world (Schenk & McIntosh, 2010) – the world is both something to be

157 perceived and something to be acted upon.

158

159 Stereoscopic vision (requiring two eyes) is not the only way the visual system derives spatial and depth

160 information from a visual scene. Monocular signals (such as shade colour, occlusion, size and elevation

161 in a plane) are common and powerful cues to depth (Howard & Rogers, 2002), allowing us to infer the

162 spatial relations of objects in three dimensions even from two dimensional representations, such as a

163 photograph. A limited number of previous studies within the feature integration theory paradigm have

164 previously shown how visual search can be improved by using monocular/pictorial cues to depth (e.g.

165 an illustration of a cube in which the faces are coloured to create the illusion of light and shade; Enns

166 & Rensink, 1990a; Enns & Rensink, 1990b; Zhang et al., 2015). These researchers compared response

167 times to the same set of polygons (squares and diamonds) arranged to give the impression of a 3D

168 cube or a 2D abstract pattern, and reported that search for the visually meaningful 3D cubes was faster

169 and less effortful than search for the 2D shapes. However, others have found that visual search was

170 negatively affected by the inclusion of monocular (pictorial) depth cues relative to simply presenting

171 the stimuli in 2D (Kyritsis et al., 2013). Another approach has investigated the way in which apparent

172 distance (or visual depth plane) acts as a visual feature (Plewan & Rinkenauer, 2016, 2017). For

173 example, a target in a search array could be identified on the basis of a single feature (its apparent

174 location relative to the viewer) or on the basis of a conjunction of features (e.g. a red shape at a

175 particular distance from the viewer). These studies have indicated that objects that appear to be closer

176 to the viewer are typically responded to more quickly. Yet, in a similar paradigm, Pomplun et al. (2013)

177 report no substantial effects of depth of plane on visual search strategy derived from eye movement

178 data. Finally a third body of work has explored visual search and foraging performance in dynamic

179 virtual reality 3D environments (Kristjánsson et al., 2020; Prpic et al., 2019), sometimes compared to

180 traditional 2D pictorial scenes (Li et al., 2016). The value of such studies includes the interaction of

181 visual search with memory and proprioceptive feedback from self-initiated whole body motion.

182

183 Importantly, previous research has not yet compared the effects of viewing the same stimuli in

184 monoscopic 2D and stereoscopic 3D on visual attention, or separated those effects from the role of

185 monocular cues to depth such as colour and shading. If stereopsis and other binocular cues to depth

186 (e.g. binocular convergence) improve our ability to act upon the world more precisely, they may

187 benefit performance in visually demanding experimental trials. On the other hand, if additional visual

188 features (depth plane, shading etc.) are required to produce a 3D percept, it follows that attention

189 must be deployed to bind these features together; this would result in slowed visual search for stimuli

190 containing these features.

191

192 *The present study*

193 In the present study we explore whether monocular and binocular cues to depth make unique

194 demands of the visual system that limit the ecological validity of feature integration theory and

195 perceptual load theory. We report two experiments, in which we replicated the paradigm used by

196 Murphy & Greene (2017b) in two and three dimensions, and operationalised high and low perceptual

197 load as conjunction and feature searches. In Experiment 1, dimensionality of the stimuli was

198 manipulated using a combination of monocular and binocular cues to depth, while in Experiment 2

199 monocular and binocular cues were independently manipulated. We carried forward Murphy and

200 Greene's hypotheses, including that the predictions of both feature integration theory and perceptual

201 load theory would be upheld. Specifically, feature integration theory predicts a significant interaction

202 of search type and array size, such that reaction time would increase with set size for conjunction but

203 not feature searches, and perceptual load theory predicts a significant interaction of perceptual load

204 and congruency, such that distractor congruency effects would be reduced or eliminated under high

205 perceptual load. It is unclear how the combination of monocular and binocular cues will affect search

206    performance. While previous research suggests that depth cues offer advantages for visuospatial

207    accuracy and visuomotor performance, results on the effects of depth on visual search identification

208    are mixed. If the binding of features denoting depth requires attentional resources, this might

209    constitute an additional source of perceptual load. Thus, we predict that the inclusion of depth cues

210    will result in increased reaction times, especially in conditions where both monocular and binocular

211    cues are provided.

212

**Experiment 1**

214

215 **Method**

216 *Participants*

217 Forty-two volunteers (17 male, 25 female) were recruited from the University College Dublin campus

218 to participate in the experiment. Participants were aged between 18-52 years ($M$ = 24.41 years, $SD$ =

219 6.79 years). All had normal or corrected-to-normal vision and all were screened for colour-blindness

220 and for stereoscopic depth perception.

221

222 *Apparatus*

223 The experiment was programmed and run using E-Prime 2.0 (Psychology Software Tools Inc.). A 47-

224 inch LG Smart Cinema 3D television screen (resolution = 1920 x 1080) was used to present the stimuli

225 in 2D or passive polarised stereoscopic 3D. To control for screen luminance effects, participants in both

226 the 2D and 3D groups wore passive-polarised 3D glasses designed for use with this television.

227

228 *Design*

229 The experimental design followed Murphy & Greene (2017b) and comprised a four-way ($2 \times 2 \times 5 \times 2$)

230 factorial design with three within-subjects variables (search type: conjunction/feature search,

231 distractor congruency: congruent/incongruent and array size: 2, 4, 6, 8 or 10 search items) and one

232 between-subjects variable (2D/3D). Participants were assigned to either the 2D or 3D condition

233 through the use of a true randomisation technique, i.e. a coin flip (Vickers, 2006), with the exception

234 of one participant who was assigned to the 2D group due to poor or no stereoacuity, and the final

235 participant who was assigned to the 2D condition to ensure equal sample sizes across groups.

236

237

238

*Task Stimuli*

240     The experiment involved the search for a target stimulus within an array, while ignoring a congruent

241     or incongruent distractor. In the 2D condition, participants were instructed to search for the target

242     (red triangle) in an array of yellow and red shapes presented to the left of a central fixation point (a

243     white cross), while ignoring a distractor to the right of the fixation point. Participants responded by

244     indicating whether the target triangle was pointing up or down (using the arrows on a keyboard).  In

245     feature search trials, the non-target stimuli in the search array were all yellow triangles, and the target

246     was thus distinguished by a single feature (colour). In conjunction search trials, the non-target stimuli

247     were red squares, yellow squares and yellow triangles; a conjunction of colour (red) and shape

248     (triangle) was thus required to distinguish the target. All shapes were created in Microsoft Office 365

249     ProPlus. The red shapes had an RGB value of (255, 0, 0) and the yellow shapes had an RGB value of

250     (255, 255, 0).

251

252     To supplement the binocular stereoscopic effect in the 3D condition, the above described stimuli were

253     adapted for the 3D condition to include apparent (monocular) depth cues; this was achieved by

254     replacing the standard two-dimensional stimuli (squares and triangles) with two-dimensional

255     representations of three dimensional objects (cubes and cones). Shading effects were used to create

256     the illusion of depth, as shown in Figure 1. RGB values for the front surface of the images, on which

257     light appeared to be shining, matched those of the 2D shapes (red: 255, 0, 0; yellow: 255, 255, 0). The

258     'shadowed' surfaces of the images had RGB values ranging from (255, 5, 5) to (184, 23, 23) for red

259     shapes and from (255, 255, 5) to (124, 124, 0) for yellow shapes. At a viewing distance of 140 cm, each

260     shape subtended 1.44 by 1.70 degrees of visual angle. The entire search array, presented to the left of

261     fixation, subtended between 2.1 x 3.4 (array size 2) and 6.5 x 7 degrees (array size 10). The distractor

262     triangle, presented to the right of fixation and subtending 1.08 by 1.34 degrees, was slightly larger

263     than the other shapes to guarantee distinctiveness and reduce eccentricity effects.

264

265    The target red triangle/cone could appear in an array of 2, 4, 6, 8 or 10 shapes and the orientation of

266    the distractor stimulus could be congruent (i.e. both pointing up or down) or incongruent with the

267    target (i.e. one pointing up and other pointing down). See Figure 1 for sample trials.

268

269                                    [Insert Figure 1 here]

270

271    *Procedure*

272    Participants were seated 140 cm from the television screen at a desk equipped with a keyboard. After

273    providing written consent, participants were instructed to don the 3D glasses and the task was

274    explained to them. All lighting in the laboratory was switched off during testing. Participants first

275    completed 30 practice trials and were given the opportunity to clarify the requirements of the task.

276    This also allowed the experimenter to confirm that the 3D effect was perceived by participants in the

277    3D condition. Participants then completed three blocks of 100 trials, comprising 15 repetitions of each

278    combination of search type, congruency and array size. Trials were presented randomly within blocks,

279    and participants were given the opportunity to take a break following completion of each block.

280    Participants were instructed to maintain fixation on the central white cross, and to respond to the

281    orientation of the target stimulus as quickly and accurately as possible. The stimuli in each trial

282    remained onscreen until a response was recorded. No performance feedback was provided.

283

284    The study protocol was approved by the Human Research Ethics Committee (Humanities) of University

285    College Dublin.

286

287    **Results**

288    All     data     are     available     in     the     Open     Science     Framework     repository,     at

289    https://osf.io/ep5gv/?view_only=7054f0862d074065baf07780aca26b8b. Data from one individual in

290    the 3D condition were removed from analysis as their accuracy across all conditions was below chance

291     (mean = 32%). Performance in the search task was generally very accurate, with mean accuracy among

292     the remaining 41 participants of 96.5% (SD = 3.6%).

293

294     Median reaction time (RT) for each participant was extracted for correct search trials within each

295     experimental condition. Median reaction time data are often preferred for such analyses as they are

296     less susceptible than mean data to the effects of outliers (Ratcliff, 1993). A 2 (search type) x 2

297     (distractor congruency) x 5 (array size) x 2 (2D/3D condition) mixed within/between-subjects ANOVA

298     was conducted. The full ANOVA results may be seen in Table 1.

299

300                             [Insert Table 1 here]

301

302     A main effect of search type was observed such that responses were slower in conjunction searches

303     (M = 728.99 ms, SE = 13.66) than feature searches (M = 677.98 ms, SE = 11.44). A main effect of array

304     size was also observed; planned contrasts showed a significant linear trend, indicating that RT

305     increased in line with the number of distractors in the array ($F_{(1, 39)}$ = 212.59, $p < .001$, $\eta_p^2 = 0.85$).

306     These main effects were qualified by a significant interaction, depicted in Figure 2. To investigate the

307     predictions of feature integration theory, a linear regression of response time against array size was

308     conducted for each search condition. Array size was a significant predictor of RT in both the

309     conjunction search task ($R^2$ = .26, $F_{(1, 408)}$ = 142.5, $p < .001$) and the feature search task ($R^2$ = .06, F

310     (1, 408) = 24.62, $p < .001$), however the conjunction search task had a slope of 20.85 ms/item, which

311     was significantly steeper than the feature search slope of 6.75 ms/item, $t(816)$ = 6.37, $p < .001$. Each

312     additional distractor in the display therefore increased reaction time by a greater magnitude in the

313     conjunction search than the feature search.

314

315     There was no significant difference in mean reaction time between participants in the 2D (M = 703.4

316     ms, SE = 17.3) and 3D conditions (M = 703.58 ms, SE = 17.72). There was also no main effect of

317    distractor congruency (congruent: M = 704.07 ms, SE = 12.68; incongruent: M = 702.92 ms, SE = 12.27)

318    and no interaction between congruency and search type/perceptual load, as would be predicted by

319    perceptual load theory. No other significant interaction effects were detected.

320

321                                    [Insert Figure 2 here]

322

323    **Experiment 1 Discussion**

324    Although the effects of array size and search type predicted by feature integration theory were

325    observed in this experiment, no effect of distractor congruency was observed. Decades of research

326    have reported robust congruency effects in perceptual load theory paradigms (Murphy et al., 2016),

327    suggesting that a visible distractor cannot be easily suppressed once perceived. We therefore

328    concluded that the distractor stimuli were not reliably perceived in this experiment. This may have

329    been due to the peripheral placement of the distractor; Beck and Lavie (2005) have observed that

330    distractors at fixation produce larger interference effects than distractors in the periphery. Moreover,

331    although participants were instructed to fixate on the central fixation cross throughout, it is possible

332    that the placement of the distractor in the periphery of a large display may have allowed participants

333    to shift their visual field (e.g. by turning their head) and exclude the peripheral distractor from view.

334

335    In addition, no main effect of 2D/3D group, and no interaction between group and any other variable

336    were observed in this experiment. There are two potential explanations for this finding: first, it is

337    possible that stereoscopic depth has no bearing on reaction time during visual search, and thus  has

338    no implications for the feature integration or perceptual load models. Alternatively, the peripheral

339    positioning of the distractor may also have undermined the stereoscopic effect produced by the LG TV

340    used in this experiment. Although the television manufacturers claim that the 3D effect should be

341    visible from a wide range of horizontal angles,  experimenters noted that the stereoscopic effect was

342    best viewed from directly in front of the screen and was somewhat compromised when viewing at a

343 different angle from behind the participant. To remedy these issues, we conducted a second

344 experiment using a centrally presented distractor, as employed in Murphy & Greene (2017b)

345 Experiment 3.

346 The design of Experiment 1 did not allow the effects of monocular and binocular cues to depth to be

347 distinguished, as flat shapes were always presented in the 2D condition and shaded shapes were

348 always presented in the 3D condition. Experiment 2 therefore includes independent manipulations of

349 stereoscopic depth (2D vs. 3D) and stimulus shading (flat vs. shaded shapes).

350 Finally, Experiment 1 employed a relatively small sample size and was thus somewhat underpowered.

351 This issue is also remedied in Experiment 2.

352

353

354

355 **Experiment 2(Murphy & Greene, 2017b)**

356 **Method**

357 *Participants*

358 One hundred and thirty participants (51 male, 79 female; age range 18 - 54 years; $M$ = 22.85, $SD$ =

359 6.72) were recruited from the University College Dublin campus. All participants had normal or

360 corrected-to-normal vision, none were colour-blind, and all were screened for stereoscopic depth

361 perception to ensure that participants allocated to the 3D condition had stereoscopic vision. Power

362 analysis using G*Power (Faul et al., 2007) indicated that this sample provided 80% power to detect

363 very small effects ($f$ values ranging from .03 to .06) in the within/between-subjects interaction terms;

364 power analysis assumed an average correlation of 0.9 among repeated measures, based on data

365 reported in Murphy & Greene (2017b). This sample provides 80% power to detect medium effects ($f$

366 = 0.25) in the between-subjects terms.

367

368 *Design*

369 This experiment employed a five-way (2 × 2 × 5 × 2 x 2) factorial design with three within-subjects

370 variables (search type, distractor congruency, and array size, as in Experiment 1) and two between-

371 subjects variables (stereoscopic depth: 2D/3D and stimulus shading: flat/shaded). Participants were

372 randomly allocated to view the task in monoscopic 2D or stereoscopic 3D, and to view either flat or

373 shaded shapes.

374

375 *Task stimuli*

376 In the task for Experiment 2, the distractor stimulus was presented in the centre of the screen

377 surrounded by a white box, with the target appearing among an array of shapes presented in a ring

378 around the distractor (see Figure 3). This adjusted the visual angle dimensions of the distractor which

379 now subtended 3.83 by 3.01 degrees. The entire search array subtended 10.2 x 8.68 degrees of visual

380 angle from a viewing distance of 140 cm.

381

382 **Procedure**

383 All other features of the design, task and procedure were identical to those used in Experiment 1.

384

385 [Insert Figure 3 here]

386

387

388 **Results**

389 All data are available in the Open Science Framework repository, at

390 https://osf.io/ep5gv/?view_only=7054f0862d074065baf07780aca26b8b. The data from one

391 participant were removed from analysis due a technical error during data recording. Mean search

392 accuracy for the remaining 129 participants was 97.3% (SD = 2.6%). Median RT for each participant

393 was extracted for correct search trials within each experimental condition. Overall median RT was

394 significantly longer in Experiment 2 (M = 731.94 ms, SD = 103.42) than Experiment 1 (M = 703.49, SD

395 = 78.26; t(128) = 3.124, p = .002), suggesting that the central placement of the distractor increased the

396 difficulty of the task.

397

398 A 2 (search type) x 2 (distractor congruency) x 5 (array size) x 2 (stereoscopic depth) x 2 (stimulus

399 shading) ANOVA was performed.  The full results of this analysis may be seen in Table 2. A main effect

400 of search type was observed, such that search was slower in high load/conjunction search trials (M =

401 766.26ms, SE = 10.50) than in low load/feature search trials (M = 697.62ms, SE = 7.88). A main effect

402 of array size was also observed, such that RT increased with each additional item in the array (2 items:

403 M = 681.48ms, SE = 7.77; 4 items: M = 700.08ms, SE = 8.14; 6 items: M = 725.66ms, SE = 8.58; 8 items:

404 M = 755.64ms, SE = 9.75; 10 items: M = 794.81ms, SE = 10.67). Critically, there was also a significant

405 interaction between search type and array size. Linear regression analysis showed that RT increased

406 with array size for conjunction trials ($R^2$ = .44, F(1,648) = 154.61, p < .001, slope = 26.13 ms/item) while

407 the slope stayed relatively flat for feature search trials ($R^2$ = .10, F(1,648 = 6.87, p = .01, slope = 3.98

408 ms/item); the slope of the line was significantly steeper in the conjunction search condition, t (1296)

409 = 8.54, p < .001. Thus, the predictions of feature integration theory were upheld.

410

411 A significant effect of distractor congruency was observed; RTs were slower in incongruent trials (M =

412 744.47 ms, SE = 9.33) than congruent trials (M = 719.41 ms, SE = 9.02), indicating that the distractor

413 stimuli were perceived and interfered with search performance. However, no significant interaction

414 between load and congruency was observed, contrary to the predictions of perceptual load theory.

415 Post hoc tests indicated a significant difference in RT between congruent and incongruent trials under

416 both low load and high load conditions, whereas perceptual load theory would predict that this effect

417 should be eliminated or greatly reduced under high load (see Figure 4). Additional analysis indicated

418 that the predictions of load theory were upheld for approximately half the sample, with many

419 participants demonstrating reverse congruency effects (i.e. faster RTs during congruent trials relative

420 to incongruent trials). See Supplemental Materials for further details of these analyses.

421

422                                    [Insert Figure 4 here]

423

424   There was no main effect of stereoscopic depth (2D vs. 3D), however a main effect of stimulus shading

425   was observed, such that longer RTs were observed in response to shaded shapes (M = 753.63 ms, SE

426   = 12.75) than flat shapes (M = 709.44 ms, SE = 12.06). These effects are qualified by an interaction

427   between these two display variables. Post hoc tests revealed that RT in response to the 3D shaded

428   condition (M = 787. 85 ms, SE = 17.54) was significantly higher than RT in the 3D flat (M = 702.56ms,

429   SE = 18.75), 2D flat (M = 716.32, SE = 17.28) or 2D shaded conditions (M = 719.41, SE = 16.54, all p's <

430   .01); none of the other pairwise comparisons showed significant differences.

431

432                                    [Insert Table 2 here]

433

434   A number of three-way interactions were also observed, but were qualified by a four-way interaction

435   of search type, array size, stereoscopic depth and stimulus shading. Figure 5 depicts the overall pattern

436   of effects; a clear interaction between search type and array size is evident across all four display

437   conditions, such that reaction time increases steeply with array size in conjunction search conditions,

438   but not in feature search conditions. The RTs in each cell of this analysis were remarkably similar for

439   the 2D flat, 2D shaded and 3D flat conditions, however in the 3D shaded condition (depicted as thick,

440   solid lines in red for conjunction search and blue for feature search), a sharp increase in overall RT was

441   observed. Thus, the same pattern of interaction between search type and array size was seen under

442   all conditions, but this effect was moderated by the combination of monoscopic and stereoscopic cues

443   to depth, with slower overall reaction times in the 3D shaded condition.

444

445                                    [Insert Figure 5 here]

**Discussion**

We investigated the effects of monoscopic and stereoscopic cues to depth on visual search, with the aim of validating feature integration theory and perceptual load theory in a 3D world. Across two experiments, the predictions of feature integration theory were upheld under both 2D and 3D conditions; a significant interaction of search type and array size was observed, as the slope for feature search trials remained relatively flat while reaction times in the conjunction search trials increased linearly with number of distractors. This provides support for the classic feature integration idea that the target 'popped out' in the low load, feature search trials, but that a serial search was required to identify the target in the high load, conjunction search trials. These data provide support for the validity of feature integration theory under more ecologically valid conditions.

In Experiment 2, this interaction of array size and search type was moderated by a combination of monoscopic and stereoscopic cues to depth. Overall search time was significantly increased in the condition that combined stereoscopic 3D with shaded shapes, but the same pattern of a steep slope in conjunction search trials and flat slope in feature search trials was observed. No other combination of cues resulted in a similar slowing; stereoscopic 3D presented with flat shapes resulted in similar RTs to monoscopic 2D with either flat or shaded shapes. Thus, the addition of stereoscopic 3D and monocular cues to depth – that is, the combination of depth cues typically found in the real world – slowed overall search reaction time, but did not interfere with the typical pattern of search observed in feature integration theory studies (Humphreys, 2016; Quinlan, 2003). Feature integration theory tells us that reaction times increase in conjunction searches because attention is required to bind the features of each item together, and the items are processed serially (Treisman, 1988). The present results indicate that binding the features of stereoscopic depth and stimulus shading into a single three-dimensional percept with colour and shape required extra attention, over and above that required by the addition of either monocular or binocular depth cues alone.

470   The finding that there was no difference in search RT between the 2D flat and 2D shaded conditions

471   indicates that including monocular cues to depth alone does not affect search efficiency. These results

472   are in contrast to previous findings that visual search was negatively affected by the inclusion of

473   monocular (pictorial) depth cues relative to simply presenting the stimuli in 2D (Kyritsis et al., 2013);

474   they also challenge research showing that search is facilitated – i.e. faster – when the constituent

475   polygons of a target image are presented in the form of an apparently three-dimensional object, such

476   as a cube, rather than rearranged into an abstract shape that appears two-dimensional (Enns &

477   Rensink, 1990a, 1990b; Zhang et al., 2015). We suggest that these latter findings may be attributed to

478   the semantic meaning imposed by the organisation of the polygons into a recognisable shape, rather

479   than the representation of depth. The flat stimuli in the present experiment were composed of two

480   features: a shape (e.g. a square) and a colour (e.g. yellow). In contrast, the shaded stimuli were

481   comprised of multiple facets and colours – for example, the red cube had three visible faces rendered

482   in three different red hues to denote depth via light and shade. The parallel slopes during visual search

483   for the flat and shaded shapes suggest that, when presented in 2D, the apparently three-dimensional

484   cube was perceived as a single shape rather than a combination of polygons.

485   Similarly, the absence of a difference between the 2D flat and 3D flat conditions rules out an

486   explanation in terms of stereopsis alone, or any methodological artefact arising from the use of the

487   3D TV screen. Computing depth from binocular disparity and creating a coherent percept from two

488   distinct channels of visual input is an effortful and time-consuming process (Welchman, 2016). One

489   marked characteristic of the 3D shaded stimuli was the illusion of volume and mass. These stimuli

490   consequently afforded the sensation of being able to "reach out and grab" the shapes, which appeared

491   to hang in mid-air. These action affordances during observation of apparently graspable objects

492   engage early attentional processes (Proverbio et al., 2011) and require crosstalk between ventral and

493   dorsal streams, which is increased when stereoscopic and pictorial depth cues are combined (Milner,

494   2017; Verhagen et al., 2008). Thus, we suggest that the provision of both monocular and binocular

495 cues to depth in the current study may have required additional processing time during visual search,

496 as participants computed motor-relevant information.

497 The predictions of perceptual load theory were not upheld in this study: in contrast with the

498 experiments reported by Murphy and Greene (2017b) using the same paradigm, we did not observe a

499 significant interaction of perceptual load and distractor congruency in either experiment. No main

500 effect of distractor congruency was observed in Experiment 1, most likely due to the peripheral

501 placement of the distractor stimulus, however this was addressed in Experiment 2, in which the

502 distractor stimulus was presented centrally and the search array items were presented in a ring around

503 the distractor. A clear distractor congruency effect was observed here, suggesting that participants did

504 process the centrally presented distractor. However, counter to the predictions of perceptual load

505 theory (Lavie, 2005), distractor interference was not found to be reduced under high perceptual load.

506 As the basic predictions of perceptual load theory were not upheld in this study, we were not able to

507 validate the model under 3D conditions. No significant interactions were observed between the critical

508 perceptual load theory variables (perceptual load and distractor congruency) and the display variables

509 of stereoscopic depth and stimulus shading, however in the absence of a significant interaction of load

510 and congruency, these results cannot be reliably interpreted. The principles of perceptual load theory

511 have previously been extended into complex multisensory tasks, including driving (Marciano &

512 Yeshurun, 2012, 2015; Murphy & Greene, 2015, 2016b; Murphy & Greene, 2017a), playing football

513 (Furley et al., 2013) and eyewitness memory (Greene et al., 2017; Murphy & Greene, 2016a);

514 nevertheless, the failure to replicate the basic distractor congruency effect presents a challenge to the

515 model and precludes confirmation of its validity in more complex environments.

516 Marciano & Yeshurun (2017) recently reported large interindividual and intraindividual differences in

517 distractor perception under high and low perceptual load, suggesting that the magnitude of the

518 perceptual load effect may be dependent on specific individual characteristics that vary at both state

519 and trait level. Here we report similar findings; just over half of the sample in Experiment 2 showed

520     the expected reduction in distractor interference under high load, while the remainder experienced

521     the opposite pattern, with larger distractor congruency effects under high load than low load.

522     Combined with Marciano and Yeshurun's results, the findings of the current study suggest that findings

523     from the classic perceptual load theory experiments (e.g. Lavie, 1995; Lavie et al., 2004) may not be

524     as robust as anticipated, or at least that they are dependent on some boundary conditions such as, for

525     example, the display or type of stimuli. However, the data presented in this paper contribute to the

526     validity of feature integration theory as a model for evaluating visual search in a three-dimensional

527     world. The predictions of feature integration theory were upheld by findings from both experiments

528     in the current study. Although this was the case regardless of 2D/3D condition, longer search times

529     were observed in conditions with a combination of monoscopic and stereoscopic depth cues. This

530     suggests that binding features into three-dimensional objects requires greater attentional effort. In

531     the interests of ecological validity, we call for this line of work to be extended beyond the visual domain

532     and to consider the integration of other sensory information as a part of a multimodal process.

533

534

535

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714

715

**Figure legends**

717

718 **Figure 1.** Sample trials of feature (top row) and conjunction (bottom row) searches in the 2D and 3D

719 conditions in Experiment 1. (A) 2D Feature search. The array size is 8 and the distractor orientation is

720 incongruent with the target. (B) 3D Feature search. The array size is 2 and the distractor orientation is

721 congruent with the target. (C) 2D Conjunction search. The array size is 4 and the distractor orientation

722 is congruent with the target. (D) 3D Conjunction search. The array size is 6 and the distractor

723 orientation is incongruent with the target.

724

725 **Figure 2**. Median reaction time for feature and conjunction searches at different array sizes in

726 Experiment 1

727

728 **Figure 3.** Sample trials of feature (top row, panels A and B) and conjunction searches (bottom row,

729 panels C and D) in Experiment 2, using either flat (panels A and C) or shaded shapes (panels B and D).

730 These stimuli were displayed under either monoscopic (2D) or stereoscopic (3D) conditions.

731

732 **Figure 4.** Median RT in congruent and incongruent trials under high load (conjunction search) and low

733 load (feature search) conditions in Experiment 2. **p < .001

734

735 **Figure 5.** Median reaction times during Experiment 2.Blue lines denote feature searches and red lines

736 denote conjunction searches. Stereoscopic depth is represented via solid lines for 3D and dashed lines

737 for 2D. Flat shapes are represented by thin lines and shaded shapes are represented by thick lines.

738 Error bars represent standard error of the mean.

739

740

741 **Tables**

742

743

744 **Table 1.** *Results of the 4-way ANOVA examining effects of search type, distractor congruency, array*

745 *size and 2D/3D group on median search reaction time in Experiment 1.*

746

| Effect | F | df | p | $\eta_p^2$ |
|---|---|---|---|---|
| **Search type** | **121.73** | **1, 39** | **<.001** | **.76** |
| **Array size** | **115.93** | **4, 156** | **<.001** | **.75** |
| Congruency | 0.14 | 1, 39 | .71 | .01 |
| Group (2D/3D) | 0.00 | 1, 39 | .99 | .00 |
| **Search type * array size** | **41.02** | **4, 156** | **<.001** | **.51** |
| Search type * congruency | 0.64 | 1, 39 | .43 | .02 |
| Search type * group | 0.75 | 1, 39 | .39 | .02 |
| Array size * congruency | 0.22 | 4, 156 | .93 | .01 |
| Array size * group | 0.35 | 4, 156 | .85 | .01 |
| Congruency * group | 0.79 | 1, 39 | .38 | .02 |
| Search type * array size * group | 0.46 | 4, 156 | .77 | .01 |
| Search type * array size * congruency | 0.36 | 4, 156 | .55 | .01 |
| Search type * congruency * group | 3.74 | 1, 39 | .06 | .09 |
| Array size * congruency * group | 0.64 | 4, 156 | .59 | .02 |
| Search type * array size * congruency * group | 0.36 | 4, 156 | .55 | .01 |

747

748

*Table 2. Results of the five-way ANOVA examining effects of search type, distractor congruency, array*

*size, stereoscopic depth and stimulus shading on median search reaction time (Experiment 2).*

| Effect | F | df | p | $\eta_p^2$ |
|---|---|---|---|---|
| *Main effects* | | | | |
| **Search type (feature/conjunction)** | **394.96** | **1, 125** | **<.001** | **.76** |
| **Distractor congruency (congruent/incongruent)** | **115.34** | **1, 125** | **<.001** | **.48** |
| **Array size (2/4/6/8/10)** | **333.95** | **4, 500** | **<.001** | **.73** |
| Stereoscopic depth (2D/3D) | 2.43 | 1, 125 | .12 | .02 |
| **Stimulus shading (flat/shaded)** | **6.34** | **1, 125** | **.01** | **.05** |
| *2-way interactions* | | | | |
| Search type * distractor congruency | 2.42 | 1, 125 | .12 | .02 |
| **Search type * array size** | **227.78** | **4, 500** | **<.001** | **.65** |
| Search type * stereoscopic depth | 3.58 | 1, 125 | .06 | .03 |
| **Search type * stimulus shading** | **6.85** | **1, 125** | **.01** | **.05** |
| Distractor congruency * array size | 1.24 | 4, 500 | .29 | .01 |
| Distractor congruency * stereoscopic depth | 0.06 | 1, 125 | .80 | .001 |
| Distractor congruency * stimulus shading | 0.002 | 1, 125 | .96 | .000 |
| **Array size * stereoscopic depth** | **3.96** | **4, 500** | **.004** | **.03** |
| Array size * stimulus shading | 1.86 | 4, 500 | .12 | .02 |
| **Stereoscopic depth * stimulus shading** | **5.49** | **1, 125** | **.02** | **.04** |
| *3-way interactions* | | | | |
| Search type * distractor congruency * array size | 1.67 | 4, 500 | .15 | .01 |
| Search type * distractor congruency * stereoscopic depth | 0.005 | 1, 125 | .94 | .000 |
| Search type * distractor congruency * stimulus shading | 0.03 | 1, 125 | .86 | .000 |
| **Search type * array size * stereoscopic depth** | **3.10** | **4, 500** | **.02** | **.02** |
| **Search type * array size * stimulus shading** | **3.03** | **4, 500** | **.02** | **.02** |
| **Search type * stereoscopic depth * stimulus shading** | **5.70** | **1, 125** | **.02** | **.04** |
| Array size * stereoscopic depth * stimulus shading | 2.04 | 4, 500 | .09 | .02 |
| Distractor congruency * stereoscopic depth * stimulus shading | 1.87 | 1, 125 | .17 | .01 |
| Distractor congruency * array size * stereoscopic depth | 0.71 | 4, 500 | .69 | .01 |
| Distractor congruency * array size * stimulus shading | 1.26 | 4, 500 | .29 | .01 |
| *4-way interactions* | | | | |

| | | | | |
|---|---|---|---|---|
| Search type * distractor congruency * array size * stereoscopic depth | 1.65 | 4, 500 | .16 | .01 |
| Search type * distractor congruency * array size * stimulus shading | 0.74 | 4, 500 | .56 | .01 |
| Search type * distractor congruency * stereoscopic depth * stimulus shading | 0.88 | 1, 125 | .35 | .01 |
| **Search type * array size * stereoscopic depth * stimulus shading** | **2.99** | **4, 500** | **.02** | **.02** |
| Distractor congruency * array size * stimulus shading * stereoscopic depth | | | | |
| *5-way interaction* | | | | |
| Search type * congruency * array size * stimulus shading * stereoscopic depth | 1.25 | 4, 500 | .29 | .01 |

*Note: Significant results (p < .05) are highlighted in bold*
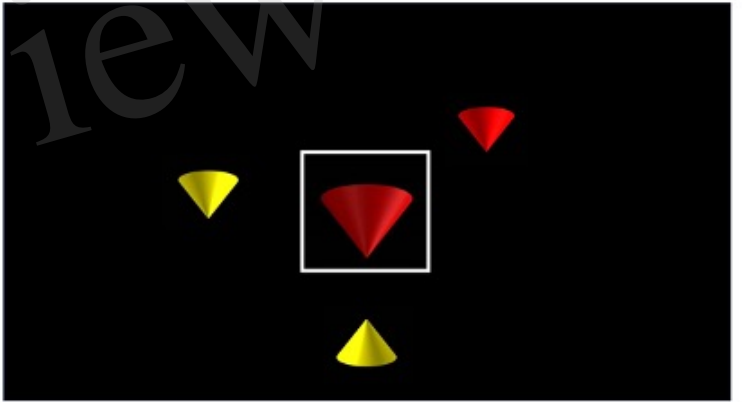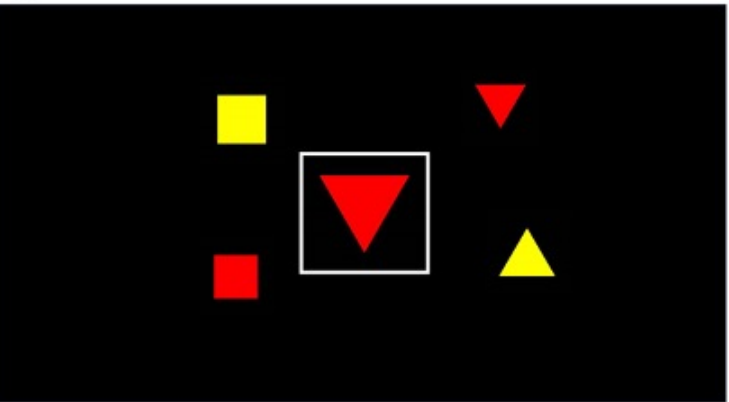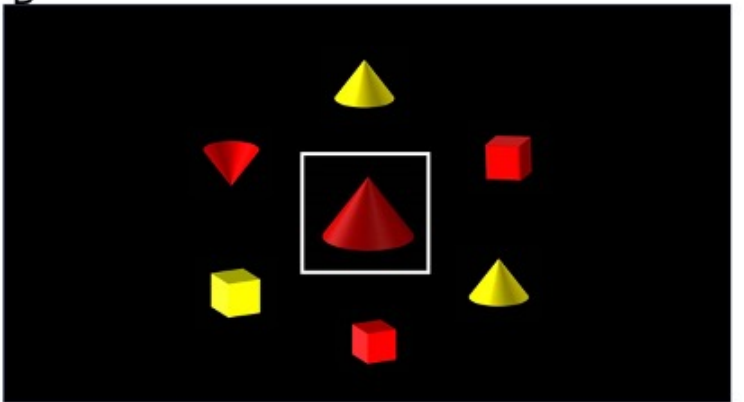
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Figure 1.JPEG
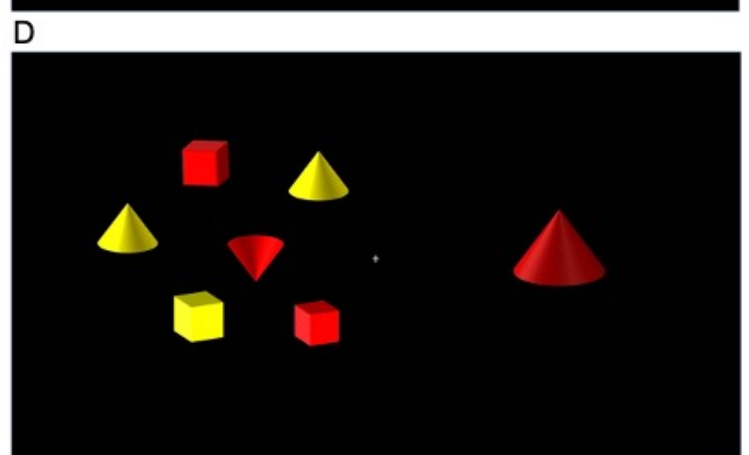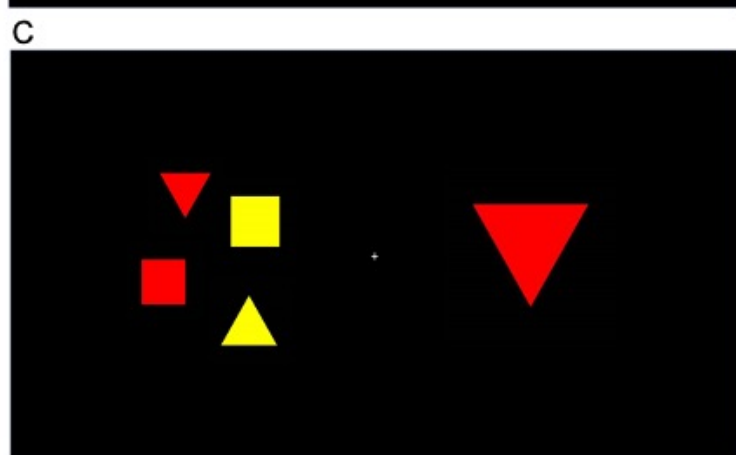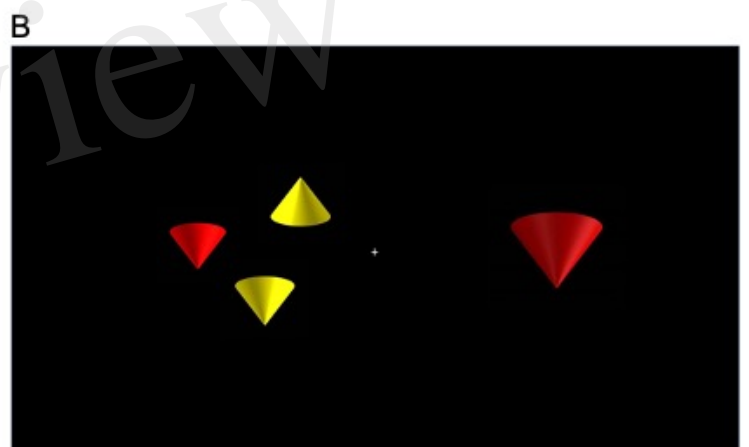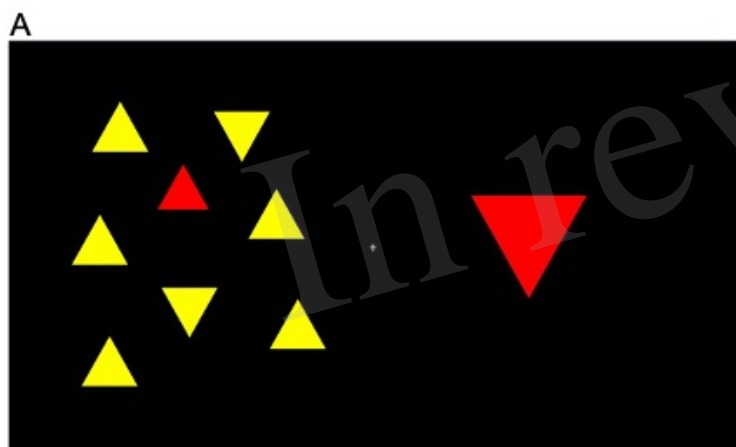
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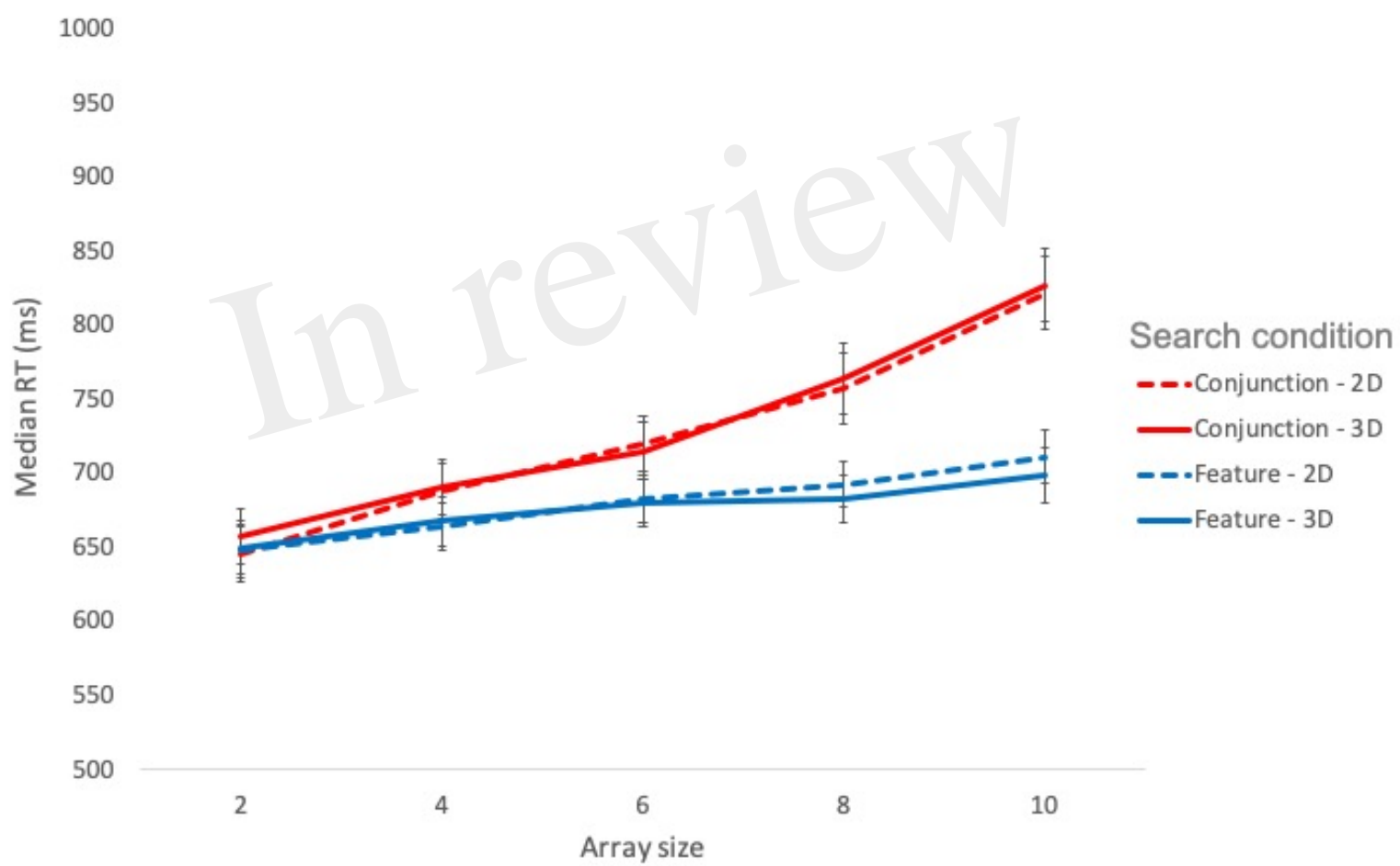
Figure 3.JPEG
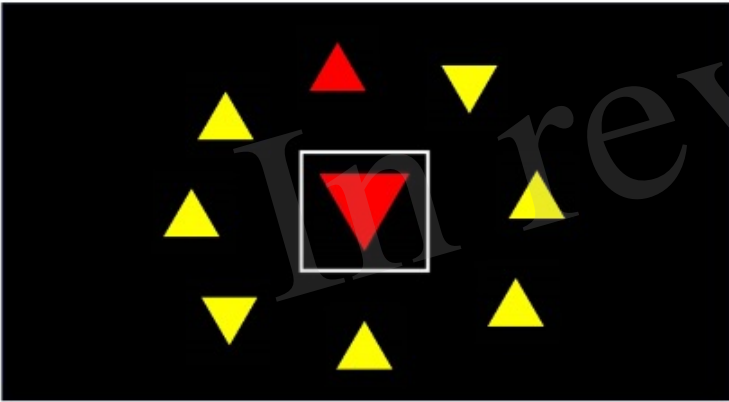
Figure 4.JPEG

Figure 5.JPEG